European Commission

LOW CARBON ENERGY OBSERVATORY

SUSTAINABLE ADVANCED BIOFUELS

Technology market report

EUR 29929 EN

Joint Research Centre

Contact information

Name: Monica PADELLA
Address: European Commission, Joint Research Centre, Ispra, Italy
Email: Monica.PADELLA@ec.europa.eu

Name: Maria GEORGIADOU
Address: European Commission DG Research and Innovation, Brussels, Belgium
Email: Maria.GEORGIADOU@ec.europa.eu

Name: Thomas SCHLEKER
Address: European Commission DG Research and Innovation, Brussels, Belgium
Email: Thomas.SCHLEKER@ec.europa.eu

JRC Science Hub
https://ec.europa.eu/jrc

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Foreword about the Low Carbon Energy Observatory

The LCEO is an internal European Commission Administrative Arrangement being executed by the Joint Research Centre for Directorate General Research and Innovation. It aims to provide top-class data, analysis and intelligence on developments in low carbon energy supply technologies. Its reports give a neutral assessment on the state of the art, identification of development trends and market barriers, as well as best practices regarding use private and public funds and policy measures. The LCEO started in April 2015 and runs to 2020.

Which technologies are covered?

- Wind energy
- Photovoltaics
- Solar thermal electricity
- Solar thermal heating and cooling
- Ocean energy
- Geothermal energy
- Hydropower
- Heat and power from biomass
- Carbon capture, utilisation and storage
- Sustainable advanced biofuels
- Battery storage
- Advanced alternative fuels

How is the analysis done?

JRC experts use a broad range of sources to ensure a robust analysis. This includes data and results from EU-funded projects, from selected international, national and regional projects and from patents filings. External experts may also be contacted on specific topics. The project also uses the JRC-EU-TIMES energy system model to explore the impact of technology and market developments on future scenarios up to 2050.

What are the main outputs?

The project produces the following report series:

- Technology Development Reports for each technology sector
- Technology Market Reports for each technology sector
- Future and Emerging Technology Reports (as well as the FET Database).

How to access the reports

Commission staff can access all the internal LCEO reports on the Connected LCEO page. Public reports are available from the Publications Office, the EU Science Hub and the SETIS website.

Acknowledgements

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Abstract

This Technology Market Report for Sustainable Advanced Biofuels has been carried out on behalf of the Commission by the UK-based contractors E4tech Ltd, following an open call for tender. Their deliverable report is included in the Annexes.

The JRC team in charge of the technology development assessment of sustainable advanced biofuels has subsequently summarised the findings of the E4tech investigations herewith, and added our own independent critical assessment of that work. While broadly in agreement with their findings, the JRC does make some important clarifications and qualifications to the E4tech report.

1 Introduction

1.1 Scope and basis of the report

The aim of the present deliverable in the framework of the LCEO is to present a market report on Sustainable Advanced Biofuels. The report notes both recent developments in this area, and explores longer term perspectives (to 2030) for these technologies. 'Advanced biofuels' are defined as those produced from ligno-cellulosic, non-food and non-feed biomass, corresponding largely to those feedstocks in the Annex IXA and B lists of the Renewable Energy Directive II (RED II)[1]. More information on this important legislation is included further in the report. These biofuels could play a potentially important role in decarbonising the transport sector and offer an economic opportunity to the EU, but many technologies are still at an early stage of development.

1.2 Introduction to subcontracted study

The company E4tech was selected as a subcontractor to provide a complete picture of the recent market status and development trends in the advanced biofuels technologies sector, both in Europe and globally. Their main tasks were to:

- Provide a concise description of recent market trends and technology deployment including for the pathways specified in Table 1, both in Europe and globally
- Compile a listing of significant major active companies and industrial players
- Compile a listing of significant demonstration projects currently running or in development, and of the first-of-kind commercial systems for the sub-technology pathways identified in Table 1
- Provide a concise assessment of the market outlook for future developments for the same technology pathways, both in Europe and globally. The outlook time horizon was for the near and medium term (i.e. up to 2030), and included a consideration of barriers to future technology development and market uptake
- Provide a concise assessment of the qualitative and quantitative information on existing support mechanisms/incentives and support policies aimed at promoting both R&D and corporate investments for advanced biofuels (and by sub-technology whenever possible), both in the EU and globally.

1.3 Technologies considered

The technologies considered in this work are summarised in Table 1. In an earlier LCEO report, a more detailed description of the majority of these individual technologies has been given; interested parties are therefore invited to review the associated Technology Development Report on Sustainable Advanced Biofuels; LCEO deliverable D2.2.12 (2018). Also in chapter 4 of the E4tech report and its associated technology overview sub-sections, more details on the Table 1 technologies can be found (see E4tech, 2018).

[1] In November 2016, the Commission released its 'Clean Energy for all Europeans' initiative, and as part of the package, adopted a legislative proposal for a recast of the Renewable Energy Directive. Most recently, the RED II was adopted by the Council on 4 December and will be published on 21 December 2018

Table 1 Conversion pathways and advanced biofuels produced: source E4tech (2018)

Conversion pathway	Acronym	Advanced biofuel produced
1. Enzymatic hydrolysis and fermentation	2G alcohol	2G ethanol, 2G butanol,
2. 2G alcohol catalysis (ETD, ATJ, MTG)	2G catalysis	Diesel, jet, gasoline
3. Aqueous phase reforming (APR) of 2G sugars with catalytic upgrading	APR	Diesel, jet, gasoline
4. Aerobic fermentation of 2G sugars	S2D	Diesel, jet, gasoline
5. Anaerobic digestion (AD) with pre-treatment	Pretreat+AD	Biomethane
6. Gasification with Fischer-Tropsch	Gasif+FT	Biomass-to-liquids (BtL) fuels
7. Gasification with methanation	Gasif+SNG	Synthetic natural gas (SNG)
8. Gasification with syngas fermentation	Gasif+ferment	Ethanol, isobutene
9. Gasification with catalytic synthesis	Gasif+alcohol	Methanol and other alcohols
10. Fast pyrolysis with catalytic upgrading	Pyrolysis	Diesel, jet, gasoline
11. Hydrothermal liquefaction (HTL) with catalytic upgrading	HTL	Diesel, jet, gasoline
12. Transesterification of residual/waste oils and fats	FAME	Fatty acid methyl ester (FAME) biodiesel
13. Hydroprocessing of residual/waste oils and fats	HVO	Hydrotreated vegetable oils (HVO) diesel, hydroprocessed renewable jet (HRJ)
14. Co-process of residual/waste oils and fats	Co-process	Hydrotreated vegetable oils (HVO) diesel, hydroprocessed renewable jet (HRJ)
15. Microalgae		

1.4 E4Tech report

E4tech (2018) delivered a project report with comprehensive data and documentation on the findings of the afore-mentioned tasks (see Annex 1 of the present report).

Both pieces of work are of high quality and provide useful information on which this report is based. 249 individual plants were identified for the fifteen technologies assessed, namely: enzymatic hydrolysis and fermentation, 2G alcohol catalysis (ETD, ATJ, MTG), aqueous phase reforming (APR) of 2G sugars with catalytic upgrading, aerobic fermentation of 2G sugars, anaerobic digestion (AD) with pre-treatment, gasification with Fischer-Tropsch, gasification with methanation, gasification with syngas fermentation, gasification with catalytic synthesis, fast pyrolysis with catalytic upgrading, hydrothermal liquefaction (HTL) with catalytic upgrading, transesterification of residual/waste oil and fats, hydroprocessing of residual/waste oil and fats, co-processing of residual/waste oils and fats in refineries, microalgae. As microalgae is a feedstock rather than a conversion technology, it was not included within E4tech's analysis of plants or players, but a market overview covering costs and major players in this area was provided by them in section 4 of their report (2018).

2 Technology trends and prospects

2.1 Supportive legislation for advanced biofuels

In RED II, the overall EU target for Renewable Energy Sources consumption has been raised to 32% by 2030, up from the previous figure of 20% by 2020. A transport sub-target wasn't included originally, but has been introduced in the final agreement. This requires Member States' fuel suppliers to supply a minimum 14% renewable energy in the energy consumed in road and rail transport by 2030.

Importantly for advanced biofuels, within the 14% transport sub-target, there is a new dedicated target for advanced biofuels produced from feedstocks listed in Part A of Annex IX of RED II. These advanced biofuels must supply a minimum of 0.2% of transport energy by 2022, 1% by 2025, and at least 3.5% by 2030.

Since 2015, a 7% cap for food/feed-competing feedstocks has already been established to comply with the mandatory 10% renewables transport sub-target in the existing RED (the so-called ILUC Directive (EU) 2015/1513). Given the regulatory framework in the EU, technological and market research in Europe is largely focussed on advanced biofuels, a situation which is expected to continue – or even consolidate – upon the entry into force of RED II as of January 2021.

2.2 Comparison of capacity with MSs advanced biofuel targets

Twenty six EU Member States (MSs) have biofuel blending mandates, while two countries Sweden and Germany, promote biofuels use through tax exemptions and GHG reduction targets respectively. While most MSs do not have sub-targets for advanced biofuels (as of 2018, six MSs have adopted legally binding targets for advanced biofuels[2]), twenty two MSs promote the use of advanced biofuels by allowing them count double towards their national targets. Such "double-counting" legislation varies between MSs. The iLUC Directive's Annex IX (Directive 2015/1513) does have a list of feedstocks which it considers qualify for advanced biofuel production, and thus are eligible for double counting, but MSs do not have to use this definition. Furthermore, the exact criteria for fuels to double-count varies between MSs. For more precise details on the legislative intricacies, please see section 5.1.1 of E4tech (2018)[3].

Despite these intricacies, E4tech (2018) manages to make a comparison between the aforementioned six MSs advanced biofuel targets and capacities in industry. In essence, current advanced biofuel targets for the six MSs can be met many times over if the fraction of HVO and FAME capacities which process advanced feedstocks are taken into account; if not then the remaining advanced biofuel capacities are considerably below the targets. The report also notes that the current advanced biofuel target is small compared to the overall biofuels target of the six MSs (see Figure 1).

2.3 JRC Overview: R&D investment and patenting activity

Regarding funding, biofuels in the EU have been receiving funding from different sources, such as:

- EU wide research and development programmes (such as FP7, H2020 and so on);
- national research programmes of Member States;

[2] These MSs advanced biofuel targets may or may not use the 'Annex IXA' definition of advanced biofuels.

[3] Please note, in this section of their report, E4Tech quote an Annex IXA consumption figure in 2016 of 3,842 ktoe. However, this figure originates from Eurostat and refers to *total* Annex IX biofuels (therefore it includes consumption of biofuels made from UCO and tallows).

- private companies and research institutions.

Figure 2 presents the public and private R&D in the EU during the period 2004-2014. Private R&D investment is steadily higher in the given period reaching the maximum value of 1 billion EUR in 2007. This peak and the general trend could be explained by a number of factors such as the economic crisis, the approval of the Renewable Energy Directive in 2009 and the debate on the indirect land use change (ILUC) impact which greatly affected first generation biofuels.

Detailed information on the patenting activities as well as in EU funded projects can be found in the Technology Development Report on Sustainable Advanced Biofuels (Deliverable D2.2.12 of the LCEO).

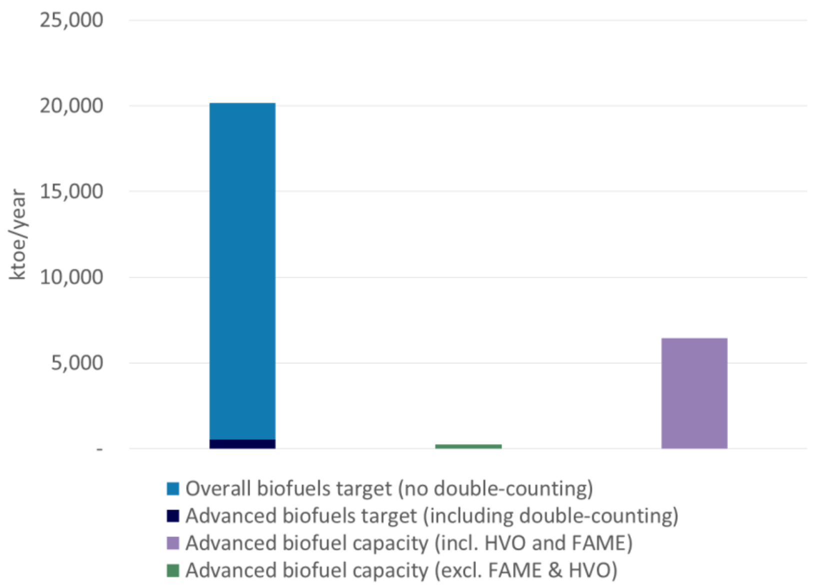

Figure 1 Advanced biofuel current capacity compared to biofuel requirements to achieve targets in the six MSs (source: E4tech, 2018)

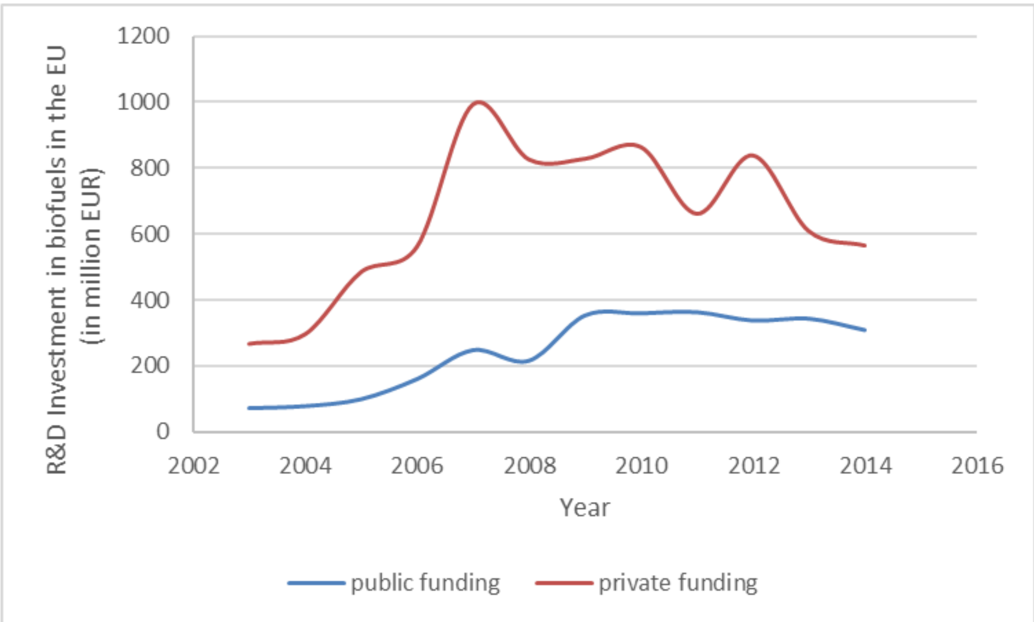

Figure 2 Public and private R&D investment in biofuels in the EU during 2004-2014. Source: JRC based on data from the IEA (2018) and own estimates.

A measure of the specialisation of a country/region in one technology is the Specialisation Index. The Specialisation Index represents patenting intensity in a given technology (e.g. biofuels) for a given country relative to the geographical area taken as reference (in this case, the world) (Fiorini et al., 2017). It is defined as the share of the number of biofuels patents in the total number of energy related patents in the EU, divided by the equivalent global number of patents, minus 1. According to the SI definition, for each country, when SI = 0, intensity is equal to the world's, when SI < 0, intensity is lower than in the world and when SI > 0, intensity is higher than in the world. Figure 3 presents the Specialisation Index regarding biofuels for selected countries (EU, US, China, Japan, Korea and Rest of the World). During the period 2004-2014, fluctuations of the SI have been observed globally without a clear trend. In the period mentioned, the EU SI ranged from -0.101 to 0.334 and the US from -0.509 to 1.000, respectively.

Additionally, Figure 4 summarises the global trends in high value patents (e.g. it refers to patent families that include patent applications filed in more than one patent office) for biofuels during the decade 2004-2014 and highlights the position of the EU as a global player. EU and US are the leaders in patenting activity with 150 and 110 high value inventions in 2012, respectively. Despite the decreased number of patents after 2012, both in the EU and the US, the EU dominates the field confirming in this way the strong international presence of the EU companies.

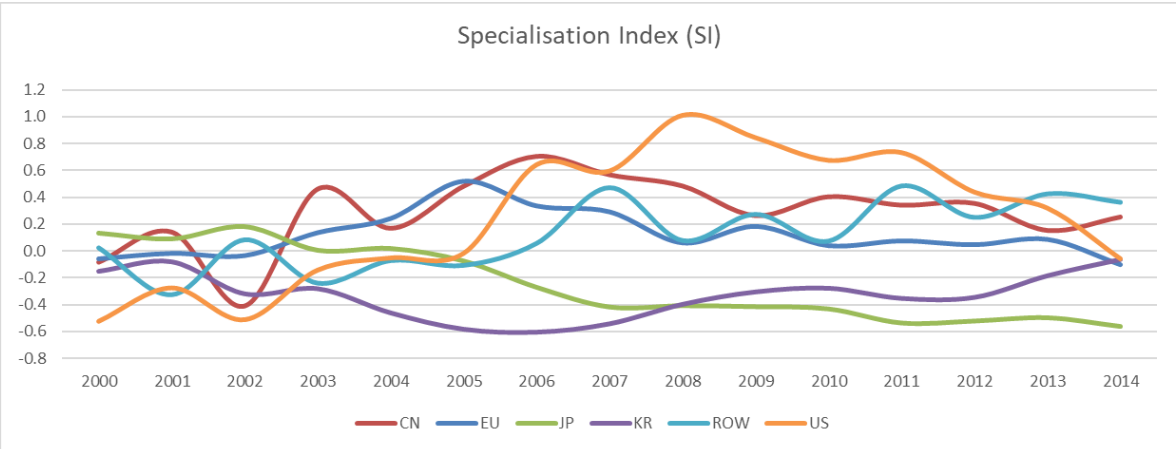

Figure 3 Development of specialisation index in biofuels in the EU and the rest of the world. Source: JRC based on data from the European Patent Office (EPO, 2018)

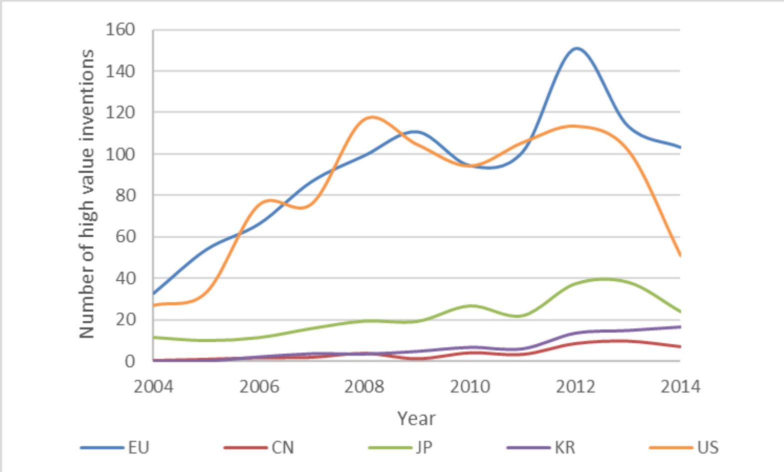

Figure 4 Global trends in high value patents for biofuels technologies. Source: JRC based on data from the European Patent Office (EPO, 2018)

3 Market Overview

3.1 Introduction

Considering the market situation, the current and planned global production capacity for each advanced biofuels' technology covered in the present report is summarised in Figure 5. The dedicated production of FAME and HVO from oil-based feedstocks is not presented in the graph, since it is already a commercial process (TRL 9), with a market structure substantially different to the other routes that are not yet fully commercialised (although co-processing is included). The current global installed capacity of dedicated production of FAME is estimated at 50,000 ktonnes/year, whereas for HVO it is 4,200 ktonnes/year.

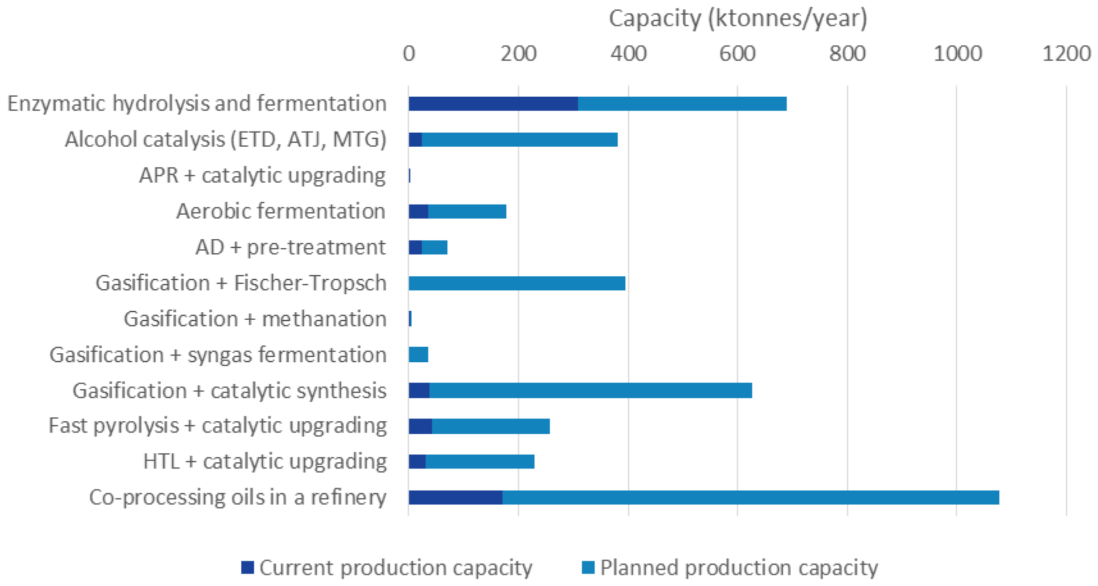

Figure 5 Existing global production capacity and planned capacity, of advanced biofuel plants, excluding FAME and HVO. Source: E4tech

Therefore, the production of FAME and HVO is much higher than the other advanced biofuel routes within scope of this study, and there are many more players globally including large and diversified fuels companies. The other technology routes which are at TRL 8 or below are those which use ligno-cellulosic or waste feedstocks. For these technologies, there are far fewer companies involved in developing each technology, and they often have a narrow focus on one particular route. Substantial additional plant capacity is planned across the advanced biofuel technologies, albeit from a low base, testifying to interest in the sector.

The production of ethanol from enzymatic hydrolysis and fermentation is an exception amongst the ligno-cellulosic technologies in that there are over 20 companies across the globe developing the technology, and several have started to license it to third party project developers. The contractor's report does qualify this somewhat, by noting that some of these companies are working to convert corn kernel fibre into ethanol, a process often referred to as 1.5 generation ethanol.

The current installed production capacity of ligno-cellulosic ethanol is significantly higher than any of the other ligno-cellulosic routes, but many plants are not operating at full capacity and some have been shut down. Anaerobic digestion pre-treatment is also being developed by a relatively large number of companies, but current installed capacity is low as plants tend to be small. Within the EU, all MSs have a blend mandate for biofuels, with the exception of Germany which has a GHG target and Sweden which provides tax exemptions for biofuels. In the majority of countries advanced biofuels count twice towards these overall biofuel targets, but as of mid-2018 only six EU MSs had adopted specific and binding targets for advanced biofuels. Current EU installed capacity of advanced biofuels is 250 ktonnes/year, rising to 6,500 ktonnes/year when pure HVO and FAME production which process advanced feedstocks are included as mentioned previously.

3.2 Summary of EU position in the Global Market

As can be seen from Figure 5 some advanced biofuels already have significant production capacities, while others have practically zero. In order to see how the EU shapes up with respect to the global situation for advanced biofuels, we first considered biofuels with production capacities of a reasonably significant volume, and then considered biofuels whose production is still at a more experimental stage. Biofuels which have production capacities of some significance are; (i) enzymatic hydrolysis and fermentation, (ii) co-processing (the leading capacity of these can be clearly seen in Figure 5), and (iii) FAME and HVO production made using advanced feedstocks.

- With regards **enzymatic hydrolysis and fermentation** plants, only a very minor fraction of current capacity for this technology is in the EU; the vast majority is situated in the RoW. However when *planned* capacities are considered, the situation is somewhat reversed, with a greater amount of capacities being planned for the EU compared to elsewhere (please see Table 2 in E4tech (2018)).
- **Co-processing** typically involves oil refineries and successful operations tend to be at very considerable production sizes. The large current capacity of this technology is dominated by one active company, and they are based in the EU. According to the E4tech report, no plants are operating with this approach outside of the EU. The situation for the future seems to very much tilt towards RoW; with a considerable 905 ktonnes co-processing capacity being planned outside the EU (please see Table 40 in E4tech (2018)), and no new EU plants at least publicly planned or under construction (information correct as of mid-2018).
- For **FAME**, the transesterification of waste oils and fats is currently dominated in terms of capacities by the EU. The relevant table in the E4tech report provides a non-exhaustive list of the major waste oil and fat FAME producing companies, and highlights those developing novel FAME technologies. For **HVO**, current capacities are approximately even when comparing the EU with RoW, and facilities tend to be of very large capacity and few in number; the industry is dominated by one EU-based company which have facilities both within and outside of the EU.

Comparatively speaking, the other advanced biofuel technologies have very low production capacities, so in these instances the split between (a) the number of plants and (b) the number of active companies was used as a means to compare the situation in the EU vs RoW. The geographical split for these technologies has been summarised in Table 2 on the next page.

Regarding the relevant shares, for gasification with methanation, and AD with pre-treatment, the EU has by far, the majority of companies and plants compared to the RoW. More noticeably, for gasification with syngas fermentation, and APR of 2G sugars with catalytic upgrading, all of the companies and plants are situated outside the EU. For the remaining Table 2 technologies, the general trend is there are both less companies and plants in the EU compared to the RoW. This is most notable for HTL with catalytic upgrading, which has only 22% of the companies and 6% of plants. The 2G alcohol catalysis pathway has just 3 facilities in total; one large-scale, one a pilot plant, and a third at lab scale, but the large scale plant is in the EU.

Concerning the market for the technology providers or for equipment manufacturing companies, using the information provided by E4tech, the JRC considered the advanced biofuel pathways for which EU companies have a significant global share of all the companies involved in that technology (see first column above). And it can be seen these EU companies are developing and working with their own technologies, i.e. technologies they created in-house, as opposed to relying on outside expertise. So in theory if these fuel pathways become proven industrially, the same companies should be in a position to sell their technologies and expand into other markets outside the EU.

Table 2 EU market share vs RoW for low production capacity advanced biofuel technologies

Advanced Biofuel Pathway - EU market share vs RoW	% of all companies in the world based in EU	% of all plants in the world based in EU
2G Alcohol Catalysis	33	0
Aqueous phase reforming (APR) of 2G sugars with catalytic upgrading	0	0
Aerobic fermentation of 2G sugars	50	30
Anaerobic digestion (AD) with pre-treatment	75	59
Gasification with Fischer-Tropsch	27	33
Gasification with methanation	88	100
Gasification with syngas fermentation	0	0
Gasification with catalytic synthesis	44	29
Fast pyrolysis with catalytic upgrading	45	25
Hydrothermal liquefaction (HTL) with catalytic upgrading	22	6

4 Market Outlook

4.1 E4tech Non-technical barriers

The deployment of sustainable advanced biofuels is hampered by technical as well as non-technical barriers. This analysis presents the most important non-technical barriers as identified by the contractors (for a full-list of the non-technical barriers, see Annex I).

Non-technical barriers impacting the supply of advanced biofuels have been identified and assessed. These barriers fall into one of four key areas:

- Project finance;
- Feedstock;
- Infrastructure, and;
- Environmental and social barriers.

Concerning ***project finance***, high capital cost and capital risk and shortage of long-term strategic investors are identified as the key barriers with most impact. Use of insurance schemes and development of funding mechanisms are proposed as measures to mitigate the effect of these barriers.

Variable ***feedstock*** quality (lack of specifications/standards) and feedstock availability are considered the most important barriers with regard to feedstock availability. Therefore, the establishment of feedstock specifications/standards by the industry and/or the government is proposed as a way to overcome this problem. Upstream investment in projects, governmental infrastructure grants and lending (e.g. for storage facilities) could contribute as well.

Concerning ***infrastructure*** constraints, identified barriers in the E4tech Market Outlook study vary per fuel, in some case the lack of vehicle homologation/compatibility with fuels are prime issues, while for other fuels an immature supply chain for feedstocks or an immature supply chain for technology components are the main blocking factors. Potential mitigation measures include: customer education campaigns; direct subsidies, sales tax/VAT exemptions, toll or parking waivers, access to priority lanes or zones; standards for higher alcohol blend levels, but also the development of regional feedstock exploitation plans to raise awareness about supply, mobilisation and use; government investment/loans for harvesting, collection, storage, as well as delivery contracts with penalties for delay, insurance and forex hedging.

With regard to ***environmental and social barriers***, unclear sustainability characteristics of feedstocks (e.g. soil quality, water, forestry carbon debt, biodiversity) and lack of factual knowledge about advanced biofuels (public awareness & perception) are considered to have a medium impact. These constraints could be overcome with: investment in sustainability research (e.g. field trials, modelling) to promote transparent tracing along the supply/production chain on the one hand, and public education campaigns, on the other.

The non-technical barriers on the demand side are grouped in two categories:

- market barriers, and;
- policy and regulatory barriers.

Lack of understanding of market size and value as a result of policy mechanisms is considered to have the highest impact. An appropriate policy framework designed to send clear pricing and demand signals; market/subsidy pricing and likely actions if under/over-supply is clearly communicated; publication of projections of market sizes and underlying assumptions could be used as mitigation measures.

With respect to policy, the lack of a clear long-term strategy, the limited policy attractiveness, and the lack of a strong decarbonisation driver for aviation & marine fuels are identified as the highest risks. The proposed measures to mitigate these risks in the EU include: the adoption of RED II; harmonised implementation rules among Member States (MS); clear commitment and rules with respect to the 2050/Paris targets, and focus on the importance of low carbon fuels; support floor prices at MS level; greater cooperation between MSs, agreement between voluntary schemes and fuel suppliers to double-counting lists; national level policies for the decarbonisation in aviation and shipping sectors (e.g. include these sectors within national targets, tax and incentive schemes).

4.2 E4tech Model results

As already mentioned, most of the 'advanced biofuels' technologies are at an early stage of deployment and are not widely commercially available. Therefore, their deployment to 2030 is likely to be limited by technology development, number of companies developing new technology, how quickly new production plants can be built, and willingness of investors to fund new plants. Given the large degree of uncertainty in how these factors will vary to 2030, different assumptions were used, grouped under three different scenarios: challenging growth, technology success, and RED II stretch. These scenarios (summarized in (**Table 3**) differ in terms of the following assumptions:

- Initiation rate (number of N^{th} commercial projects that start construction per year (globally), per developer)
- Launch-point (number of years of operation of plant required before the next scale-up of plant)
- Success rate (probability of any particular project being successful from inception to operation)

The potential global production of advanced biofuels in 2030 under the first two principal scenarios is summarised in Figure 6, broken down between the EU and the rest of the World. The production of FAME and HVO from oil-based feedstocks is already a commercial process (TRL9) and the market structure for these routes is significantly different to the other routes which are not yet fully commercialised. Therefore, these routes are excluded in the modelling for the market outlook in 2030. In the technology success scenario, the production of advanced biofuels (excluding HVO and FAME) in 2030 is expected to raise above 12,000 ktonnes/year globally according to findings of E4tech. On the contrary, in the challenging growth scenario it is projected to be just under 6,000 ktonnes/year.

Table 3 Summary of assumptions across the three scenarios for advanced biofuel deployment to 2030 (Source: E4tech (2018))

Scenario	**Challenging growth**	**Technology success**	**RED II Stretch (not presented)**
Initiation rate	1 for all technologies apart from AD, 5 for AD	2 for all technologies apart from AD, 10 for AD	Between 3 and 5 for all technologies apart from AD, 25 for AD
Launch-point	1 – 3 years	0.5 - 2 years	0 – 1 years
Success rate	50-90%	75-95%	100%

A breakdown of the production volumes in EU for each technology is given in Figure 7 (for a challenging growth scenario) and in Figure 8 (for a technology success scenario). In the two scenarios modelled by the contractors, a common pattern is observed in that 2G alcohol is clearly, and by a considerable margin, the dominant technology from the middle of the next decade onwards. The '2G Catalysis' in Figure 7 and Figure 8 route uses part of the 2G alcohol production, i.e. it is not additional, but it inherently assumes large-scale production of 2G Alcohol will occur.

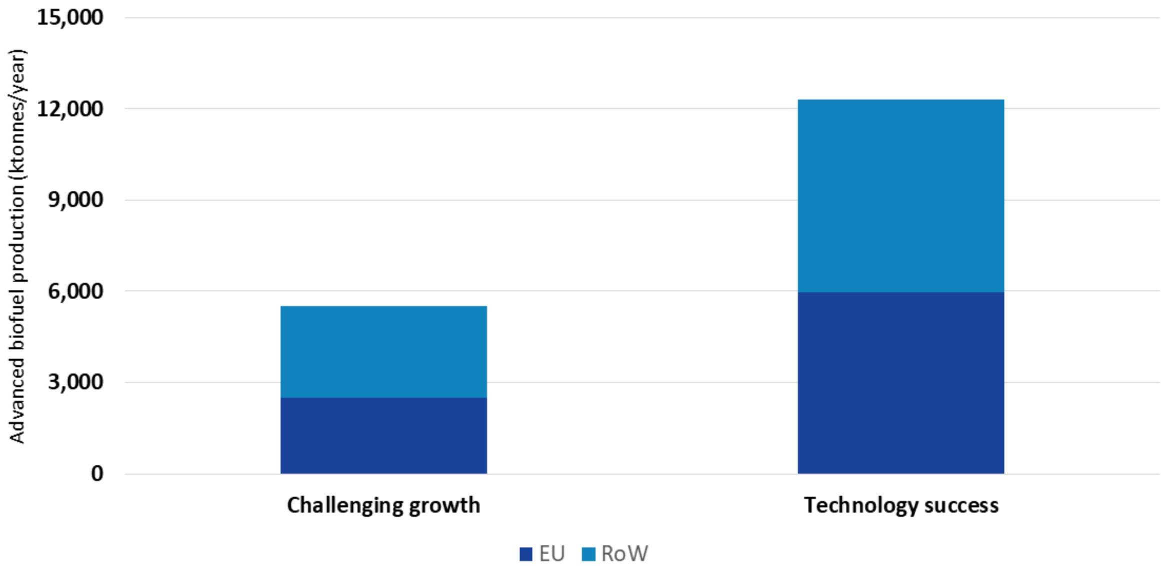

Figure 6 Global advanced biofuel production potential in 2030 across the two scenarios (excl. FAME, HVO, co-processing and alcohol catalysis) Source: E4tech (2018)

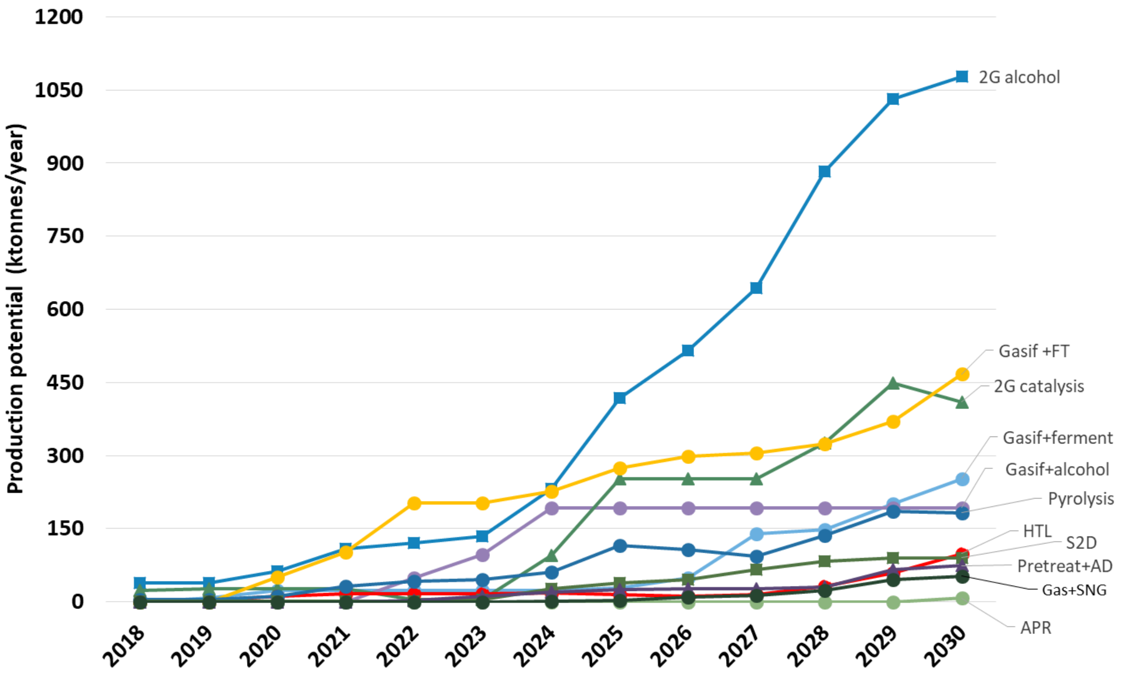

Figure 7 Anticipated EU production potential to 2030 under the challenging growth scenario (Source: E4tech, 2018)

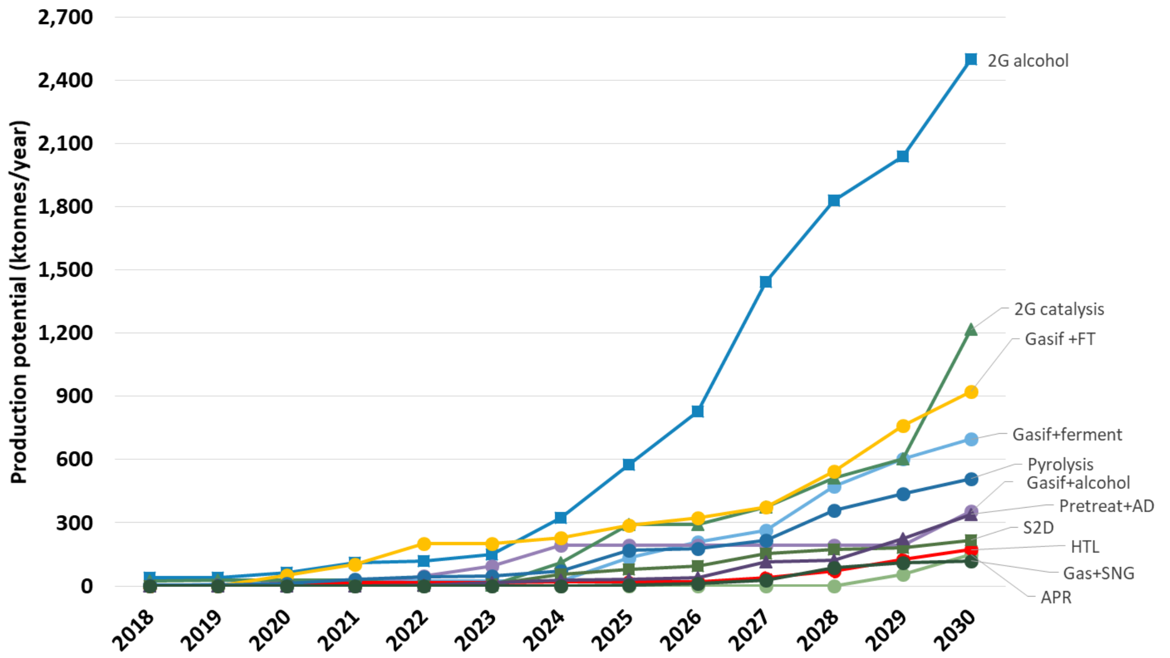

Figure 8 Anticipated EU production potential to 2030 under the technology success scenario. Source: E4tech, 2018)

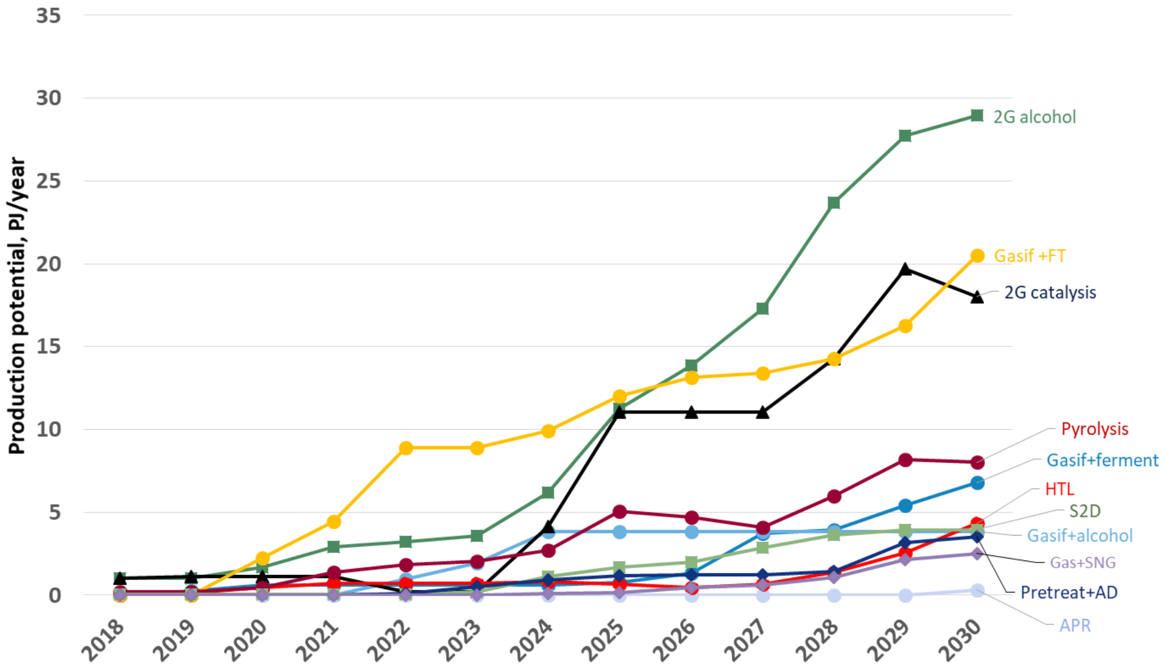

Figure 9 Anticipated EU production potential to 2030 under the challenging growth scenario, in terms of energy contents of final fuels. Source: E4tech, 2018

In the challenging growth scenario (see **Figure 9**), the projected production increases are more linear for the other fuels - there is not the notable rise in production as foreseen for 2G Alcohol from 2024 onwards. Gasification + Fischer-Tropsch and some pyrolysis appear to be the most produced fuels, although 2G Catalysis production eventually rises to become practically the next-most produced fuel by 2030. A similar situation can be seen in the 'technology success scenario', a more linear growth for the other fuels is foreseen, and by 2030, 2G Catalysis fuels followed by Gasification + Fischer-Tropsch fuels show the next highest production levels respectively.

It should be noted that even global deployment of advanced biofuels is insufficient to reach the 3.5% target without double-counting in the two principal scenarios. Therefore, a third scenario 'RED II stretch' was developed by the contractors in order to demonstrate the rate of capacity increase that would be required in order to meet these targets. However, the 'RED II Stretch' scenario is considered over-optimistic and the anticipated biofuels production per pathway under this scenario is not presented.

The large production advantage foreseen by the model for 2G Ethanol appears less pronounced when describing production volumes in terms of total energy content produced as opposed to tonnes. This is due to the comparatively lower energy content of per tonne of ethanol compared to the pure hydrocarbon nature of the two next closest pathways, namely 2G Catalysis and Gasification + Fischer-Tropsch.

4.3 E4tech and JRC-EU-Times Model results comparison

The JRC-EU-TIMES model offers a tool for assessing the possible impact of technology and cost developments: it is used throughout the LCEO project both for the technology and market reports, where applicable. The JRC-EU-TIMES model represents the energy system of the EU28 plus Switzerland, Iceland and Norway, with each country constituting one region of the model. For the purpose of the present report, high-level comparison between E4tech and JRC-EU-TIMES models is presented in the remainder of this section whereas more detailed information on the JRC-EU-TIMES model itself is provided in Annex 3.

Inherent differences in modelling approaches

There are significant and fundamental differences between the JRC-EU-TIMES and E4tech models which make direct comparison of their results challenging. JRC-EU-TIMES model uses a bottom-up approach in a sense that technologies are represented explicitly. The model can however also include top-down (or normative) elements that represent limitations or policies. Specifically for 2nd generation biofuel, the model projects the achievement of at least 3.5% of transport-generated energy demand by 2030. The model is designed to analyse the role of all energy technologies and their innovation needs in order to meet European policy targets related to energy and climate change. The model provides estimates on the cost effective technology pathways for the EU to meet its climate and energy goals under different energy scenarios (Nijs et al., 2018). In particular, the JRC-EU-TIMES model contains scenarios based on the degree to which CO_2 emissions would need to be reduced in future, with either a "business as usual approach" or a future with a much reduced level of CO_2 emissions.

In contrast, the E4tech model uses a bottom-up approach that considers technical as well as non-technical barriers and a specific focus on the potential development of advanced biofuel supplies up to 2030. It has separate sub-considerations for "pre-commercial" routes i.e. those at pilot or demo scale and "commercial" routes i.e. those using waste oils and fats but which are commercially successful and established, such as FAME, HVO and co-processing. The former require assumptions on the rate of technology success in order to get an idea as to how successful they will be in future, while the latter, already successful with millions of tonnes of annual production in the EU alone currently, have a different constraint to their future expansion, namely the need to be able to source increasing amounts of sustainable feedstock supply.

Regarding feedstocks, JRC-EU-TIMES model considered wood resources as the main advanced biofuel feedstock, while E4tech considered principally waste oils and fats (for advanced HVO, FAME and co-processing production), followed by a general lignocellulosic material category which includes materials such as corn stover, straw and energy grasses. In particular E4tech refer to the list of feedstocks in Annex IX of EU Directive 2015/1513 (included in Annex 2 of this document).

Geographically and regarding timeframes there are also differences between the models; JRC-EU-TIMES model considers EU developments while E4tech's model considers developments in both the EU and the rest of the world (RoW). And while both models consider what will happen up to 2030, JRC-EU-TIMES model extends its analysis further to 2040 and 2050.

JRC-EU-TIMES model has a future cumulative capacity of 2nd generation biofuel production which directly comes from a pre-defined target: in other words, the model works towards achieving at least 3.5% of transport-generated demand for energy in 2030 using 2nd generation biofuel. Conversely, the E4tech model computes projected production capacity of 2nd generation biofuels in 2030 elaborating on an analysis of planned and running production plants (see Annex 1, Section 7.2).

Results comparison

Due to the conceptual differences between the two models, comparative aspects are discussed at a broad level. Both models foresee an increase in the production of 2nd generation biofuels. The JRC-EU-TIMES model anticipates a cumulative capacity of 2nd generation biofuel production in 2030, which is seen to increase in all scenarios (Nijs et al, 2018), and which directly comes from the target used in the model. E4tech model results foresee a trend of increasing production capacity up to 2030 and – differently from one of the assumptions made in JRC-EU-TIMES – the option of CCS linked to biofuel production was not considered in E4tech's analysis. Conversely, E4tech analysis includes RED II Annex IX (b) feedstocks (i.e. used cooking oils (UCO) and animal fats/tallow which are capped at 1.7% of transport-generated demand for energy in 2030.

Results regarding future advanced biofuel production capacities are given by the JRC-EU-TIMES model in terms of PJ, therefore it's easiest to consider the E4tech results in the same units. Furthermore, E4tech's results are presented as "production potential" in a given year which corresponds to 90% of plant capacity, itself assumed to be the maximum production plants can realistically achieve. For reporting, they split biofuel production into routes using (i) ligno-cellulosic based feedstocks (which they term 'pre-commercial technology routes'), and (ii) waste oils and fats type feedstocks, which already have a comparatively much higher production level, i.e. the FAME, HVO and co-processing routes. Importantly, the E4tech results for these latter routes are only considered at a global basis. Therefore we consider future production levels for biofuels made from the other (lignocellulosic) types of feedstocks, for which E4tech have provided future EU scenarios.

E4tech considered briefly a third scenario wherein the REDII's 2030 target of 3.5% of transport energy demand from Annex IX (a) type biofuels is met, equating to roughly 500 PJ/year, although with so-called 'double-counting' rules, this energy figure could be lower. This scenario which imposes the achievement of the RED II target for advanced biofuels is clearly closer to the 2030 estimates of the JRC-EU-TIMES model, which foresees a future cumulative capacity without double-counting of between 600 and 700 PJ by 2030 (please see Figure 11 in this report, and Figure 6 in E4tech (2018)). However, the rate of deployment of advanced biofuel technologies that is required under this scenario is considered by E4tech (2018) as exceedingly ambitious.

According to E4tech, in the EU under a scenario where some imports of 2G alcohol are allowed, EU Annex IX (a) biofuel production potential could reach 91 GJ/year in their lowest challenging growth scenario, and 229 GJ/year in their technology success scenario (see section 7.3.3 E4tech (2018)). Considering the aforementioned 90% capacity factor E4tech consider, this translates into approximately 100 PJ or 254 PJ of future capacity, not meeting the RED II 3.5% target for advanced biofuels in 2030 as a result.

5 JRC remarks on E4tech modelling scenarios

The E4tech Market Outlook analysis identifies non-technical barriers noted in section 4.1 for the deployment of advanced sustainable biofuels. The barriers are not technology-specific but take a broad approach. The JRC advises caution with regards to the future production projections specifically for lignocellulosic ethanol as assessed in the E4tech study.

5.1 Main advanced biofuel technology for 2030

It is important to separate HVO and FAME production figures in the future scenarios defined and assessed in the E4tech study. Both HVO and FAME are commercially viable productions, i.e. they are produced regularly in millions of tonnes each year, can be considered robust technologies that produce biofuels at reasonable cost, and they are successful products in the fuel market.

Therefore, apart from FAME and HVO, the main advanced biofuel technology produced in 2030 by a considerable margin according to the E4tech model, will be lignocellulosic ethanol (see Figure 7 and Figure 8). Production ranges from just under 1.1 million tonnes to over 2.4 million tonnes by 2030, depending on which scenario is viewed. The next most produced fuels would be 2G Catalysis and Gasification + Fischer-Tropsch.

The potential development of advanced biofuel supply to 2030 was modelled by E4tech for all of the pre-commercial routes on a bottom-up basis, and used three criteria to do so, starting from (i) current known and planned capacity and players, (ii) an assumed technology success across advanced biofuels, and (iii) estimated development timescales and rate of build of new plants (E4tech, 2018).

5.2 Technology success rate appears high

The report clarifies (p149) that the modelling scenarios were designed to reflect "a pessimistic and optimistic view for advanced biofuels", along with an additional scenario to simulate how RED II target could be met.

Focussing initially on the pessimistic challenging growth scenario (Figure 7), the model predicts just under 1.1 million tonnes of lignocellulosic ethanol will be manufactured in the EU by 2030. It is the view of the JRC that this scenario for this technology is actually somewhat optimistic, especially given its trend-to-date. To put that estimate of future production in context, the European fuel ethanol industry as a whole will produce just over 4.3 million tonnes in 2018 (USDA, 2018). The technology growth foreseen by the E4tech model is principally based upon (i) an assumed project success rate and (ii) the apparent beginnings of cellulosic ethanol production in industrial facilities, most notably in the US, along with the number of new projects being undertaken in this field.

Regarding point (i) the 'challenging growth' scenario has a technology growth and success rate which assumes that at least one in two lignocellulosic plant projects will be successful. This can be seen as optimistic if one considers the difficulties which stand-alone lignocellulosic plants have experienced, for example in the previous ten years up to now.

Regarding point (ii) i.e. the beginnings of large-scale cellulosic ethanol production as reported by the Ethanol Producer magazine (2018) and as referenced in the report, warrant a closer inspection as the majority of this production is coming from so-called 1.5 generation facilities. The article states that cellulosic ethanol production has been growing – in the last five years, for example, US production has increased from zero to an estimated 38 Mlitres/yr in 2017, or 30,000 tonnes per year. However, the article notes that commercial production is only coming from 8 facilities in the US. 7 of these plants are using 1.5G (generation) technology, where corn (maize) kernel fibre is used which is already available at existing 1st generation ethanol plants. 6 of these plants are using technology from one provider. Making 1.5 generation ethanol certainly has a number of advantages, it makes use of a captive feedstock which is already at the facility, so there are no harvest, collection, or transportation costs associated with the feedstock. Secondly, this feedstock is known to be less recalcitrant than other cellulosic feedstocks (Cagle, 2017). Cagle also notes this feedstock is already made up of 37% glucose sugar, and has a low lignin content of 8%.

Of the remaining two plants considered in the Ethanol Producer piece, one is certainly also using corn kernel fibre but with its own technology. It is predicted to produce approx. 2,400 tonnes of ethanol in 2018. The situation with the one remaining plant is less clear. It is also not clear if the ethanol made from the 37% glucose in the corn kernel fibre is counted as lignocellulosic or advanced.

The E4tech report notes some production of cellulosic ethanol appears to be taking place in Brazil (forecast production of approx. 20,000 tonnes this year). The USDA (2018a) note total cellulosic ethanol estimated production for 2018 should show an increase of 6,000 tonnes compared to 2017 - assuming the existing plants are able to overcome current operational/mechanical challenges at the plant level (USDA, 2018a). It is unclear in USDA (2018a) what are the operational or mechanical challenges which these facilities must still overcome.

Overall, the development of both energy and cost effective pre-treatment, hydrolysis and fermentation, remain the challenges hindering large scale deployment of lignocellulosic biomass conversion to ethanol. These barriers have been reviewed in the deliverable D2.1.12 in the frame of the LCEO. In brief, the number of substrates used in pilot and demonstration plants for biofuel production remains small; the effective conversion of lignocellulosic raw materials, which contain varying sugar mixtures depending on raw material input (e.g. C5 and C6 sugars) is challenging; and separation of products needs to be improved.

It remains to be seen if the technological jump in stand-alone i.e. 'pure' cellulosic ethanol production that does not appear to have happened to date will come about in the next ten years. There are indications that some companies may be close to operating commercially, with regular production and at scale.

5.3 Note on biofuel prices

Appendix C of E4tech (2018) Table 59 "Estimated advanced biofuel prices" presents a list of advanced biofuel prices per tonne, described as approximations for the price of biofuels in the EU. They only provide an indication of what price the market *may be willing to pay* for those fuels based on the fossil fuel price, reference biofuel price and double counting. The methodology used to come to the figures is explained but it is important to reiterate that it does not use information from biofuel processing chains or test plants. Therefore, while the logic behind estimating biofuel prices in order to then estimate possible EU market shares is clear, JRC recommends the prices in this section of the E4tech report should only be used for this purpose.

For example, JRC notes the low *market prices* of second generation methanol and ethanol, neither of which are yet in meaningful production. Table 59 indicates the market price of a tonne of cellulosic ethanol is €770, but it is not in agreement with the other pricing graph in the report, Figure 67. Figure 67 indicates second generation ethanol has a 2015 *production cost* of ~ €800 to €1200 per tonne, with a median value of approximately €1000. In summary, Table 59 serves a useful purpose in the report of helping estimate EU market shares between biofuels. But those prices should not be used as an indicator of actual advanced biofuel costs.

6 Summary, Conclusions, Recommendations

In summary, JRC agrees in general with the results of the E4tech study, and applauds its quality and level of detail. Nonetheless, the principal advanced biofuel foreseen by the study for 2030 – aside from FAME and HVO – is cellulosic ethanol, and JRC recommends an additional level of conservatism when considering this fuel within the scenarios as shown in the E4tech modelling.

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List of abbreviations and definitions

AD	Anaerobic Digestion
APR	Aqueous Phase Reforming
ATJ	Alcohol to Jet
BTL	Biomass-to-Liquids
EPO	European Patent Office
ETD	Ethanol to Diesel
EU	European Union
FAME	Fatty Acid Methyl Esters
FT	Fischer-Tropsch
HTL	Hydrothermal Liquefaction
HVO	Hydro-treated Vegetable Oil
IEA	International Energy Agency
JRC	European Commission's Joint Research Centre
LCEO	Low Carbon Energy Observatory
MTG	Methanol to Gas
RED	Renewable Energy Directive
RoW	Rest of the World
SNG	Synthetic Natural Gas
TRL	Technology Readiness Level
US	United States
USDA	United States Department of Agriculture

Annexes

Annex 1. E4tech 2018 report

Report on market and industrial development intelligence for sustainable advanced biofuels

Final Report

JRC/IPR/2017/C.4/0074/RC-VL

Ares (2017) 5979282

E4tech (UK) Ltd for the European Commission Joint Research Centre, Institute for Energy, Transport and Climate

December 2018

Contents

Executive summary

Scope and objectives of the study

Advanced biofuels could play an important role in decarbonising the transport sector and offer an economic opportunity to the EU, but many technologies are still at an early stage of development, and support is needed for their commercialisation.

This report provides an overview of the current development status and commercial deployment of advanced biofuels, incentives and support policies which are available to producers of advanced biofuels, the market outlook to 2030, and an assessment of the barriers to advanced biofuel deployment and actions required to overcome these.

Within this report 'advanced biofuels' are defined as those produced from ligno-cellulosic (LC), non-food and non-feed biomass, corresponding largely to those feedstocks on the Annex IXa and b lists of the Renewable Energy Directive (2015).

Market status of advanced biofuels

The technology readiness level (TRL) of the advanced biofuel technologies considered in this study is summarised in Figure 1, and the current and planned global production capacity for each technology is summarised in Figure 2.

The production of FAME and HVO from oil-based feedstocks is already a commercial process (TRL9), therefore the market structure for these routes is significantly different to the other routes which are not yet fully commercialised. The current global installed capacity of FAME (50,000 ktonnes/year) and HVO (4200 ktonnes/year, excluding co-processing)[1] is substantially higher than the other advanced biofuel routes within scope of this study, and there are many more players globally including large and diversified fuels companies.

The other technology routes which are at TRL 8 or below are those which use ligno-cellulosic feedstocks. For these technologies, there are far fewer companies involved in developing each technology, and they often have a narrow focus on one particular route. Substantial additional plant capacity is planned across the advanced biofuel technologies, albeit from a low base, testifying to interest in the sector.

The production of ethanol from enzymatic hydrolysis and fermentation is an exception amongst the ligno-cellulosic technologies in that there are over 20 companies across the globe developing the technology, and several have started to license it to third party project developers. The current installed production capacity of ligno-cellulosic ethanol is significantly higher than any of the other ligno-cellulosic routes, but many plants are not operating at full capacity and some have been shut down. Anaerobic digestion pre-treatment is also being developed by a relatively large number of companies, but current installed capacity is low as plants tend to be small.

[1] Note that for FAME, HVO and co-processing, production capacity figures refer to the production capacity of the plant overall and do not reflect the percentage of waste fats and oils actually used by the plant.

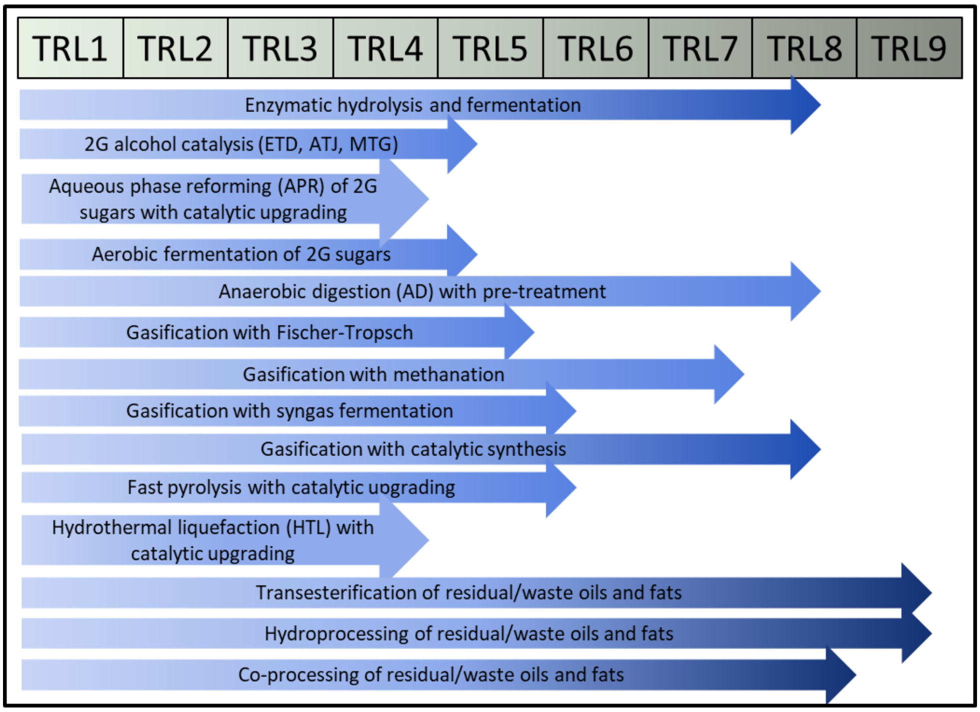


Figure 1 Technology Readiness Level (TRL) status of advanced biofuels considered in this study

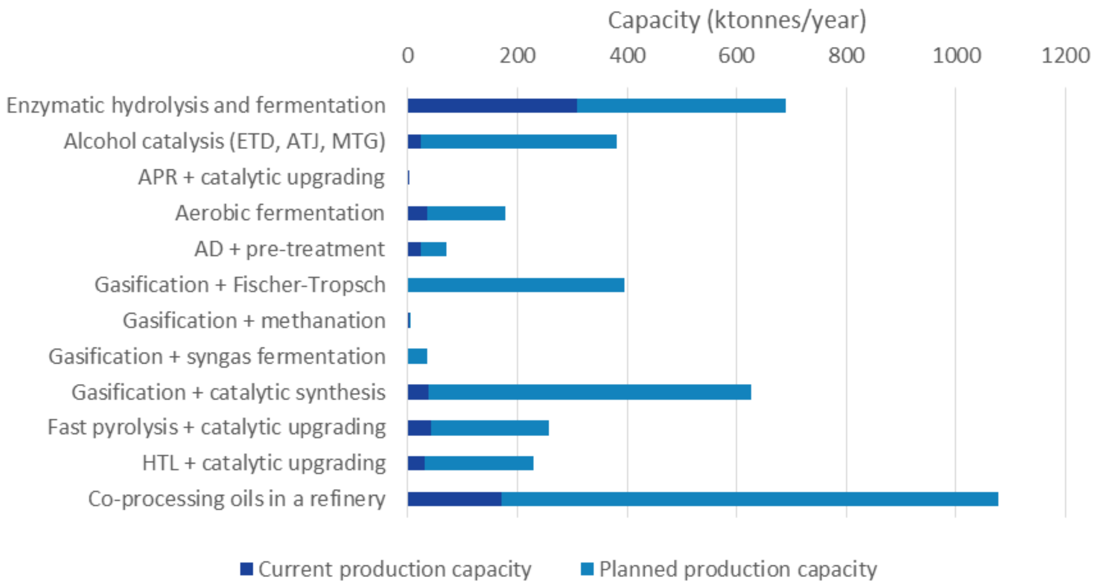


Figure 2 Existing global production capacity, and planned capacity, of advanced biofuel plants (excludes FAME and HVO which have a current installed capacity of 50,000 ktonnes/year and 4200 ktonnes/year respectively)

Within the EU, all MSs have a blend mandate for biofuels, with the exception of Germany which has a GHG target and Sweden which provides tax exemptions for biofuels. In the majority of countries advanced biofuels double-count towards these overall biofuel targets, but as of mid-2018 only six EU MSs had adopted specific and binding targets for advanced biofuels. Current EU installed capacity of advanced biofuels is 250 ktonnes/year, rising to 6,500 ktonnes/year when estimated HVO and FAME production from wastes and residues is included. This is sufficient to meet the advanced biofuel targets adopted by some MSs for 2020, but still a small proportion of the overall MS biofuel target of 20,000 ktonnes/year.

Policy support

In most cases advanced biofuel plants at demonstration scale and above are present in countries which have some form of support mechanism, and those countries which have a number of different types of support mechanisms generally have the largest number of installed or planned plants. The number of policies in each country and the number of current and planned plants in that country is illustrated in Figure 3 (note not all countries were included in the policy research).

Different types of policies act at different stages of the supply chain (including for example feedstock production, plant construction and fuel supply). For the USA and EU, which have a large number of different support mechanisms, these generally act across the supply chain, recognising the need to address multiple barriers to the scale-up of this industry. Grants and loans such as the European NER300 scheme and the USA Biorefinery Assistance Programme can support the financing of new plants, and feedstock supply chains can be supported through policies such as the USA Biomass Crop Assistance Programme. On the demand side, blend mandates such as the USA Renewable Fuel Standard, and tax incentives such as those offered by Finland and Slovakia, provide market support for advanced biofuels. Strong blend mandates in the USA and Europe can impact the development of plants in external countries such as Brazil, Indonesia and Malaysia, which do not necessarily have strong advanced biofuel support policies themselves.

Key to the development of the advanced biofuel industry in the EU seems to be the presence of policies across the supply chains, ranging from support for plant financing to scale-up novel technologies, to demand for the fuels.

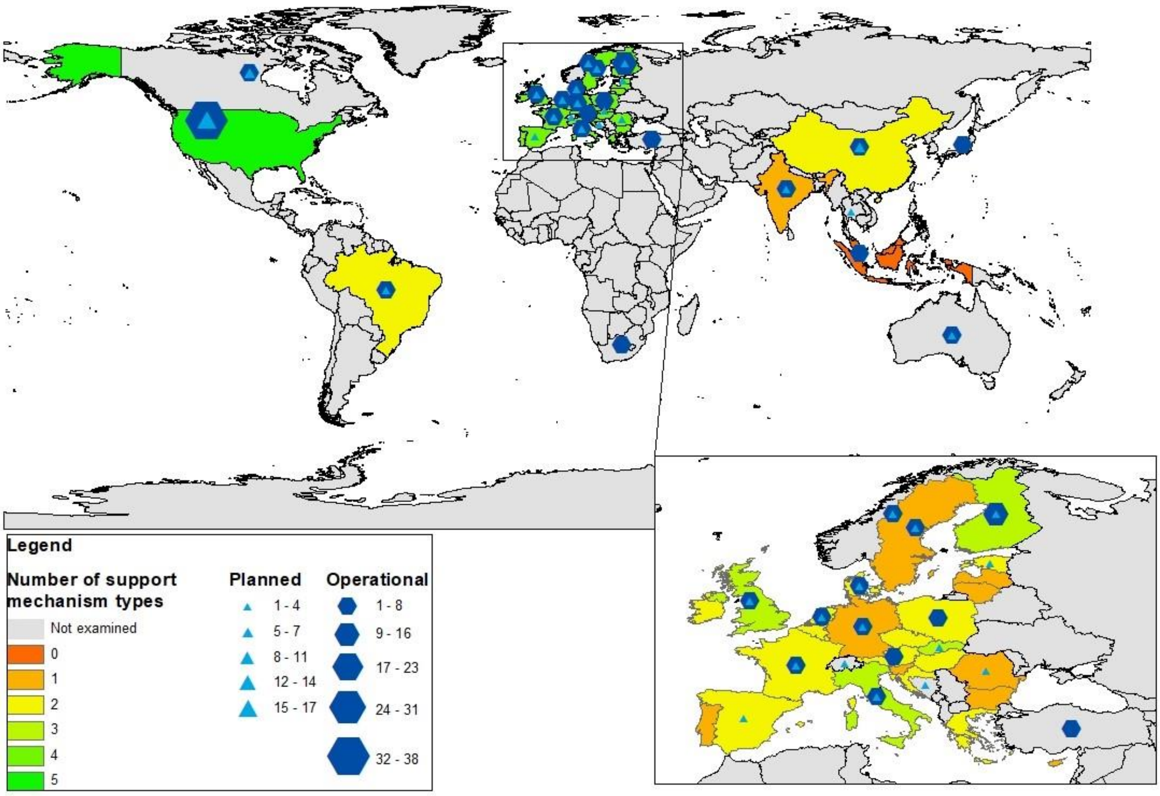


Figure 3 Number of different types of advanced biofuel support mechanism available in each country reviewed, and number of planned and operating plants

Market potential to 2030

The potential development of the advanced biofuel supply to 2030 was modelled for all of the pre-commercial routes on a bottom-up basis, starting from current known and planned capacity and players, assuming technology success across advanced biofuels, and estimating development timescales and the rate of build of new plants. For the commercial routes using waste oils and fats (FAME, HVO and co-processing) the development of the industry is anticipated to be limited by the availability of sustainable feedstock, so an alternative approach was adopted.

The advanced biofuel production potential over time (excluding FAME, HVO and co-processing) is assessed for two scenarios: a challenging growth scenario and a technology success scenario. In both of these scenarios a supportive policy environment for advanced biofuels is assumed, so that all players currently developing advanced biofuel technologies continue to develop their technology and build plants.

Production potential of advanced biofuels in 2030 across the two scenarios is illustrated in Figure 4, and the ramp-up over time for the technology success scenario is illustrated in Figure 5.

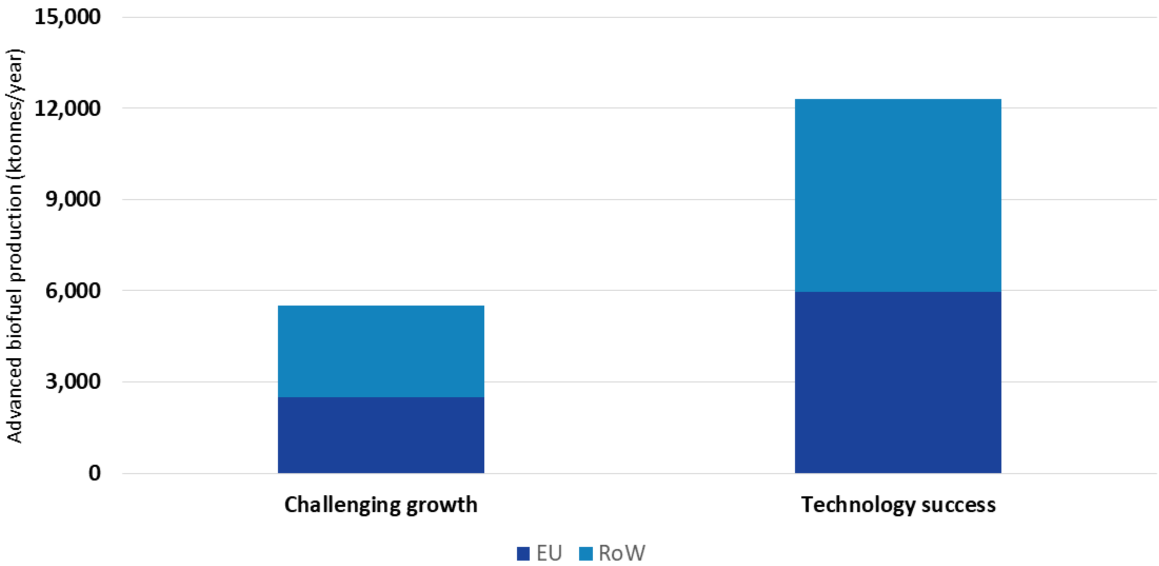


Figure 4 Global advanced biofuel production potential in 2030 across scenarios 'challenging growth' and 'technology success' (excl. FAME, HVO, co-processing and alcohol catalysis)

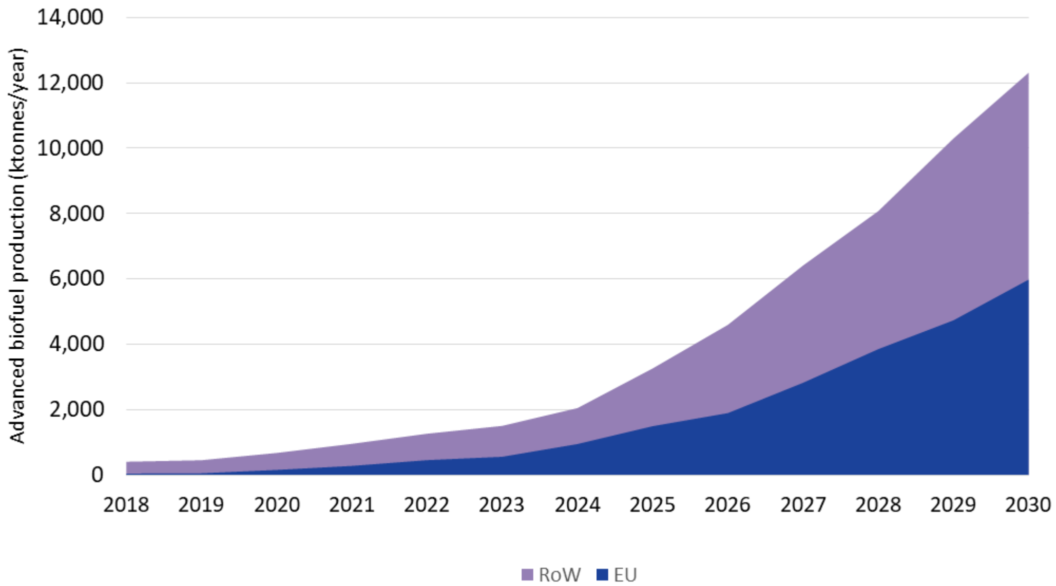


Figure 5 Advanced biofuel production potential, technology success scenario (excl. FAME, HVO, co-processing and alcohol catalysis)

These deployment scenarios are compared to the legislation in the proposed RED II: 3.5% target for fuels made from Annex IXa feedstocks with the option for Member States to double-count the contribution from these fuels towards the target, and 1.7% cap on fuels made from Annex IXb feedstocks. Under the 'challenging growth' and 'technology success' scenarios EU production of advanced biofuels is insufficient to reach the target even if double-counting is allowed. Even global deployment of advanced biofuels is insufficient to reach the 3.5% target without double-counting in these two scenarios. Therefore a third scenario 'RED II stretch' was developed in order to demonstrate the rate of capacity increase that would be required in order to meet these targets.

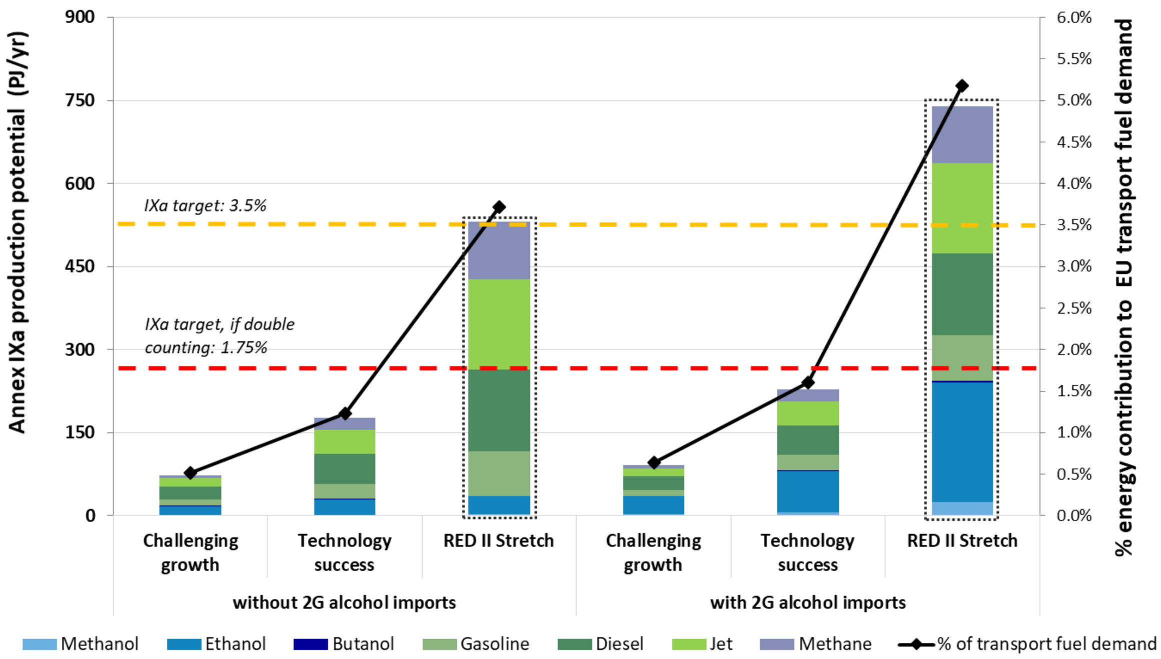


Figure 6 EU Annex IXa biofuel production potential in 2030

Globally, the 2030 advanced biofuel production would require less than 1% of available (i.e. currently un-used) agricultural residues, forestry residues and MSW across both scenarios, taking account of existing uses of the resource, sustainability and accessibility. Under the 'technology success' scenario EU biofuel production would require 8% of available EU agricultural residues, forestry residues and MSW.

There are a wide range of production costs across the advanced biofuel routes considered. The most expensive routes are aerobic fermentation of 2G sugars due to low yields, and alcohol to jet due to the additional cost of producing ligno-cellulosic ethanol. Of the pre-commercial routes, several could be competitive with diesel at $100/barrel in 2030, assuming they attain commercial maturity: ligno-cellulosic fermentation, AD + pre-treatment, gasification + methanation, syngas fermentation and gasification + catalytic synthesis. However for other routes this will remain very challenging, due to poor yields or, in the case of catalytic ethanol synthesis, anticipated high cost of LC ethanol.

Barriers to advanced biofuel deployment, and actions to address these

The scope of this study covered non-technical barriers only, but for some technology routes there may also remain significant technical challenges in scaling up that technology. The key non-technical barriers to the increased supply of advanced biofuels concern project financing, availability of sufficient high-quality sustainable feedstock, and the infrastructure required to secure feedstocks and refuel vehicles. On the demand side, key barriers to deployment are: the competition from higher-value products, certification and consumer acceptance of new fuel blends, and weak or uncertain policy support.

Strong and consistent policies are important in order to overcome demand-side barriers to advanced biofuels. These policies should be clearly defined, send clear pricing and demand signals, and have a sufficient timeline to provide certainty to investors over several project development cycles. A long-term policy vision for the strategic support of advanced biofuels is important to foster investor confidence in the support offered. Governments and industry should work together to support the development of new refuelling infrastructure for fuels which are likely to be of strategic importance.

On the supply-side, accessing finance for projects can be facilitated by government policies aimed at bringing in strategic investors, such as low cost loans or loan guarantees, capital grants, or tax incentives. Supply chain infrastructure and business models will require further development in order for advanced biofuel projects to access the sustainable low-cost feedstock that they require, and it is essential that policies have clear definitions of what constitutes sustainable feedstock.

A focus on guaranteeing and communicating sustainability, and public understanding of alternative fuel types will become increasingly important in the future as penetration of advanced biofuels increases in the market.

1 Objectives and scope of this report

1.1 Objectives

Advanced biofuels have the potential to result in very low GHG emissions compared with fossil fuels, and lower sustainability impacts compared with food crop based biofuels. However, many technologies are still at an early stage of development, and support is likely to be important to bring them towards commercialisation and therefore make significant volumes of advanced biofuels available within the EU. The EU has substantial existing capabilities in biofuels, particularly advanced biofuels, and therefore the development of this industry also offers economic opportunity to the EU.

In order to design policy and provide support for advanced biofuels, it is vital that the European Commission understands the current state of play of these technologies, including their development and deployment status and the companies involved. This will support the Directorate-General for Research and Innovation (DG RTD) to focus demonstration funding and innovation support in the most effective way.

In order to achieve these aims, this study provides the European Commission with:

- A complete picture of the current market status and technological and industrial development status of advanced biofuels in Europe and globally
- An understanding of the market outlook for advanced biofuels in the EU and globally, including projected future production volumes and biofuel production costs
- An understanding of the barriers to advanced biofuels in the EU and globally, including actions which could overcome these barriers
- A review of current incentives and support policies for technology investment and deployment that are available to advanced biofuel producers / developers within the EU and globally.

1.2 Scope

This report focusses on ‘advanced biofuels’, which are defined as those produced from **ligno-cellulosic, non-food and non-feed biomass**. Generally such feedstocks come on the Annex IX list of EU Directive 2015/1513, but where some feedstocks fall into these categories but are not on that list, they are still included within this study.

Table 1: Conversion technologies within scope of this study, and the biofuels which can be produced via each technology

Conversion pathway	Acronym	Advanced biofuel produced
1. Enzymatic hydrolysis and fermentation	2G alcohol	2G ethanol, 2G butanol,
2. 2G alcohol catalysis (ETD, ATJ, MTG)	2G catalysis	Diesel, jet, gasoline
3. Aqueous phase reforming (APR) of 2G sugars with catalytic upgrading	APR	Diesel, jet, gasoline
4. Aerobic fermentation of 2G sugars	S2D	Diesel, jet, gasoline

Conversion pathway	Acronym	Advanced biofuel produced
5. Anaerobic digestion (AD) with pre-treatment	Pretreat+AD	Biomethane
6. Gasification with Fischer-Tropsch	Gasif+FT	Biomass-to-liquids (BtL) fuels
7. Gasification with methanation	Gasif+SNG	Synthetic natural gas (SNG)
8. Gasification with syngas fermentation	Gasif+ferment	Ethanol, isobutene
9. Gasification with catalytic synthesis	Gasif+alcohol	Methanol and other alcohols
10. Fast pyrolysis with catalytic upgrading	Pyrolysis	Diesel, jet, gasoline
11. Hydrothermal liquefaction (HTL) with catalytic upgrading	HTL	Diesel, jet, gasoline
12. Transesterification of residual/waste oils and fats	FAME	Fatty acid methyl ester (FAME) biodiesel
13. Hydroprocessing of residual/waste oils and fats	HVO	Hydrotreated vegetable oils (HVO) diesel, hydroprocessed renewable jet (HRJ)
14. Co-process of residual/waste oils and fats	Co-process	Hydrotreated vegetable oils (HVO) diesel, hydroprocessed renewable jet (HRJ)
15. Microalgae*		

**As microalgae is a feedstock, it is not included within the databases of plants or players, but a market overview covering costs and major players is provided in section 4.*

The work for this project is split into five key tasks:

- Task 1: Market overview
- Task 2: Database of major active companies and industrial players
- Task 3: Database of plants
- Task 4: Market outlook to 2030
- Task 5: Incentives and support policies for investment in, and deployment of, advanced biofuel technologies

The databases (tasks 2 and 3) are provided as a separate excel document, and a concise description of the content, scope and methodology that was followed for data collection is provided in chapters 2 and 3 respectively. Using this information, the market overview of each advanced biofuel technology within scope is provided in chapter 4, covering a technology overview, major players in that technology, current and planned production capacity, plant and production costs, and assessment of EU market share. In chapter 5 a comparison of current capacity with advanced biofuel targets in each EU MS is given, and chapter 5.1.1 covers current incentives and support policies. Finally chapter 7 contains the methodology and results of the market outlook for advanced biofuels to 2030, including costs, deployment and barriers affecting deployment.

2 Database of major active companies and industrial players

As part of this study a database of the major companies working in each of the conversion technologies within scope was put together, in order to provide an overview of the industrial development status of each route. This section describes the scope and content of that database, and the methodology that was followed. The information itself is provided in full in the database and contributes to the market overview provided in chapter 4.

2.1 Scope

The database aims to cover the top 20 players in each technology route by installed capacity (including also planned capacity), although for some technologies there may be less than 20 known players worldwide. The focus has been on capturing those companies developing technology or adapting their existing technology to use new feedstocks. In some cases companies who are simply project developers or component suppliers have also been captured if they are considered to play a major role within that technology chain. Feedstock suppliers, off-takers or downstream fuel blenders, and companies which have gone bankrupt are not within scope of this database. Moreover, the focus is on companies at TRL 5 or above, so universities and companies which are currently only at lab-scale have not been included. Where a company has been brought out by another company, the name of the new owner is the main database entry, but in a comment or in brackets after this name the previous name is also provided. Companies engaged in transesterification of residual fats and oils have also not been included as this is a widely deployed commercial technology with hundreds of players worldwide (see section 4.13).

2.2 Content

The database contains the following information on each company, where it was possible to obtain this information:

- Sub-technology or technology pathway(s) being developed by company
- Organisation name
- Location of headquarters (country and continent)
- Does company have operations within the EU?
- Other main countries of operation
- Main activity of company (technology development, project development, component development etc.)
- Short summary of the role / activities of the company in that pathway
- Status of most advanced plant to-date (none, pilot, demonstration, first-of-a-kind, commercial)
- Turnover (million €)
- Main sources of funding
- Key partnerships with other industry players
- Establishment date of company (or of this business unit, where the advanced biofuel production division is within a larger company)
- Number of employees
- Link to web site

2.3 Methodology

The following key steps were followed in order to populate as much information as possible in the database:

- Initial information gathered based on information already known to E4tech, existing published literature, and internet searches
- This information was emailed out to companies in order for them to validate, revise or add to the information
- Any updates or revisions were incorporated into the database

132 unique companies were identified through the initial screen, and information was gathered on all of these. This information came from a variety of sources, including existing E4tech internal databases, the JRC technology development report[2], the IEA Bioenergy task 39 database, patent analysis by the JRC, and other publically available reports, studies and articles.

Information was sent out for validation to 130 of these companies. We followed up by phone with 13 of the companies. A reply was received from 18 companies, validating and updating the information, which was then incorporated into the database. Within the database there is a column indicating whether the information provided in that row has been validated by the company themselves. Despite this rigorous data collection process and extensive validation with the industry, it was not possible to populate all of the fields for all of the companies, in which case these are left blank in the database.

3 Database of industrial-scale demonstration and/or first-of-kind commercial plants

As part of this study a database of the plants in each of the conversion technologies within scope was put together, in order to inform the development of research and innovation support for advanced biofuels. This section describes the scope and content of that database, and the methodology that was followed. The information itself is provided in full in the database and contributes to the market overview provided in chapter 4. As for the companies database, transesterification plants have not been included, but more information on these plants is provided in section 4.13.

3.1 Scope

Within each technology pathway all demonstration and first-of-a-kind commercial scale facilities have been included within the database (TRL 6 – 9). For pathways at an earlier stage of development (aqueous phase reforming, aerobic fermentation, AD with pre-treatment, fast pyrolysis, hydrothermal liquefaction and gasification with Fischer-Tropsch, methanation, syngas fermentation and catalytic synthesis) pilot plants (TRL 5) have also been included. Plants which have stopped operating are within scope, as long as they were operational within the last 10 years. Plants which are currently ‘planned’ are within scope, as long as those plans have progressed within the past 5 years. We also require that some steps have been taken by the companies to realise the plant, for

[2] Rocca, S., Padella, M., O’Connell, A., Giuntoli, J., Kousoulidou, M., Baxter, D., Marelli, L. for the JRC (2016) Technology development report sustainable advanced biofuels 2016,

example feasibility studies, formation of joint ventures or consortia etc. so that companies which simply announce ambitious expansion plans for roll-out of multiple units of their technology with no evidence to suggest these might materialise do not distort the results.

3.2 Content

The database contains the following information on each plant, where it was possible to obtain this information:

- Advanced biofuel conversion technology used in this plant
- Project/plant name
- Name of main company developing plant
- Organisations involved in the project consortium
- Short summary of project achievements / aims
- Plant location
- Feedstock(s) used
- Technology status (pilot, demonstration or first commercial)
- Product(s) made
- Annual biofuel production capacity[3]
- Annual utilisation / operating hours
- Co-products made
- Start-up year
- Project status (operating, in commissioning, under construction etc.)
- Capital investment costs (M€)
- Operating costs (M€/year)
- Funding source for plant
- Levelised production cost (in euro per litre), if known
- Short summary of project achievements (or aims, if plant is not yet operational)
- Link to website and/or summary report

3.3 Methodology

For populating the plants database, the same key steps were followed as for the companies' database (section 2.3).

Initially 249 individual plants were identified, and information was gathered on all of these, using the sources detailed in section 2.3. Emails were sent out to the main company developing each plant, in order to validate and update the information. Emails were sent out covering 234 of the 249 plants. It was not possible to contact all of the plant developers, because for example the company who developed the plant had gone bankrupt. The information was reviewed and updated for 51 of the plants, and within the database there is a column indicating whether the information provided in that row has been validated by the plant developer. Despite this rigorous data collection process and extensive validation with the industry, it was not possible to populate all of the fields for all of the companies, in which case these are left blank in the database.

[3] Note that throughout this report where the term 'capacity' is used, it refers to production capacity of the plant.

Some calculations were performed in order to obtain the information required above. For both capex and opex costs, the information was recorded in the original currency in which it was paid, along with the year in which it was paid. The capex cost is then inflated up to 2016 using either the European Power Capital Cost Index (PCCI) (without nuclear) for plants in Europe or the North American Power Capital Cost Index (without nuclear).[4] Then the 2016 conversion factor for the original currency into euros was applied. This is only an approximation as plants were likely constructed over several years, but the difference is generally small in inflation factor between different years. The PCCI data was only available up to 2016. Therefore for capex and opex costs incurred in 2017 or 2018, an average annual inflation rate for the euro of 1.54%[5] and for the dollar of 2.13%[6] in 2017 was applied to deflate these costs to 2016 values.

4 Market Overview

4.1 Enzymatic hydrolysis and fermentation

4.1.1 Technology overview

Biomass feedstocks such as corn stover, straw and energy grasses are subjected to thermal and/or chemical pre-treatment. This is typically followed by separation of the lignin fraction, and then hydrolysis using enzymes to convert the cellulose and hemicellulose fractions to sugars. The soluble C5 and C6 sugar molecules are biologically fermented to ethanol/butanol using yeast or bacteria. Ethanol/butanol is then separated from the fermentation broth using distillation and/or more novel techniques (including membranes or molecular sieves). The lignin is typically burnt onsite for heat & power generation, but its use for speciality chemical applications is also being explored.

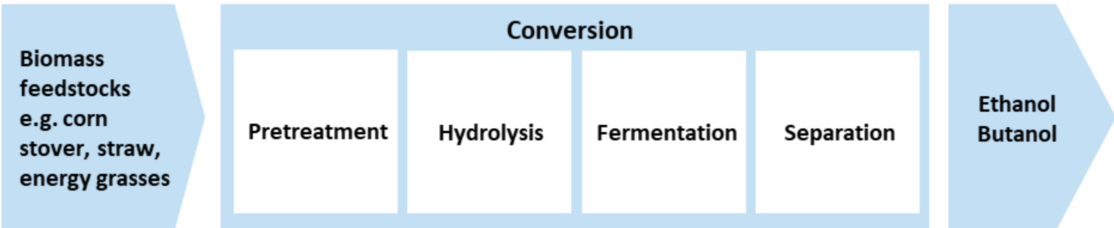


Figure 7: Enzymatic hydrolysis and fermentation value chain

Ligno-cellulosic ethanol production is at TRL 7-8 (CRL 1-2), based on a number of first commercial plants having already been constructed at capacities of up to 555.2 ML/yr (although some, but not all these plants are currently operating). In contrast, ligno-cellulosic butanol production is at TRL 5-6 (CRL 1), based on pilot activities and early toll demonstration activities at small-scale.

[4] IHS Markit (2018) Costs and Strategic Sourcing, Available from: https://ihsmarkit.com/Info/cera/ihsindexes/index.html
[5] Rate Inflation (2018) Available from: https://www.rateinflation.com/inflation-rate/euro-area-historical-inflation-rate
[6] Inflation Data (2018) Historical Inflation Rate, Available from: https://inflationdata.com/Inflation/Inflation_Rate/HistoricalInflation.aspx

4.1.2 Major players in this technology

There are a number of companies currently active in developing hydrolysis and fermentation technology to produce alcohols from ligno-cellulosic feedstocks, based in North America, Europe and Asia. Table 2 lists companies which are developing technology for the complete conversion of ligno-cellulosic feedstock into alcohols. Companies which are developing projects, such as Flint Hills Resources using Edeniq technology, Enviral using Clariant technology, and Goldwater Srl. are included in the database but not within Table 2. It should be noted that the Edeniq technology used by Pacific Ethanol, Flint Hills Resources and Little Sioux Corn Processors is currently a bolt-on technology for 1G ethanol plants to convert their corn kernel fibre into cellulosic ethanol, sometimes known as 1.5G technology. A number of other companies also have 1.5G technology, as highlighted in Table 2, where plant capacities shown are for the ligno-cellulosic ethanol produced, which is typically less than 5% of total ethanol produced at the plant.[7]

Some additional companies focussing predominantly on pre-treatment are included in the database, but not within Table 2. These include Biogasol, Fiberight and Sweetwater Energy. Companies such as Abengoa and DuPont which are no longer active in the enzymatic hydrolysis and fermentation industry are also not included within Table 2.

Table 2: Major players in enzymatic hydrolysis and fermentation industry

Company name	Location of headquarters (country)	Total capacity in the EU* (ktonnes/year)		Total capacity in the RoW* (ktonnes/year)	
		Planned	Current	Planned	Current
American Process Inc.	USA	-	-	-	3.6
BlueFire Renewables	USA	-	-	-	-
Borregaard	Norway	-	-	-	16
Chempolis Ltd.	Finland	-	5.0	49	-
Clariant	Switzerland	100	1.0	-	-
COFCO	China	-	-	-	-
D3Max*	USA	-	-	-	-
Edeniq*	USA	-	-	-	5.2
Henan Tianguan Group	China	-	-	-	40
Hindustan Petroleum Company Ltd.	India	-	-	-	-
ICM*	USA	-	-	15	-
Iogen Corporation/ Raizen	Canada	-	-	-	34.6

[7] Business Wire (2017), Edeniq Secures $5 Million in Growth Equity, Has 27 Plants in Cellulosic Ethanol Pipeline , Available from: https://www.businesswire.com/news/home/20170619005287/en/Edeniq-Secures-5-Million-Growth-Equity-27 , Accessed 7th December 2018.

Company name	Location of headquarters (country)	Total capacity in the EU* (ktonnes/year)		Total capacity in the RoW* (ktonnes/year)	
		Planned	Current	Planned	Current
Lesaffre	France	-	-	-	-
Orsted-Inbicon	Denmark	63	-	-	-
POET-DSM Advanced Biofuels	USA	-	-	-	60
Praj	India	-	-	-	0.79
Quad County Corn Processors*	USA	-	-	-	6.0
Renmatix	USA	-	-	-	0.5
SEKAB	Sweden	-	-	-	-
Shandong Longlive Group	China	-	-	-	60
St1**	Finland	39	8.7	39	-
Toray	Japan	-	-	-	-
Versalis	Italy	55	-	-	65

'Current capacity' covers plants which are operational and in commissioning, 'planned capacity' covers plants which are planned and under construction

** Shows developers of 1.5G ethanol technology*

*** For St1, only plants using the Bionolix technology (using municipal and commercial waste) and Cellulonix technology (from wood waste) are included. Those using the Etanolix technology to process food waste are not within scope.*

4.1.2.1 Strengths and weaknesses of key players

Enzymatic hydrolysis and fermentation technology is being developed by a number of companies around the world. In contrast to other pathways, the industry has a number of very large and highly diversified businesses involved, and a number of first commercial plants have been built in recent years. However, this strength has not necessarily been a guarantee of success – in 2017 there were a number of significant set-backs for the industry. DuPont merged with Dow Chemicals and announced that it was exiting the cellulosic ethanol business (shuttering their plant), with Abengoa and Biochemtex (now purchased by Versalis) also both ceasing operations at their cellulosic ethanol plants following financial trouble with their respective parent companies. However, cellulosic ethanol production has been growing – in the last five years for example US production has increased from zero to an estimated 38 Mlitres/yr in 2017.[8]

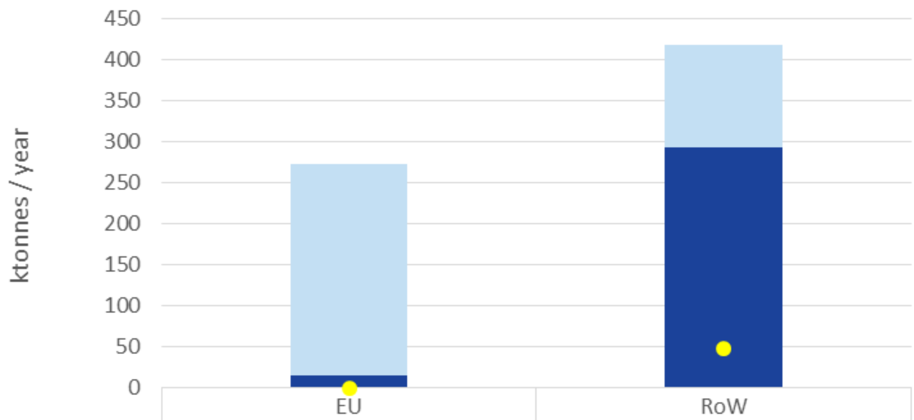
Many plants continue to operate well below their nameplate capacity, giving rise to higher costs of production, and a lack of operational data to convince investors to provide capital to follow-on projects. Cost reduction remains a key focus, with improvements to pre-treatment ongoing, and some of the players producing enzymes on-site (although there are not enough plants and data

[8] Schill, S.R. (2018) for Ethanol Producer Magazine, Zero to 10 Million in 5 years, Available from: http://ethanolproducer.com/articles/15344/zero-to-10-million-in-5-years

points exist to sufficiently distinguish the merits of one approach over another). Ensuring consistent feedstock quality and establishing robust supply chains remain challenging, with farmer confidence in the growth of the industry having been dented. There appears to be some success with those players that are adopting a lower risk route by adding modest cellulosic ethanol abilities onto existing corn ethanol plants, such as Quad County Corn Processors, and Edeniq in the US, and developers in China. Installed capacity at these bolt-on plants is generally lower than standalone plants, but this approach could be scaled in the future.

4.1.3 Current and planned production capacity

Current production capacity of hydrolysis + fermentation technology is dominated by countries outside the EU, particularly the USA, China, India and Brazil. Planned future capacity is higher in the EU than the rest of the world, which may reflect the likelihood of strong targets for advanced biofuels from 2020 to 2030.



	EU	RoW
Planned production capacity	258	125
Current production capacity	15	293
Known production volumes	-	49

Figure 8 Enzymatic hydrolysis and fermentation: current installed capacity, planned capacity and production volumes for the EU28 compared to the rest of the world

Whilst only Finland and Sweden have currently operating capacity in Europe, there are planned plants in Slovakia, Denmark, Finland and Romania. The planned capacity in Denmark and Finland only relates to one plant in each of these countries. There are two planned plants in Slovakia, and one in Romania all using Clariant technology. The plant constructed by Beta Renewables in Italy is not included within Figure 9 because it is currently not operational.

Information on current production volumes was generally not available for individual plants, but was available for some key regions. In the USA, the number of 'cellulosic biofuel' (D3) RINs generated in 2017 for ethanol provides an indication of actual production volumes of cellulosic ethanol plants in the USA.[9] Figures suggest that no cellulosic ethanol was exported from the USA in 2017[10], and of the

[9] United States Environmental Protection Agency (2018) 2017 Renewable Fuel Standard Data, Available from: https://www.epa.gov/fuels-registration-reporting-and-compliance-help/2017-renewable-fuel-standard-data, Accessed on 4/9/2018

D3 RINs generated in 2017, 15% were generated by importers rather than domestic fuel producers. Nevertheless the figures suggest that cellulosic ethanol capacity in the USA is substantially under-utilised: In 2017 30 ktonnes of cellulosic ethanol RINs were generated, whilst total cellulosic ethanol capacity in the USA (operational or in commissioning) is currently 75 ktonnes/year (with over 150 ktonnes/year recently shuttered).

Cellulosic ethanol capacity also appears to be underutilised in Brazil. Estimates from the US Foreign Agricultural Service in Brazil[11] indicate that in 2017 only 13 ktonnes of cellulosic ethanol was produced, compared to an overall Brazilian capacity of 100 ktonnes/year. Nevertheless this represents a 3 times increase on 2016 cellulosic ethanol production, and annual production is anticipated to further increase to 20 ktonnes/year in 2018 (all from sugarcane bagasse).

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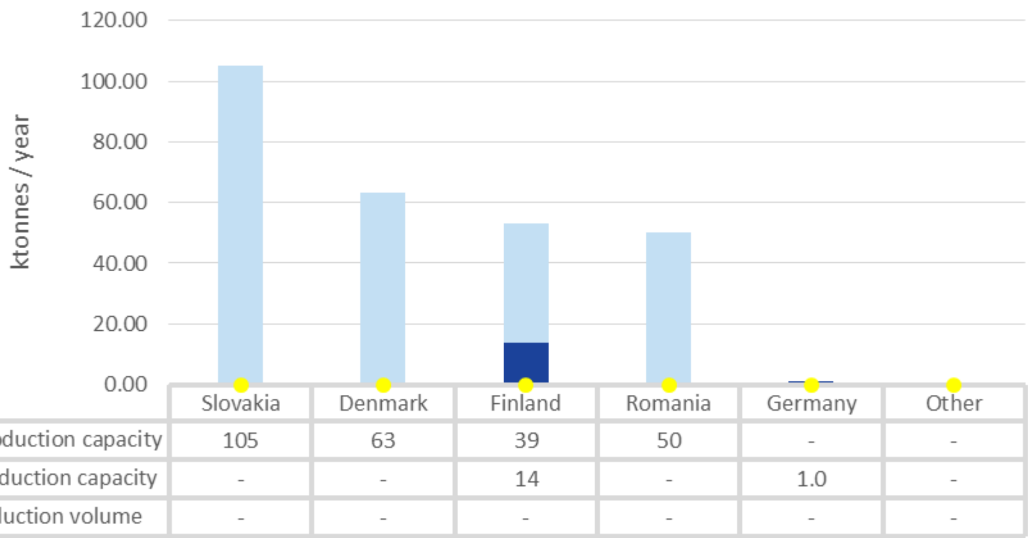


Figure 9 Enzymatic hydrolysis and fermentation: current installed capacity, planned capacity and production volumes by EU Member State, covering top 6 MSs by installed capacity

4.1.4 Plant and production costs

Table 3: Capex and opex costs for enzymatic hydrolysis and fermentation plants

Technology status	Plant capacity (ktonnes/year)	Capex cost (million €$_{2016}$)	Opex cost (million €$_{2016}$ / year)
Pilot	2.7	N/A	N/A
Demonstration	0.08-60	7.7-151	N/A
First of a kind commercial	2.24-83	14-314	N/A
Commercial	0.79-180	125-451	N/A

Data is based on all plants, whether planned, operating or shut; note that the min and max of the cost range do not necessarily correspond to the min and max plant capacity within that range

[10] EPA (2018) Table 2: Total RVO for Each Compliance Year, Available from: https://www.epa.gov/fuels-registration-reporting-and-compliance-help/annual-compliance-data-obligated-parties-and#total-rvo, Accessed on 7/12/2018
[11] Barros, S. (2018) for the USDA Foreign Agricultural Service, Brazil Biofuels Annual 2018, Available from: https://www.fas.usda.gov/data/brazil-biofuels-annual-4

The scale of plants at each technology readiness status varies widely for enzymatic hydrolysis and fermentation. This is largely because of the plants being built by St1, which operate commercially, yet because they use food waste as a feedstock they typically operate at small scale close to the source of the waste. All of the demonstration plants in the database have a capacity of less than 15 ktonnes/year, apart from one at 40 and one at 60 ktonnes/year. This reflects the fact that the classification of plants as 'demonstration' is due not only to their size, but also to their commercial readiness. It should be noted that capex cost information was not available for either of these very large 'demonstration' plants, so the maximum capex cost figure of €151M refers to a plant with capacity of only 1.6ktonnes/annum. If capex cost information was available for these plants, it may therefore be significantly higher.

The scale of those plants which are considered to be 'first commercial' also varies widely, but is generally above 10 ktonnes/year, apart from one plant using MSW as a feedstock (now shut) and the aforementioned St1 plants. Of the first commercial plants with a capacity above 10 ktonnes/year, those with a capex cost of less than €100M are located in India and Brazil, suggesting that in Europe and North America capex costs of a first commercial hydrolysis + fermentation plant would be at least €100M.

It is noticeable that some of the commercial plants have a smaller capacity than the 'demonstration' plants. All of the commercial plants at less than 5 ktonnes/year are operated by St1, or Pacific Ethanol. Pacific Ethanol have a planned plant which they classify as 'commercial', which will be added on to the side of an existing 1G ethanol plant, and therefore can operate commercially at small-scale. However no information on the capacity of this plant was available, so it does not feature in Table 2 or Figure 8.

4.1.5 EU market share

Roughly 1/3 of global activity in the enzymatic hydrolysis and fermentation industry, in terms of number of companies, number of plants, and production capacity, takes place in the EU. Given the scale of the global 2G ethanol industry, this is significant. Production volumes were only known for three plants, all outside the EU28 (US, Norway, India). Therefore the known economic value of their product is €37.5M.

Table 4: EU28 market share of enzymatic hydrolysis and fermentation industry.

	Number of companies (HQ)	Number of plants*	Production capacity *(ktonnes/year)	Known economic value** (million €)
EU	12	11	272	-
Rest of World	25	32	418	38
Global total	37	43	691	38
% EU	32%	26%	39%	0%

**Number of plants and production capacity refers to plants which are currently operational, in commissioning, under construction or planned; **Known economic value was calculated based on known production volumes and estimated 2G biofuel prices. For prices and methodology see Appendix C.*

4.2 2G alcohol catalysis (ETD, ATJ, MTG)

4.2.1 Technology overview

Alcohol catalysis is a chemical process that first involves the dehydration of short chain alcohols (e.g. methanol, ethanol, n-butanol, and isobutanol) to form alkenes (e.g. ethene, butene, isobutene)[12]. This is followed by oligomerisation reactions (combining alkene molecules into longer chains), then hydrogenation (adding hydrogen) and isomerisation (branching to meet fuel specifications). The final step is distillation into the required product fractions, which could be gasoline, diesel or jet.

The process described above has a variety of acronyms in common usage (e.g. ETD, ATJ, MTG), depending on the starting alcohol and finished product. The '2G' refers to the alcohol being derived from ligno-cellulosic or waste/residue feedstocks, but the process is identical to '1G' alcohol catalysis using alcohols derived from starch/sugar crops, or alcohols derived from fossil fuels.

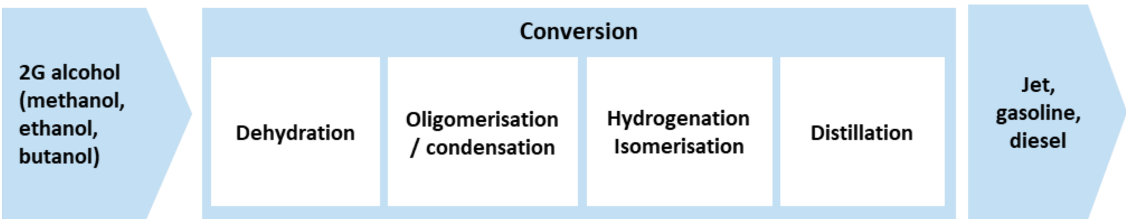


Figure 10: 2G alcohol catalysis value chain

Each catalysis step involves a relatively standard fossil fuel industry process; however the overall integrated plant can be relatively complex. Since 2G alcohols are (almost) chemically identical to their 1G alcohol or fossil alcohol counterparts, the TRL of catalytic conversion is largely unrelated to the origin of the alcohol. A first commercial fossil MTG plant was previously operated, but currently 2G alcohol catalysis is currently at TRL 5-6 (CRL 1), as demonstration-scale plants are under construction. Most developers are currently mainly focused on upgrading 1G alcohols, but there are larger demonstration plants planned using 2G alcohols that may be operational by 2020.

4.2.2 Major players in this technology

There are a limited number of players in (2G) alcohol catalysis, and all are based either in the USA or in Europe. There seems to be significant activity aimed at developing new plants to produce either a mix of jet fuel and gasoline, or exclusively jet fuel. This is likely to be as a result of increasing interest in aviation biofuels to achieve CO_2 reductions in this sector, and their inclusion in European policy and that of certain Member States. Byogy, Ekobenz and Gevo are all developing first commercial plants. Sundrop was developing a first commercial plant, but these plans have now been cancelled, citing a change in economics and political reasons. The Pacific Northwest National Laboratory in the USA (PNNL) have been developing AtJ technology alongside Lanzatech, but are not included within Table 5 as they are a research institute.

Most of the technologies being developed to-date use ethanol as a feedstock, although Gevo use isobutanol, and Sundrop had been planning a methanol-to-gasoline process. As there is chemically no difference between 1G and 2G alcohol, the production capacity of plants noted in Table 5, Figure 11 and Figure 12 refers to their capacity to produce fuels from alcohols, and does not necessarily

[12] If starting with methanol, this is first dehydrated to dimethyl-ether (DME) before further dehydration to alkenes

indicate that these plants use or will use 2G alcohols. Where information has been obtained from developers on the use of 1G vs. 2G alcohols feedstocks, this is included in the database.

Table 5: Major players in 2G alcohol catalysis industry

Company name	Location of headquarters (country)	Total capacity in the EU* (ktonnes/year)		Total capacity in the RoW* (ktonnes/year)	
		Planned	Current	Planned	Current
Byogy	USA	-	-	242	-
Ekobenz	Poland	-	23	-	-
Gevo	USA	-	-	-	0.23
Lanzatech (AtJ)	USA	82	-	30.4	-
Lanzatech/PNNL	USA	-	-	-	-
Sundrop	USA	-	-	-	-
Swedish Biofuels	Sweden	5.0	0.0048	-	-

'Current capacity' covers plants which are operational and in commissioning, 'planned capacity' covers plants which are planned and under construction

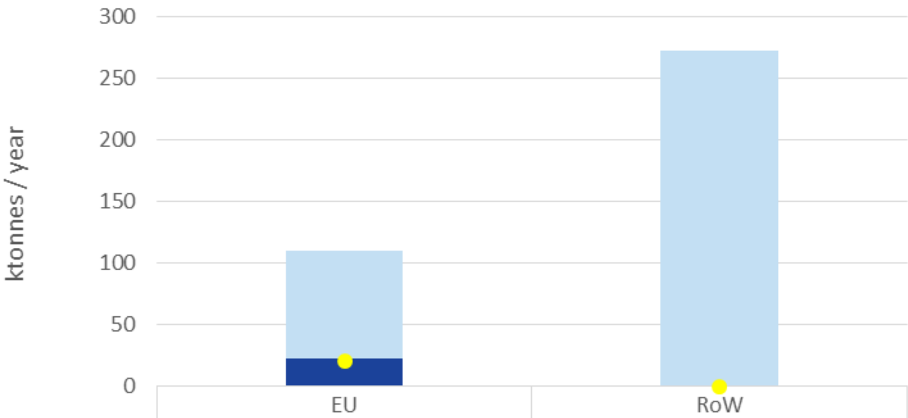
4.2.2.1 *Strengths and weaknesses of key players*

Whilst there are relatively few companies currently actively involved in 2G alcohol catalysis, the pipeline of planned and operating projects reaching first commercial scale suggests there is some strength starting to develop in the industry. The majority of the players are focussed on the production of jet fuel, which is seen as the key growth area in the near-term. There is much less interest in diesel production, given the expected rapid future electrification of light duty vehicles. The success of the route is also extremely dependent on the market arbitrage opportunity between alcohol and jet prices, and with small players involved, there are not necessarily very large balance sheets that can absorb large market swings.

The key players in this technology (Table 5) tend to be small (less than 100 staff) and focussed strongly on the alcohol catalysis technology development, and do not tend to be large diversified business interests. However, some developers do have separate business operations focused on the production of the feedstock intermediate alcohol (e.g. Gevo isobutanol, Lanzatech ethanol), which provides some additional security as to the sourcing of their feedstocks at a reasonable cost. Achieving ASTM certification is a key challenge facing suppliers of renewable jet fuel (as it takes many years and significant cost) – however, the majority of the AtJ players have already overcome this hurdle.

4.2.3 Current and planned production capacity

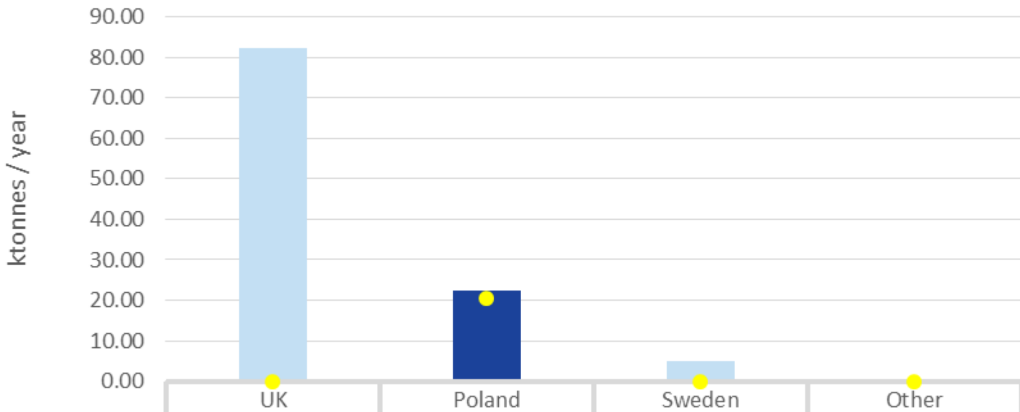
The current installed capacity of 2G alcohol catalysis is low, and dominated by the Ekobenz facility in Poland which is currently in commissioning.. Planned alcohol catalysis capacity in the EU is dominated by Lanzatech, and in the RoW is attributable to both Byogy and Lanzatech. Gevo have also announced intent to scale up their alcohol catalysis capacity, but no concrete plans were identified at this stage. .



	EU	RoW
Planned production capacity	87	272
Current production capacity	23	0.23
Known production volumes	21	0.014

Figure 11 2G alcohol catalysis: current installed capacity, planned capacity and production volumes for the EU28 compared to the rest of the world

The only EU countries with existing or planned production capacity of 2G alcohol catalysis are the UK, Poland and Sweden, comprising one plant in Poland currently in commissioning, and one planned plant each in the UK and Sweden.



	UK	Poland	Sweden	Other
Planned production capacity	82	-	5.0	-
Current production capacity	-	23	0.0048	-
Known production volume	-	21	-	-

Figure 12 2G alcohol catalysis: current installed capacity planned capacity and production volumes by EU Member State, covering up to top 6 MSs by installed capacity

4.2.4 Plant and production costs

Table 6: Capex and opex costs for 2G alcohol catalysis plants

Technology status	Plant capacity (ktonnes/annum)	Capex cost (million €$_{2016}$)	Opex cost (million €$_{2016}$ / year)
Pilot	0.23	4.86	N/A
Demonstration	0.37-82	2.4-55	N/A

Technology status	Plant capacity (ktonnes/annum)	Capex cost (million €$_{2016}$)	Opex cost (million €$_{2016}$ / year)
First of a kind commercial	23-241	23-442	N/A

Data is based on all plants, whether planned, operating or shut; note that the min and max of the cost range do not necessarily correspond to the min and max plant capacity within that range

4.2.5 EU market share

Table 7: EU28 market share of 2G alcohol catalysis industry. Number of plants, production capacity and total capex refers only to plants which are currently operational

	Number of companies (HQ)	Number of plants*	Production capacity *(ktonnes/year)	Known economic value** (million €)
EU	2	4	110	-
Rest of World	4	8	272	-
Global total	6	12	382	-
% EU	33%	33%	29%	-

**Number of plants and production capacity refers to plants which are currently operational, in commissioning, under construction or planned; **Known economic value was calculated based on known production volumes and estimated 2G biofuel prices. For prices and methodology see Appendix C.*

In terms of number of companies and plants, the EU has a significant share of global activity in alcohol catalysis.

4.3 Aqueous phase reforming (APR) of 2G sugars with catalytic upgrading

4.3.1 Technology overview

Aqueous phase reforming (APR) is the catalytic transformation of biomass-derived oxygenates (such as sugars, sugar alcohols and polyols) into hydrogen, carbon dioxide and a mixture of alkanes, acids, ketones and aromatics. The reaction is carried out in an aqueous solution over catalysts at elevated temperature and pressures[13]. A series of condensation reactions then lengthen the carbon chains in the mixture of hydrocarbons, before hydrotreatment (adding hydrogen – which can also be added during the APR step) and isomerization (branching to meet fuel specifications). Distillation then produces the final gasoline, diesel or jet fuel.

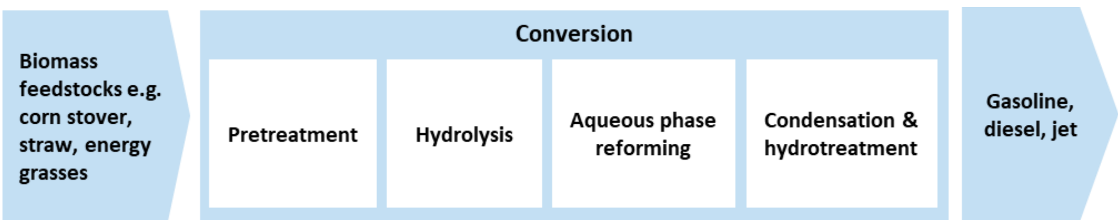


Figure 13: Value chain for APR of 2G sugars with catalytic upgrading

[13] Kirilin, A., V., 2013. Aqueous-phase reforming of renewables for selective hydrogen production in the presence of supported platinum catalysts. Available from: https://www.doria.fi/bitstream/handle/10024/93807/kirilin_alexey.pdf?sequence=2

Current R&D within the APR academic community is focused predominantly on H_2 production rather than liquid fuels, and processes are mostly concentrated on using 1G sugar feedstocks, rather than 2G sugars. APR using 1G sugars is at TRL 5-6 (CRL 1) given the pilot scale plants operated by Virent. On the other hand, APR using 2G sugars is at TRL 4-5 (CRL 1) given that Virent have produced biocrude using Virdia's[14] ligno-cellulosic sugars followed by upgrading to bio-jet at lab scale.[15]

4.3.2 Major players in this technology

Virent is currently the only player in APR technology. Virent was brought by Tesoro Corporation in 2016, but Virent still exists as a separate sub-entity, so the name Virent is used in this report[16]. Virent focusses on converting plant-based sugars into hydrocarbons via the aqueous phase reforming process followed by catalytic upgrading. Their patented technology is known as BioForming®. Virent has partnered with Shell for gasoline and jet fuel production, and with Toray and Coca Cola for bio PET production.

Table 8: Major players in the APR industry.

Company name	Location of headquarters (country)	Total capacity in the EU* (ktonnes/year)		Total capacity in the RoW* (ktonnes/year)	
		Planned	Current	Planned	Current
Virent/Shell	Netherlands	-	-	-	0.041
Virent	USA	-	-	-	0.041

'Current capacity' covers plants which are operational and in commissioning, 'planned capacity' covers plants which are planned and under construction

4.3.2.1 Strengths and weaknesses of key players

Virent is the only developer of aqueous phase reforming technology, which is therefore a significant risk to the future success of this advanced biofuel production route. Virent was brought by Andeavor (formerly Tesoro) in 2016, and there is an ongoing move by large refiner Marathon Petroleum to buy Andeavor. It is unclear at the moment whether the Virent technology will continue to be developed or its commercialisation funded under Marathon. Virent only have pilot-scale plants, and no new plants have come online since 2013. Whilst Shell did take an interest in the technology, there appears to be more recent interest in moving into biochemicals production (where profit margins are potentially higher) than in transport biofuels.

4.3.3 Current and planned production capacity

The only existing production capacity in APR are two plants operated by Virent and one operated by Shell, all pilot plants. Production capacity data was not available for one of the Virent plants, but is anticipated to be similar to the other pilot plants (0.04 ktonnes/year). All are installed outside of the EU. Installed capacity is low compared to other advanced biofuels, and there are no known plans for

[14] Virdia was acquired by Stora Enso in 2014. Available from: http://www.biofuelsdigest.com/bdigest/2014/06/23/stora-enso-acquires-virdia-in-up-to-62m-deal/
[15] E4tech for DfT (2017). Advanced drop-in biofuels – UK production capacity outlook to 2030. Available from: https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/652538/advanced-drop-in-biofuels-uk-production-capacity-outlook-2030.pdf
[16] Nb. Tesoro was renamed Andeavor in August 2017, and Andeavor was acquired by Marathon Petroleum in April 2018. Virent still operates as a brand, so here we continue here to refer to Virent.

future installations. Because the only known capacity is outside the EU, no breakdown by MS is given here.

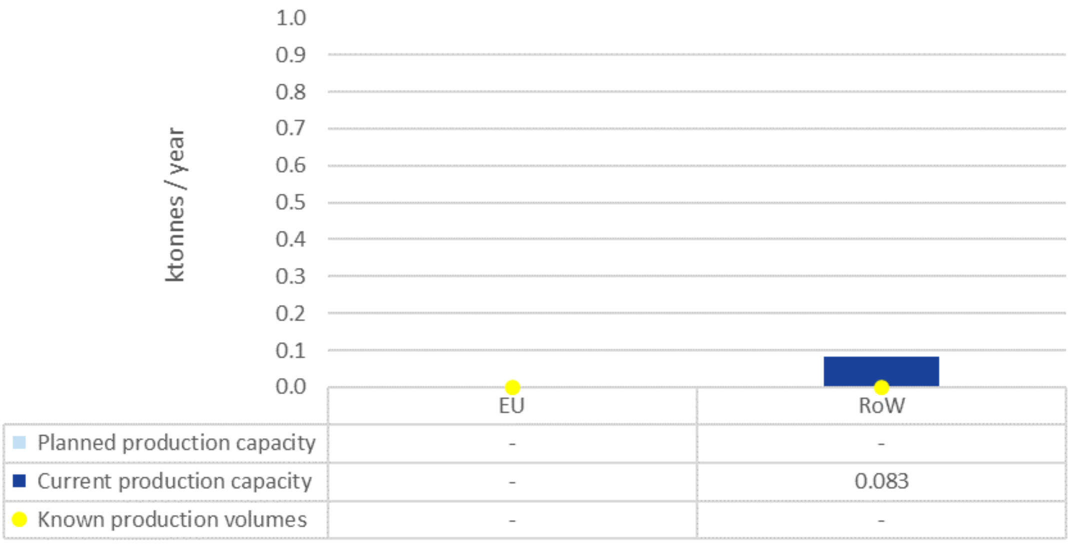


Figure 14 APR: current installed capacity, planned capacity and production volumes for the EU28 compared to the rest of the world

4.3.4 Plant and production costs

With only three pilot plants operational worldwide, no capex or opex cost data was available for APR plants.

4.3.5 EU market share

All known APR plants are installed outside the EU, and the key technology developer, Virent, is also based in the USA. Therefore to-date the EU has very little market share in this technology.

4.4 Aerobic fermentation of 2G sugars

4.4.1 Technology overview

2G sugars can be biologically converted by aerobic fermentation, which occurs at atmospheric pressure in the presence of air, to generate specific hydrocarbon precursors. This is followed by product recovery, purification and further upgrading to gasoline, diesel or jet fuels.

The 3 main biological routes in development are:

- Heterotrophic algae or yeast converting sugars into lipids within their cells. These lipids are extracted using solvents (killing the cells), cleaned and upgraded to transport fuel using conventional FAME or HVO diesel technology.
- Genetically modified yeast consume sugars and excrete long-chain liquid alkenes, e.g. the C15 alkene farnesene. These alkenes are recovered from the fermentation broth, purified and hydrotreated to jet/diesel.

- Genetically modified bacteria consume sugars and excrete short-chain gaseous alkenes, e.g. isobutene. These can then be sold into the chemical sector, or oligomerised and hydrotreated to gasoline/jet.

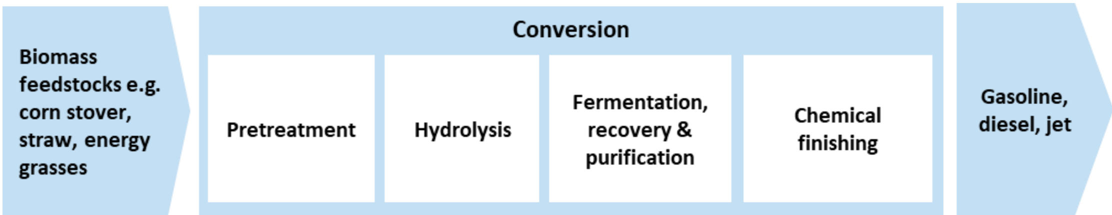


Figure 15: Value chain for aerobic fermentation of 2G sugars

Aerobic fermentation is currently being done using 1G sugar feedstocks, although some pilot work is on-going on 2G sugars. Consequently, aerobic fermentation using 1G feedstocks is at TRL 7-8 (CRL 1-2), while aerobic fermentation using 2G feedstocks is currently at TRL 5 (CRL 1).

4.4.2 Major players in this technology

There are four companies active in the development of aerobic fermentation technology: Amyris and Renewable Energy Group based in the USA, Global Bioenergies based in France and DSM based in the Netherlands. Amyris and Global Bioenergies have the most developed aerobic fermentation technology: Amyris has constructed a commercial-scale plant in Brazil producing farnesene from sugarcane (which was recently sold to DSM), and Global Bioenergies operate a demonstration-scale plant in conjunction with Fraunhofer CBP. Renewable Energy Group, who are major players in the USA in biodiesel, acquired a demonstration-scale fermentation facility in 2014 from LS9 which has the capability to do both aerobic and anaerobic fermentation. It is currently run as a toll demo plant offering contract manufacturing.

Each of these companies focus on different products. Amyris have to-date mostly focused on producing farnesene, primarily for the chemicals market. Nevertheless, farnesene can also be transformed into a fuel product and Amyris is active in biojet production thanks to its JV with Total. DSM is included within Table 9 as they purchased a 33 ktonnes/year farnesene plant from Amyris in Brazil, however they are targeting the chemicals, not fuels, market. Global Bioenergies produce isobutene, which can be used in the fuels or chemicals markets. From isobutene they have also successfully produced isooctane and ETBE which have been tested at over 34% blend in gasoline by Global Bioenergies' partner Audi. Whilst several companies have done tests with 2nd generation sugars, none of them are currently focussing on using 2G sugars in their large-scale production process, nevertheless they have been included within this study because they could use 2G sugars in the future.

Table 9: Major players active in the aerobic fermentation industry

Company name	Location of headquarters (country)	Total capacity in the EU* (ktonnes/year)		Total capacity in the RoW* (ktonnes/year)	
		Planned	Current	Planned	Current
Amyris	USA	-	-	104	0.0046
DSM	Netherlands	-	-	-	33*
Global Bioenergies	France	40	0.11	-	-

Company name	Location of headquarters (country)	Total capacity in the EU* (ktonnes/year)		Total capacity in the RoW* (ktonnes/year)	
		Planned	Current	Planned	Current
Renewable Energy Group (REGI)	USA	-	-	-	1.4

'Current capacity' covers plants which are operational and in commissioning, 'planned capacity' covers plants which are planned and under construction. Capacity refers to total aerobic fermentation capacity, only a small percentage of sugars used are currently 2G sugars.
**This refers to the Brotas-1 plant which was developed by Amyris but sold to DSM in 2017*

4.4.2.1 Strengths and weaknesses of key players

Amyris is the most established developer of aerobic fermentation technology, with a portfolio of operational pilot, demonstration and commercial plants. Global Bioenergies is also establishing capabilities, with one operational plant and one planned for start-up in 2021. Both companies have grown rapidly since establishment in 2003 and 2008 respectively, although they are still modest sized companies, and not diversified. DSM and Renewable Energy Group have to-date not developed their own technology. Companies in this pathway are targeting the chemical / pharmaceutical sector to begin with, which is generally higher value than bulk transport fuels, and should help to prove the technology and reach the scale and low production costs required for fuels. Their focus is likely to mostly remain on chemicals as capital remains tight whilst scaling up, although partnerships with larger vehicle or fuel suppliers are starting to be developed. The different feedstocks utilised, different technologies employed and different products manufactured in this pathway provides some potential diversity/resilience benefits compared to other pathways, although the number of players remain relatively small.

4.4.3 Current and planned production capacity

Existing global production capacity in aerobic fermentation is almost entirely associated with the Amyris Brotas 1 facility in Brazil (32.5 ktonnes/year capacity) which has recently been sold to DSM. Actual production at the REG plant is likely to be significantly lower than the capacity noted here (0.1 ktonnes/year) because it is used for contract manufacturing.

Planned production capacity in the EU reflects only one planned plant: that of Global Bioenergies in France. The planned production capacity in the RoW is mostly comprised of two planned plants from Amyris in Australia and Brazil.

It should be noted that whilst these plants have the capacity to take 2G sugars, all of them are currently operating or planning to operate using sugar from sugar cane.

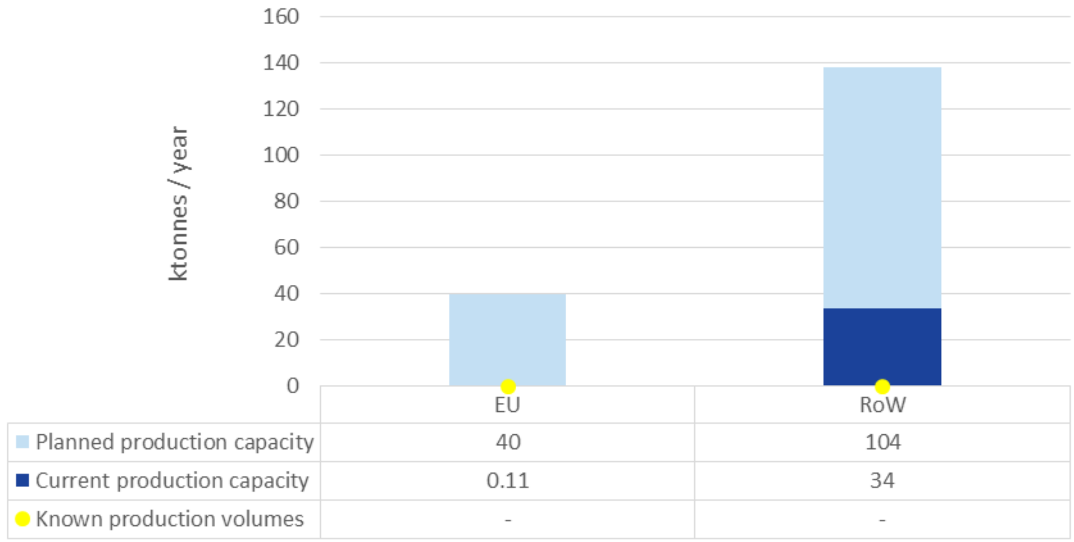


Figure 16 Aerobic fermentation: current installed capacity, planned capacity and production volumes for the EU28 compared to the rest of the world

The only significant aerobic fermentation capacity in EU Member States is the Global Bioenergies planned plant in France. The current production capacity in Germany noted in Figure 17 reflects a single pilot plant there which was developed by Global Bioenergies. Within Europe there is also an operating pilot plant in France (Global Bioenergies) on which capacity data was not available, and there has previously been a toll demo plant in Spain (Amyris) but this is now shut so not included in Figure 17.

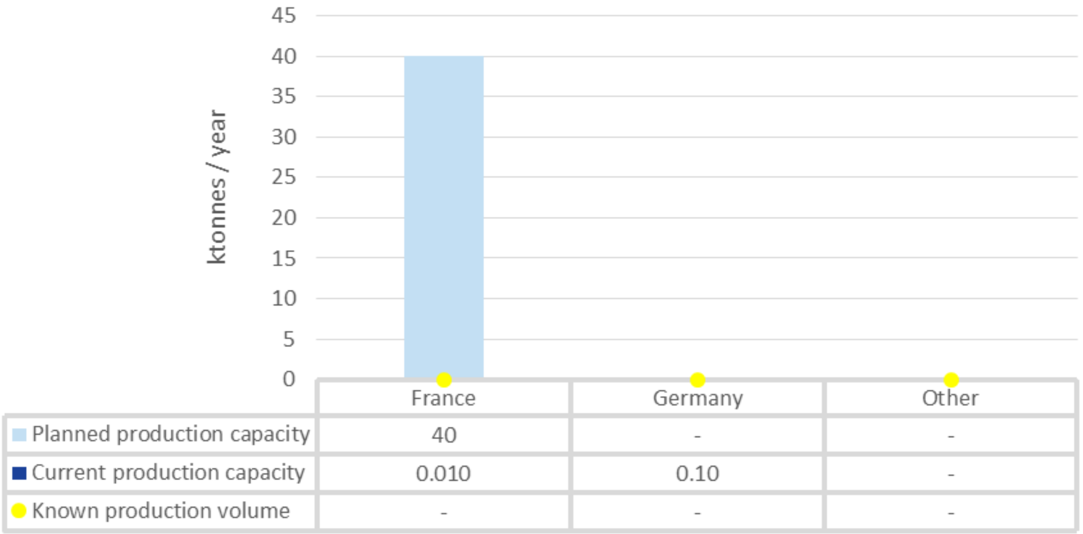


Figure 17 Aerobic fermentation: current installed capacity, planned capacity and production volumes by EU Member State, covering top 6 MSs by installed capacity

4.4.4 Plant and production costs

Capex cost data was only available for three of the aerobic fermentation plants, and are all from the same company.

Table 10: Capex and opex costs for aerobic fermentation plants

Technology status	Plant capacity (ktonnes/year)	Capex cost (million €$_{2016}$)	Opex cost (million €$_{2016}$ / year)
Pilot	N/A	1.04	N/A
Demonstration	0.004-1.42	9.8	N/A
First of a kind commercial	40	113	N/A
Commercial	23-81	N/A	N/A

Data is based on all plants, whether planned, operating or shut; note that the min and max of the cost range do not necessarily correspond to the min and max plant capacity within that range

4.4.5 EU market share

The EU has over 20% of global companies, plants and production capacity in aerobic fermentation (Table 11). However this reflects only two companies and only one sizeable plant, which is still currently in the planning stage.

Table 11: EU28 market share of aerobic fermentation industry.

	Number of companies (HQ)	Number of plants*	Production capacity *(ktonnes/year)	Known economic value** (million €)
EU	2	3	40	-
Rest of World	2	7	138	-
Global total	4	10	178	-
% EU	50%	30%	22%	-

**Number of plants and production capacity refers to plants which are currently operational, in commissioning, under construction or planned; **Known economic value was calculated based on known production volumes and estimated 2G biofuel prices. For prices and methodology see Appendix C.*

4.5 Anaerobic digestion (AD) with pre-treatment

4.5.1 Technology overview

Anaerobic digestion (AD) is a commercially available and widely used biological process for converting biomass into biogas, which is a mixture of methane, carbon dioxide and traces of other gases. Current feedstocks for AD typically include manures, sewage sludge, food processing residues, food waste, as well as some crops such as maize and agricultural residues like grass silage. These feedstocks are broken down by bacteria to fatty acids and alcohols, with these intermediate products converted into methane and carbon dioxide, water and some remaining solid material (digestate). The biogas produced can be burnt to produce heat and power, or upgraded by separating out and cleaning up the biomethane for use as a transport fuel or for injection in to the gas grid.[17]

Ligno-cellulosic feedstocks such as grassy and woody energy crops, straw and wood, are not commonly used today in AD as they are very slow to break down. This is because their molecular structure is poorly accessible to microorganisms and their enzymes. AD pre-treatment technologies

[17] E4tech, Ecofys, 2018. Innovation needs assessment for biomass heat. Available from: https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/699669/BE2_Innovation_Needs_Final_report_Jan18.pdf

are therefore designed to improve the accessibility of the sugars within these ligno-cellulosic feedstocks. These technologies include physical, chemical or biological methods, and combinations of thermal and chemical processes. The most appropriate pre-treatment technology depends heavily on the feedstock composition, including moisture content, lignin content, and presence of other material such as stones. Costs and energy requirements will also be heavily influenced by the AD plant scale and availability of waste heat.

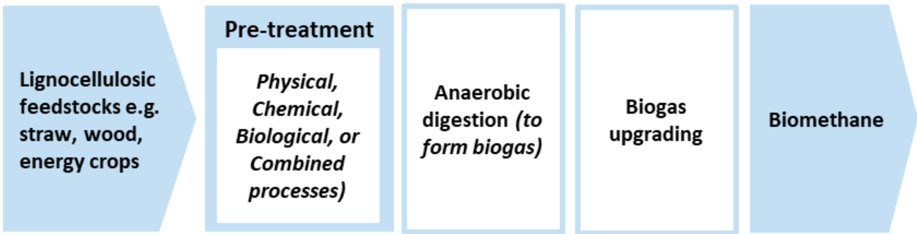


Figure 18: Value chain for AD with pre-treatment

AD biomethane for transport is at TRL 9 already (when using common feedstocks such as manures, sewage sludge, food wastes, maize and grass silage), but less mature otherwise. Many AD plants already mix straw with animal slurries (as manure), but use of only steam-treated straw in AD is at the early stages of commercialisation (TRL 7-8; CRL 1-2) with one large demonstration plant operating, and there are a range of other thermal/chemical pilot activities. Alkaline pre-treatment of straw for AD using sodium hydroxide is apparently at full scale in China (although specific project details remain scarce).[18] Fiberight will be launching its first commercial plant (TRL 8; CRL 2) in Maine towards the end of 2018 that will convert MSW into biomethane.[19] Pre-treatment of energy grasses and wood for AD is at research stage.[17] So in summary, AD with pre-treatment technology is at the early stages of commercialisation, as it is being sold by some developers, mainly in China and Germany.[17] However, the efficiency of these technologies is yet to be proven.

4.5.2 Major players in this technology

Anaerobic digestion with pre-treatment is still a relatively new field of interest, and as such as the key active players in this technology (Table 12) are only a small sub-set of all the large number of companies worldwide active in anaerobic digestion without pre-treatment. The vast majority of the companies identified are located in the EU, along with one in the USA and two in China. It is possible that there are more Chinese companies active in AD + pre-treatment than could be identified, as sources state that alkaline pre-treatment is at full scale in China,[20] so it is likely that there is more than two companies developing these plants.

Table 12: Major players active in the anaerobic digestion + pre-treatment industry

Company name	Location of headquarters	Total capacity in the EU* (ktonnes/year)	Total capacity in the RoW* (ktonnes/year)

[18] Clemens, J., 2016. Straw fermentation technology sharing. Available from: http://www.bngsummit.com/wp-content/uploads/2016/11/11.straw_clemens.pdf
[19] Company feedback
[20] Clemens, J. (2016) Straw Fermentation Technology Sharing, available from: http://www.bngsummit.com/wp-content/uploads/2016/11/11.straw_clemens.pdf

	(country)	Planned	Operational	Planned	Operational
Air Liquide	France	-	-	-	8.1*
Biobang	Italy	-	-	-	-
Biogas Systems GmbH	Austria	-	0.43	-	-
BioGTS	Finland	-	-	-	-
CaviMax Ltd.	UK	-	-	-	-
Chifeng Yuanyi Biomass Technology Co., Ltd.	China	-	-	-	-
DeTong (Chengdu DeTong Environmental Engineering)	China	-	-	-	-
E-PIC S.r.l	Italy	-	-	-	-
Fiberight (AD)	USA	-	-	46	-
Future Biogas Limited**	UK	-	5.1	-	-
HoSt	Netherlands	-	-	-	-
Lehmann	Germany	-	0.41	-	-
MWK Bionik	Germany	-	-	-	-
Rika Biogas Technologies Ltd.	UK	-	-	-	-
Verbio	Germany	-	10	-	-
Xergi	Denmark	-	-	-	-

'Current capacity' covers plants which are operational and in commissioning, 'planned capacity' covers plants which are planned and under construction

*Air liquide constructed the upgrading facility for an AE + pre-treatment plant, but it is not clear who developed the pre-treatment technology

**Future Biogas Limited use the technology of Biogas Systems GmbH

4.5.2.1 Strengths and weaknesses of key players

Compared to the other advanced biofuel production routes, there are a fairly large number of companies involved in developing pre-treatment technology for anaerobic digestion. Many of the players are established anaerobic digestion companies, with experience of the technology and supply chains, which is a strength in terms of existing revenues and staff skills. There is a large opportunity in terms of the number of existing AD plants that already generate revenue onto which pre-treatment could be added relatively quickly, and established AD companies would be well positioned to carry out this retrofit work. However it should be noted that the majority of the players in this sector are still small firms that cannot pursue dozens of projects simultaneously.

There are a wide range of possible pre-treatment technologies which can be used with anaerobic digestion, and which are still being developed and scaled-up. Partly this is because different feedstocks require different pre-treatment approaches, but it also reflects that the industry has not yet converged on one or two optimal technologies, which could be a weakness in terms of establishing supply chains or further technology development.

4.5.3 Current and planned production capacity

Existing production capacity in the EU is dominated by two demonstration plants run by Future Biogas and Verbio. There are two planned AD + pre-treatment plants outside the EU, one planned plant in the UK by Rika Biogas Technologies Ltd., and one under construction by Fiberight. Verbio has recently purchased DuPont's facility in the USA which had capacity to produce 83 ktonne/year of ligno-cellulosic ethanol. They intend to produce renewable natural gas at the plant, but the scale at which it will be operated is not publicised, so the capacity of this plant is not included in Figure 19. Information on the capacity of the planned plants was not available so they are not shown in the graph, and the capacity of the Fiberight plant is an estimation only. The lack of information on planned plants may reflect the fact that AD + pre-treatment is a novel technology being developed within the much larger and more established AD industry, so planned plants are not well publicised. It may also be because individual plants tend to be smaller, so there is likely to be less publicity around the awarding of large government grants for these plants.

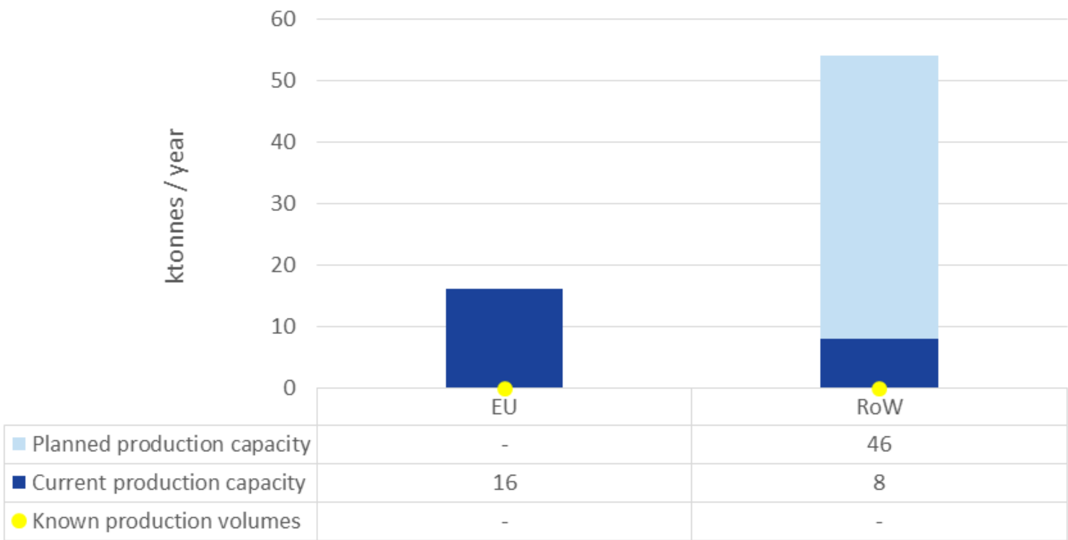


Figure 19 AD with pre-treatment: current installed capacity, planned capacity and production volumes for the EU28 compared to the rest of the world

Current installed capacity of AD + pre-treatment in Europe (Figure 20) is comprised of two plants in the UK, two in Germany and one in Austria. For several operational plants (in Germany, France and Denmark) no information on their capacity was available, so they do not show up in Figure 20. As highlighted above, information was not available on any planned plants.

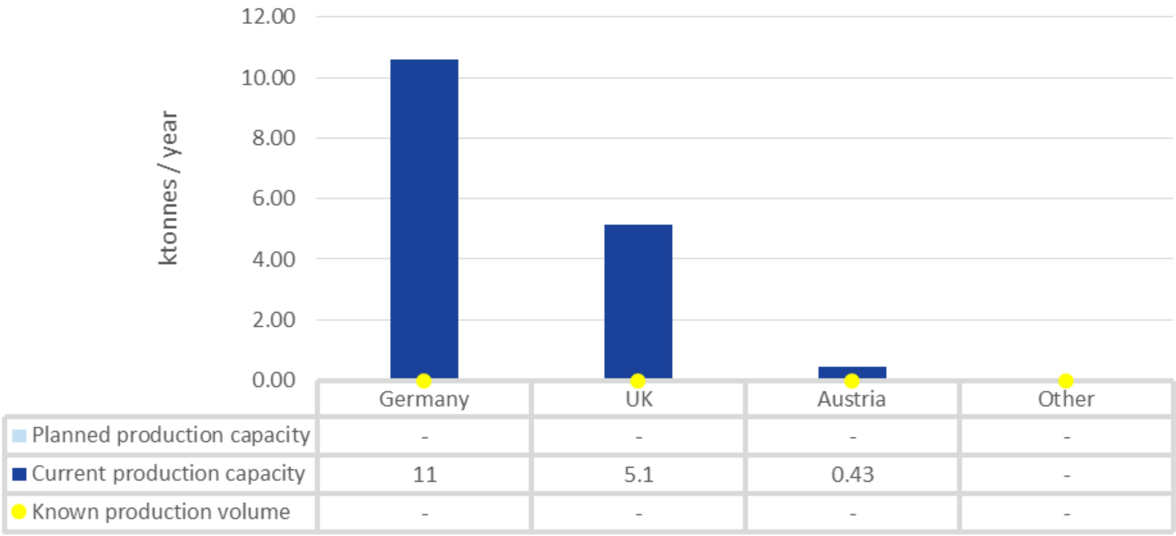


Figure 20 AD with pre-treatment: current installed capacity, planned capacity and production volumes by EU Member State, covering top 6 MSs by installed capacity

4.5.4 Plant and production costs

Limited information was available on the capex cost of AD + pre-treatment plants. The only first commercial plant currently being planned has a cost significantly lower than that of some other technologies such as hydrolysis with fermentation.

Table 13: Capex and opex costs for AD with pre-treatment plants

Technology status	Plant capacity (ktonnes/year)	Capex cost (million €$_{2016}$)	Opex cost (million €$_{2016}$ / year)
Pilot	8.1	-	-
Demonstration	2.5-10.2	-	-
First of a kind commercial	46	61	-
Commercial	-	-	-

Data is based on all plants, whether planned, operating or shut; note that the min and max of the cost range do not necessarily correspond to the min and max plant capacity within that range

4.5.5 EU market share

The EU has a dominant market share in the AD + pre-treatment industry (Table 14) in terms of number of companies, number of plants and production capacity, based on the information available. No information was available on current production volumes.

Table 14: EU28 market share of AD + pre-treatment industry.

	Number of companies (HQ)	Number of plants*	Production capacity *(ktonnes/year)	Known economic value** (million €)
EU	12	10	16	-
Rest of World	4	7	54	-

	Number of companies (HQ)	Number of plants*	Production capacity *(ktonnes/year)	Known economic value** (million €)
Global total	16	17	70	-
% EU	75%	59%	23%	-

**Number of plants and production capacity refers to plants which are currently operational, in commissioning, under construction or planned; **Known economic value was calculated based on known production volumes and estimated 2G biofuel prices. For prices and methodology see Appendix C.*

4.6 Gasification with Fischer-Tropsch

4.6.1 Technology overview

Biomass feedstocks, such as forest residues, energy crops and Municipal Solid Waste, are typically pre-treated, usually by drying, and sorting/sizing if required. Gasification then converts the biomass into syngas, using high temperatures, a limited oxygen environment and potentially elevated pressures. Syngas is a gas mixture comprised primarily of carbon monoxide and hydrogen. The syngas is then cooled, cleaned of ash, tars and chemical contaminants, and then conditioned via a water-gas shift reaction to meet the downstream catalyst specifications, before carbon dioxide is removed and the syngas is compressed. During Fischer-Tropsch (FT) synthesis, conditioned syngas is reacted over metallic catalysts to produce a mixture of long-chain hydrocarbons, which may then be upgraded to a finished fuel via standard refinery processes (such as hydrocracking and distillation).[21] The FT process also typically produces co-products such as naphtha, and highly thermally integrated plants can also generate excess electricity for sale to the grid.

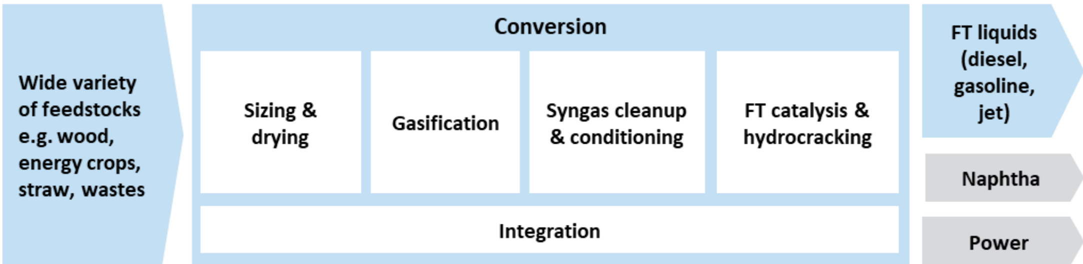


Figure 21: Value chain for gasification with FT

Gasification with FT is at TRL 8-9 for fossil feedstocks such as coal (CRL 2-3), while the process is currently only at TRL 5-6 for biomass feedstocks, such as forestry residues, waste wood and MSW (CRL 1). However, there are a few first commercial plants currently under construction, which are due to come online after 2020.

4.6.2 Major players in this technology

Of the companies included in Table 15, Velocys and Fulcrum BioEnergy are most actively developing large new gasification + Fischer-Tropsch plants. Expander Energy, Sunshine Kaidi and Red Rock Biofuels also have plants planned. The availability of feedstocks suited to gasification (such as woody

[21] E4tech, 2017. Future fuels for flight and freight competition – Feasibility study. Available from: https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/637662/dft_f4c-feasibility_final_report.pdf

biomass and an increasing interest in municipal solid waste), and the location of market demands, has led to North America and Northern Europe being the main focus regions for project development.

There are a number of companies such as UPM and NSE Biofuels (a joint venture between Neste and Stora Enso) who had plans for Fischer-Tropsch plants in the past, but have not progressed with these. These companies are therefore not listed in Table 15. The Växjö Värnamo Biomass Gasification Center (VVBGC) and the Southern Research Institute are also not included as they are research institutes, although both of these organisations have run pilot plants.

Table 15: Major players active in the gasification + Fischer-Tropsch industry

Company name	Location of headquarters (country)	Total capacity in the EU* (ktonnes/year)		Total capacity in the RoW* (ktonnes/year)	
		Planned	Current	Planned	Current
Expander Energy	Canada	-	-	5.8	-
Frontline Bioenergy	USA	-	-	-	0.041
Fulcrum BioEnergy Inc.	USA	-	-	31	-
Johnson Matthey	UK	-	-	-	-
Red Rock Biofuels	USA	-	-	44	-
Sunshine Kaidi New Energy Group Co. Ltd.	China	225	-	-	0.41
Syntech Bioenergy	USA	-	-	-	-
Thyssen Krupp	Germany	-	0.060	-	-
TRI (ThermoChem Recovery International)	USA	-	-	-	0.014
Velocys	UK	30	-	59	-
West Biofuels	USA	-	-	-	-

'Current capacity' covers plants which are operational and in commissioning, 'planned capacity' covers plants which are planned and under construction

4.6.2.1 Strengths and weaknesses of key players

Whilst there are quite a few different developers of FT technology in the EU and US, their level of activity varies, and most remain smaller players developing single projects. Only a few of the actors in this pathway are larger diversified industrial players, such as Thyssen Krupp, Sunshine Kaidi and Johnson Matthey, and even their involvement is limited to single potential projects. Nevertheless, there have been a number of announcements from high-profile fuel suppliers and airlines in support of particular projects, suggesting that projects are attracting interest and investment from larger companies.

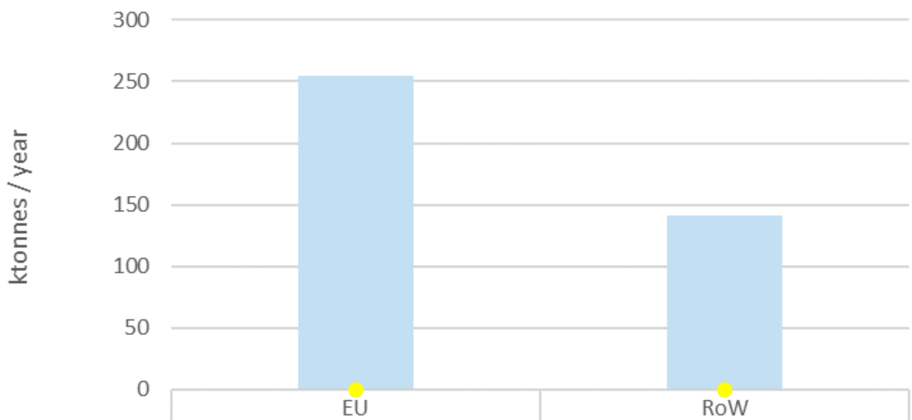
A strength of several of the companies involved in this pathway is that they bring experience of the technology components from other applications. Velocys for example have deployed their FT reactor at a gas-to-liquids plant, Johnson Matthey have significant catalyst experience, and TRI and Thyssen Krupp have operated large-scale biomass gasifiers. However, there is still a lack of expertise in the integration of these component technologies at scale, including the necessary syngas clean-up and conditioning steps that lie between gasification and FT synthesis steps – most of the actors have been previously focused on one of the technology components.

FT synthesis components have quite frequently been piloted as a slip-stream of an existing gasifier, but given the cost of the FT synthesis and the specific syngas conditioning, retrofitting larger FT units onto existing biomass gasification facilities is not seen as opportunity to develop this pathway – all the envisioned projects will be very large, standalone facilities. The final upgrading of FT waxes to finished jet and diesel products also currently looks most likely to happen on-site, and not at downstream refineries.

4.6.3 Current and planned production capacity

Global installed capacity of gasification + Fischer-Tropsch plants is very low, at only 0.7 ktonnes/year. The planned production capacity outside the EU is comprised of projects planned by Red Rock Biofuels, Velocys, Fulcrum and Expander Energy, all of which will take place in North America. Even the combined production capacity of these plants is substantially smaller than the 225 ktonnes/year plant planned by Sunshine Kaidi New Energy Group in Finland. This very large project is assumed to be still in the planning stage, but it has not been possible to confirm this with the developer.

It was not possible to confirm known production volumes with plant developers, but given that all of the current operating production capacity is comprised of pilot plants, many of which are at universities or research institutes, it is likely that actual production volumes of fuel produced via this pathway are substantially lower than the current (very small) installed capacity.



	EU	RoW
Planned production capacity	255	140
Current production capacity	0.060	0.71
Known production volumes	-	-

Figure 22 Gasification + Fischer-Tropsch: current installed capacity, planned capacity and production volumes for the EU28 compared to the rest of the world

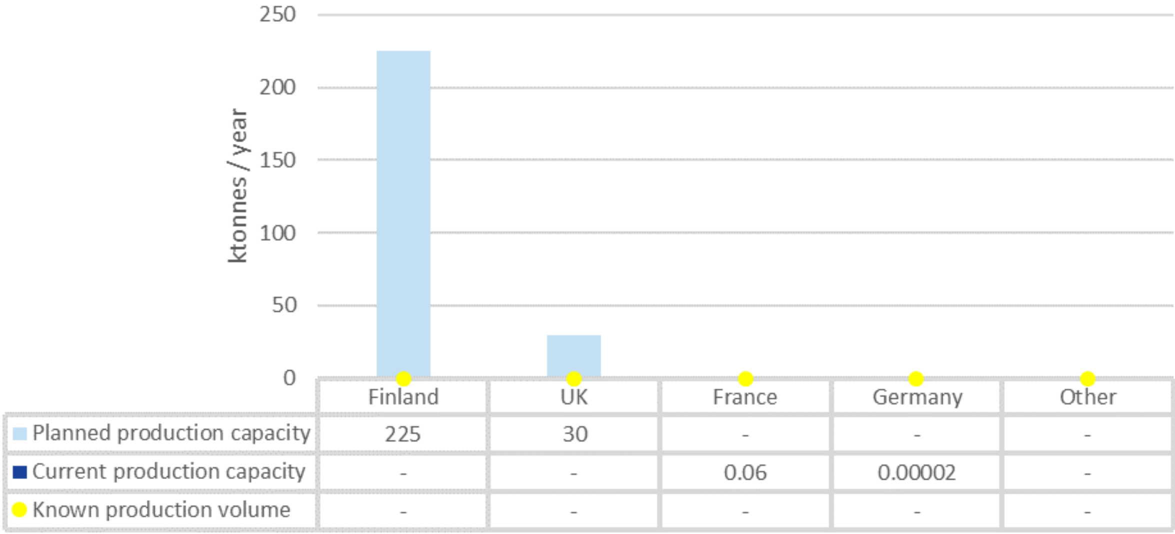


Figure 23 Gasification + Fischer-Tropsch: current installed capacity, planned capacity and production volumes by EU Member State, covering top 6 MSs by installed capacity

There is little existing gasification + Fischer-Tropsch production capacity within Europe: only the pilot-scale BioTfuel plant in France. The planned production in Finland is due entirely to a large project planned by the Sunshine Kaidi New Energy Group, which in 2016 was allocated a €88.5M NER300 grant, but it is unclear whether this project will go ahead. There is also one plant planned in the UK at 30 ktonnes/year production capacity, involving a consortium of Velocys, British Airways and Shell, which will transform MSW into jet fuel.

4.6.4 Plant and production costs

With few operating biomass gasification + Fischer-Tropsch plants globally today, the figures in Table 16 for capex and opex costs are based predominantly on planned plants. The high capex cost of the pilot BioTFuel plant (€178M) is because this plant has a very large torrefaction and gasification unit but only a pilot-scale FT plant.

Table 16: Capex and opex costs for gasification + Fischer-Tropsch plants

Technology status	Plant capacity (ktonnes/year)	Capex cost (million $€_{2016}$)	Opex cost (million $€_{2016}$ / year)
Pilot	0-1.41	34-175	N/A
Demonstration	2.3-36	N/A	N/A
First Commercial	30-225	179-886	N/A

Data is based on all plants, whether planned, operating or shut; note that the min and max of the cost range do not necessarily correspond to the min and max plant capacity within that range

4.6.5 EU market share

Europe has only 22% of the companies and 33% of the plants in gasification and Fischer-Tropsch, but 64% of the current and planned production capacity. This is mostly due to the large plant planned in Finland, which has a large capacity and total capex.

As can be seen in Figure 22, the planned production capacity significantly outweighs the current installed capacity and is higher in the EU than the RoW, although as noted above this is largely due to one very large planned plant in the EU. Economic value from FT diesel and jet produced via gasification and Fischer-Tropsch catalysis is likely to increase in the future if these plants reach the operational stage.

Table 17: EU28 market share of gasification + Fischer-Tropsch industry

	Number of companies (HQ)	Number of plants*	Production capacity *(ktonnes/year)	Known economic value** (million €)
EU	3	5	255	-
Rest of World	8	10	141	-
Global total	11	15	396	-
% EU	27%	33%	64%	-

**Number of plants and production capacity refers to plants which are currently operational, in commissioning, under construction or planned; **Known economic value was calculated based on known production volumes and estimated 2G biofuel prices. For prices and methodology see Appendix C.*

4.7 Gasification with methanation

4.7.1 Technology overview

Biomass feedstocks, such as forest residues, energy crops and Municipal Solid Waste, are typically pre-treated, usually by drying, and sorting/sizing if required. Gasification then converts the biomass into syngas, using high temperatures, a limited oxygen environment and potentially elevated pressures. For this route, dual fluidised bed gasifier designs are typically used, whereby steam is introduced into the gasification chamber to boost the amount of methane in the syngas. The syngas is then cooled, cleaned of ash, tars and chemical contaminants, and then conditioned via a water-gas shift reaction to meet the downstream catalyst specifications, before the syngas is compressed.

During methanation, conditioned syngas is reacted over metallic catalysts to produce a gas mixture composed primarily of methane and carbon dioxide. The carbon dioxide is then removed and the gas purified in order to produce ‘biomass-derived synthetic natural gas’ (bioSNG), which can be injected into the gas grid or used directly for vehicle refuelling.

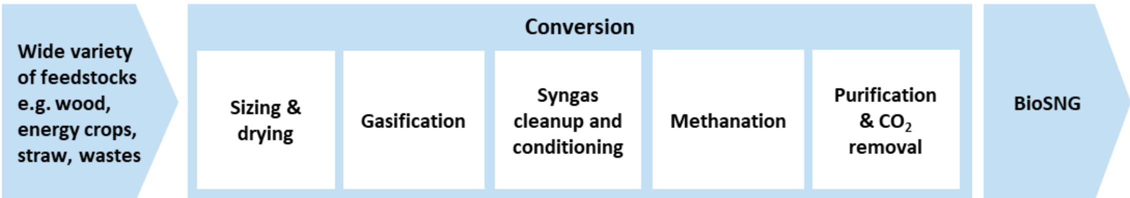


Figure 24: Value chain for gasification with methanation

This process is at TRL 7-8 (CRL 1-2)[22], since there is one small first commercial plant in Sweden, running on forestry residues, that has been in operation intermittently since 2014.[23] [24]

4.7.2 Major players in this technology

All of the companies currently engaged in gasification + methanation technologies are in the EU (Table 15). The methanation technology has a range of applications, including in natural gas synthesis from coal and in 'power to gas' plants producing methane from hydrogen and CO_2. Therefore companies such as Amec-Foster-Wheeler and Haldor-Topsoe which develop methanation technology for a wide range of uses are not included in the major players' database, even though they are included in several of the project consortia.

Moji is a joint venture between The Research Centre of the Netherlands (ECN) and Dahlman Renewable Technology to commercialise the gasification and tar removal technologies they have developed. The most recent public information suggests that Göteborg Energi is planning to close its demonstration-scale gasification + methanation plant (GoBiGas Phase 1), having failed to find a buyer for it.[25] The plant is nevertheless included in Table 18, Figure 25 and Figure 26 until its closure is confirmed.

Table 18: Major players active in the gasification with methanation industry

Company name	Location of headquarters (country)	Total capacity in the EU* (ktonnes/year)		Total capacity in the RoW* (ktonnes/year)	
		Planned	Current	Planned	Current
Advanced Plasma Power (APP)	UK	1.0	0.03	-	-
Cortus Energy	Sweden	-	0.06	-	-
Engie	France	-	0.24	-	-
EON Biofor Sverige Ab	Sweden	-	-	-	-
Göteborg Energi	Sweden	-	-	-	-
Hydromethan AG	Switzerland	-	-	-	-
Moji	Netherlands	0.69	-	-	-
Repotec	Austria	-	0.60	-	-

'Current capacity' covers plants which are operational and in commissioning, 'planned capacity' covers plants which are planned and under construction

[22] E4tech, 2017. Advanced Renewable Fuels Demonstration Competition – Feasibility Study. Available from: https://d1v9sz08rbysvx.cloudfront.net/ee/media/media/f4c%20and%20sector%20files/dft_comp2feasibility_final-report_with-appendices.pdf
[23] Bioenergy International, 2017. GoBiGas gasification plant up for sale. Available from: https://bioenergyinternational.com/biogas/gobigas-gasification-plant-sale
[24] Göteborg Energi (n.d.). GoBiGas. Available from: https://gobigas.goteborgenergi.se/English_version/Start
[25] Walsh, L. (2018) Innovative GoBiGas gasification plant mothballed, ENDS waste & bioenergy, 5 April 2018, available from: https://www.endswasteandbioenergy.com/article/1461215/innovative-gobigas-gasification-plant-mothballed (Accessed 27th September 2018)

4.7.2.1 Strengths and weaknesses of key players

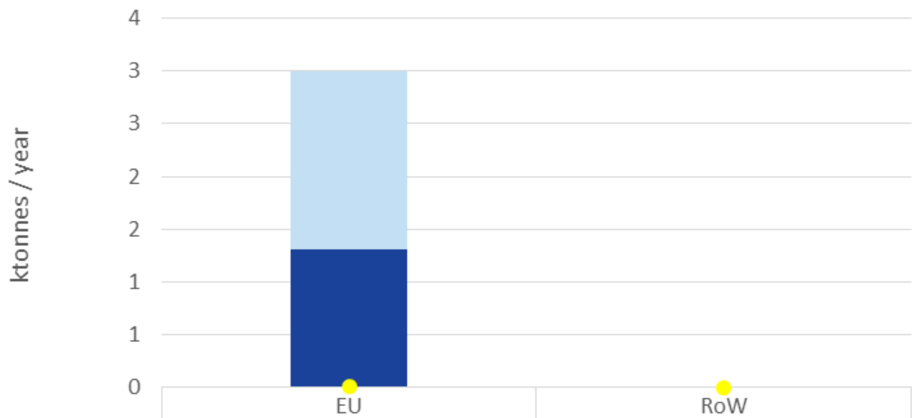
There are only a modest number of players in the pathway, and all are based in Europe. The companies most actively involved in gasification + methanation technology development are generally small players focussed only on this technology pathway, e.g. APP, Moji, Cortus, although Repotec does have other existing heat & power gasification plants. There are some larger industrial actors (EON, Engie) who are not developing their own technology, but may have bought technology licences for projects, although are now no longer as actively involved. The technology has been successfully proven, but investor interest remains limited. The level of activity in this pathway is therefore not high, with generally slow progress on demonstration activities, and no large-scale commercial plants planned.

Although the bioSNG conversion technology is more efficient in producing biomethane than gasification pathways to liquid diesel and jet, the market price of biomethane is generally much lower, and/or attracts less government support, than liquid biofuels (or else the market for use of bioSNG directly in heavy goods vehicles is limited). This leaves projects vulnerable to gas market price changes – for example, Göteborg Energi's second phase of their plant (GoBiGas2 at 48 ktonnes/year) did not go ahead primarily for this reason. EON also had plans for a very large (119 ktonnes/year$_{SNG}$) project, with a further pipeline of projects, but this vision has been on-hold for many years and the projects are assumed to be now cancelled.

4.7.3 Current and planned production capacity

All of the known existing and planned gasification + methanation technology production capacity is in the EU (Figure 25), however this is dominated by a small number of plants. The existing production capacity is 1ktonne/year, with actual production volumes likely far lower as the remaining plants are mostly pilot facilities. The GoBiGas phase 1 plant (12 ktonnes/yr) is being mothballed.

There have also been some substantially larger plants planned which are likely not going ahead. The 119 ktonnes/year Bio2G plant which was planned by EON is officially 'on hold', but has not been included here as it has been in the planning stages for over five years. The GoBiGas phase 2 plant was also a large (48 ktonnes/year) planned plant in Europe, which has also been cancelled.



	EU	RoW
Planned production capacity	1.7	-
Current production capacity	1.3	-
Known production volumes	0.0091	-

Figure 25 Gasification + methanation: current installed capacity, planned capacity and production volumes for the EU28 compared to the rest of the world

There are leading companies in gasification + methanation in the UK, the Netherlands, Austria, France and Sweden despite the low installed capacity in these regions (Figure 26). The two planned plants (the Ambigo plant in the Netherlands being built by Moji, and the Advanced Plasma Power plant in the UK) are substantially smaller than the GoBiGas phase 1 plant, suggesting that further technology demonstration at this scale is still needed.

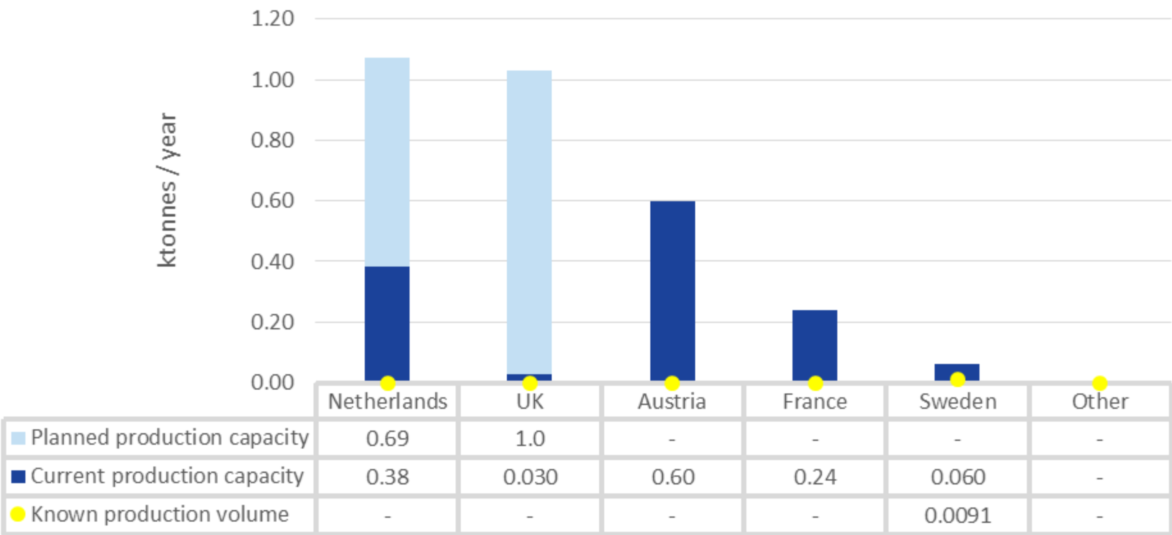


Figure 26 Gasification + methanation: current installed capacity, planned capacity and production volumes by EU Member State, covering top 6 MSs by installed capacity

4.7.4 Plant and production costs

The capex cost of pilot plants to date has been below €10M for all those for which data was available. On moving to demonstration-scale however the capex costs vary more substantially. Based on the evidence available, the variation appears to be largely associated with plant scale. Within first commercial plants, the capex cost given in Table 19 is the cost of the GoBiGas Phase 2 plant, which will now not go ahead. At 48 ktonnes/year capacity, this plant lies at the lower end of first commercial plants.

Table 19: Capex and opex costs for gasification + methanation plants

Technology status	Plant capacity (ktonnes/year)	Capex cost (million €$_{2016}$)	Opex cost (million €$_{2016}$ / year)
Pilot	0.38	4.8-6.1	N/A
Demonstration	0.24-12	16-160	N/A
First Commercial	48-119	337	N/A

Data is based on all plants, whether planned, operating or shut; note that the min and max of the cost range do not necessarily correspond to the min and max plant capacity within that range

4.7.5 EU market share

The EU dominates the gasification + methanation industry, and the one company headquartered outside the EU is in Switzerland. However the industry has suffered some set-backs in recent years, with the sale of the GoBiGas phase 1 plant and decision not to progress with the phase 2 plant.

Table 20: EU28 market share of gasification + methanation industry.

	Number of companies (HQ)	Number of plants*	Production capacity *(ktonnes/year)	Known economic value** (million €)
EU	7	7	3	-
Rest of World	1	-	-	-
Global total	8	7	3	-
% EU	88%	100%	100%	-

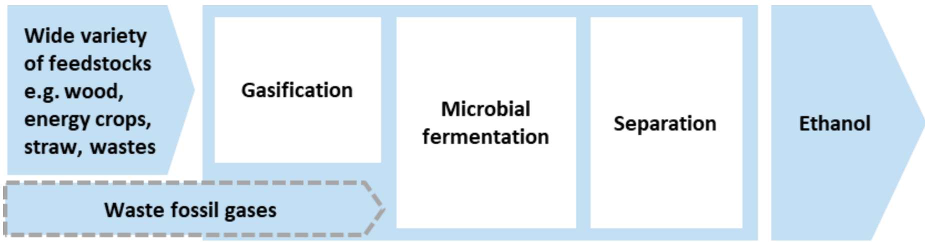
**Number of plants and production capacity refers to plants which are currently operational, in commissioning, under construction or planned; **Known economic value was calculated based on known production volumes and estimated 2G biofuel prices. For prices and methodology see Appendix C.*

4.8 Gasification with syngas fermentation

4.8.1 Technology overview

Biomass feedstocks, such as forest residues, energy crops and Municipal Solid Waste, are typically pre-treated, usually by drying, and sorting/sizing if required. Gasification then converts the biomass into syngas, using high temperatures, a limited oxygen environment and potentially elevated pressures. Syngas is a gas mixture comprised primarily of carbon monoxide and hydrogen. The syngas is then cooled, and cleaned of ash, tars and chemical contaminants. However, the syngas typically does not need extensive conditioning before being fed to biological micro-organisms, which ferment the syngas into ethanol and other co-product chemicals. Ethanol is then separated from the fermentation broth using distillation and/or more novel techniques (including membranes or molecular sieves).

Instead of using gasification to produce syngas, waste fossil gases that are rich in carbon monoxide (e.g. from steel mills) can also be cooled, cleaned up, injected into the fermentation reactor and converted to ethanol. Other microbes also have the potential to convert H_2 and CO_2 into ethanol, hence could use different waste fossil gas sources.[26,27]



[26] n.d. Technical background on the LanzaTech Process. Available from: http://www.arpae-summit.com/paperclip/exhibitor_docs/14AE/LanzaTech_Inc._131.pdf
[27] IRENA, 2016. Innovation Outlook: Advanced Liquid Biofuels. Available from: http://www.irena.org/-/media/Files/IRENA/Agency/Publication/2016/IRENA_Innovation_Outlook_Advanced_Liquid_Biofuels_2016.pdf

Figure 27: Value chain for gasification with syngas fermentation

Gasification with syngas fermentation is at TRL 5-7 when using biomass as feedstock (CRL 1), due to the construction of a large demonstration plant in the US that is no longer operating. The process is at TRL 7-8 when using industrial fossil carbon-rich waste gases as feedstock (CRL 1-2), with a first commercial plant that came online in China in 2018[28], and another planned to come online in Europe in 2020[29].

4.8.2 Major players in this technology

There are currently few companies worldwide developing gasification + syngas fermentation to ethanol technology and these are all headquartered in the USA. Lanzatech is a key developer of this technology, and Aemetis is planning to build a facility in California using Lanzatech technology. It should be noted that Lanzatech are also developing technology for the fermentation of industrial waste gases, but this fossil feedstock is not within the scope of this study. Jupeng Bio bought the Ineos Bio gasification + syngas fermentation technology and several plants after Ineos decided to pull out of bioethanol production, and Synata Bio is a new company (established in 2015) that took over the Coskata gasification + syngas fermentation technology when Coskata went bankrupt.

Table 21: Major players active in the gasification with syngas fermentation industry

Company name	Location of headquarters (country)	Total capacity in the EU* (ktonnes/year)		Total capacity in the RoW* (ktonnes/year)	
		Planned	Current	Planned	Current
Aemetis	USA	-	-	35	-
Jupeng Bio	USA	-	-	-	-
Lanzatech	USA	-	-	-	0.015
Synata Bio	USA	-	-	-	-

'Current capacity' covers plants which are operational and in commissioning, 'planned capacity' covers plants which are planned and under construction

4.8.2.1 Strengths and weaknesses of key players

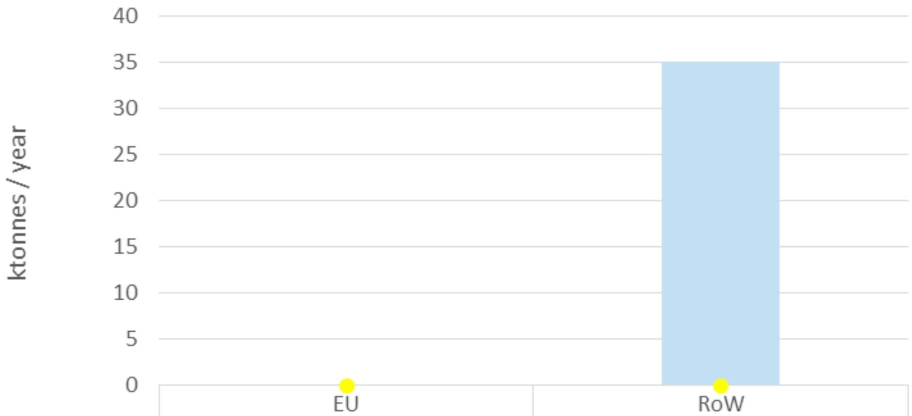
Lanzatech is currently the most active developer of syngas fermentation technology. Lanzatech have been developing a number of variations of their technology including both biomass-derived syngas fermentation and the fermentation of waste fossil industrial gases, which helps mitigate some of their exposure to technical or policy risk – although they are currently more focused on steel mill gas projects (out of scope) rather than advanced biofuel facilities. Both Jupeng Bio and Synata Bio have taken over the technology of other past players (respectively Ineos Bio and Coskata), but do not have concrete plans for further plants. Therefore whilst the Lanzatech-Aemetis partnership seems strong, it is a clear weakness of this industry that there is only one player developing technology and planning new plants. There are no major industrial actors involved directly in developing the technology, although Lanzatech do have some large industrial investors and partnerships with steel producers, airlines and fuel suppliers.

[28] LanzaTech, 2018. World's first commercial waste gas to ethanol plant starts up. Available from: http://www.lanzatech.com/worlds-first-commercial-waste-gas-ethanol-plant-starts/ [Accessed 10th July 2018]

[29] Globenewswire, 2018. ArcelorMittal and LanzaTech break ground on €150million project to revolutionise blast furnace carbon emissions capture. Available from: https://globenewswire.com/news-release/2018/06/11/1519303/0/en/ArcelorMittal-and-LanzaTech-break-ground-on-150million-project-to-revolutionise-blast-furnace-carbon-emissions-capture.html [Accessed 10th July 2018]

4.8.3 Current and planned production capacity

All of the current and planned production capacity today is outside of the EU, although even outside the EU deployment is fairly limited as the capacity included in Figure 28 refers to only two plants. Current production capacity is associated with a pilot plant built by Lanzatech in Tokyo, and planned production capacity is a plant planned by Aemetis in the USA using Lanzatech technology. Lanzatech also operate a pilot facility in the USA for testing a number of technologies including syngas fermentation, but information on the capacity of this was not available. Ineos Bio (bought by Jupeng Bio) had operated a 24 ktonnes/year first commercial facility in Vero Beach, Florida. The plant was sold in 2017, to Frankens Energy and partners, who do not appear to have plans to continue to operate the plant, so this plant is not included within Figure 28.



	EU	RoW
Planned production capacity	-	35
Current production capacity	-	0.015
Known production volumes	-	-

Figure 28 Gasification + syngas fermentation: current installed capacity, planned capacity and production volumes for the EU28 compared to the rest of the world

There is no existing or planned production capacity of gasification + syngas fermentation technology in the EU so a breakdown by member state is not provided.

4.8.4 Plant and production costs

For gasification + syngas fermentation plants, capex costs were available for plants at pilot and at first commercial scale.

Table 22: Capex and opex costs for gasification + syngas fermentation plants

Technology status	Plant capacity (ktonnes/year)	Capex cost (million €$_{2016}$)	Opex cost (million €$_{2016}$ / year)
Pilot	0-0.12	24	N/A
Demonstration	N/A	N/A	N/A
First Commercial	24-35	117-137	N/A

Data is based on all plants, whether planned, operating or shut; note that the min and max of the cost range do not necessarily correspond to the min and max plant capacity within that range

4.8.5 EU market share

The EU has no market share in gasification + syngas fermentation technology, however the industry as a whole is small and still developing.

Table 23: EU28 market share of gasification + syngas fermentation industry

	Number of companies (HQ)	Number of plants*	Production capacity *(ktonnes/year)	Known economic value** (million €)
EU	-	-	-	-
Rest of World	4	4	35	-
Global total	4	4	35	-
% EU	0%	0%	0%	-

**Number of plants and production capacity refers to plants which are currently operational, in commissioning, under construction or planned; **Known economic value was calculated based on known production volumes and estimated 2G biofuel prices. For prices and methodology see Appendix C.*

4.9 Gasification with catalytic synthesis

4.9.1 Technology overview

Biomass feedstocks, such as forest residues, energy crops and Municipal Solid Waste, are typically pre-treated, usually by drying, and sorting/sizing if required. Gasification then converts the biomass into syngas, using high temperatures, a limited oxygen environment and potentially elevated pressures. Syngas is a gas mixture comprised primarily of carbon monoxide and hydrogen. The syngas is then cooled, cleaned of ash, tars and chemical contaminants, and then conditioned via a water-gas shift reaction to meet the downstream catalyst specifications, before the syngas is compressed.

During the catalysis step, conditioned syngas is reacted over metallic catalysts. Development is currently focused on production of either:

- Methanol
- Dimethyl-ether, DME (either directly or via methanol)
- Ethanol (either directly or via methanol)
- Mixtures of short-chain alcohols (using alkali-metal doped catalysts)

The product made varies by developer and market, and depends on the catalysts selected, the process conditions and syngas composition.

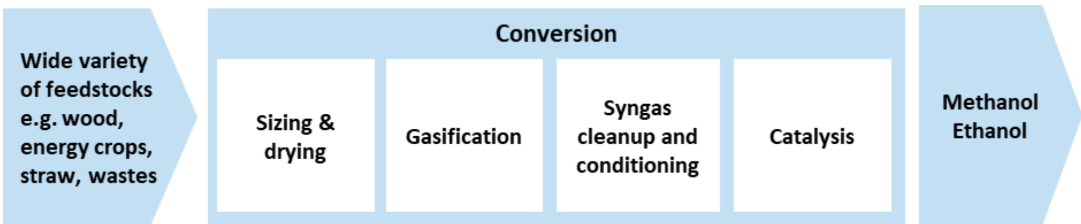


Figure 29: Value chain for gasification with catalytic synthesis

Gasification + methanol catalysis plants have been commercially available for fossil feedstocks such as coal for several decades, but have only recently been commercially applied for the conversion of MSW, at TRL 8 (CRL 2). Gasification + ethanol catalysis is also currently at TRL 8 when using MSW feedstock, via the upgrading of methanol to ethanol. However, other gasification + catalysis routes e.g. to DME or mixed alcohols are currently at TRL 5 (CRL 1), due to past pilot activities that are no longer operational.

4.9.2 Major players in this technology

Enerkem are currently the major player in gasification + catalysis technology, with the largest operational capacity, and plants planned both within the EU and in the rest of the world. The Enerkem process initially produces methanol, but this can then be upgraded to ethanol, as in the Edmonton plant. Future Enerkem plants producing both methanol and/or ethanol are included within the database. Thyssen Krupp are not included within Table 24, despite being involved in many of the projects, as they are providers of technology components rather than primary developers of gasification + catalytic synthesis projects.

Table 24: Major players active in the gasification with catalytic synthesis industry

Company name	Location of headquarters (country)	Total capacity in the EU* (ktonnes/year)		Total capacity in the RoW* (ktonnes/year)	
		Planned	Current	Planned	Current
Biomass Energy Corporation	Japan	-	-	-	-
BioMCN	Netherlands	-	-	-	-
CORE Biofuels	Canada	-	-	12	-
Enerkem	Canada	479	-	32	34
Mitsubishi Heavy Industries	Japan	-	-	-	0.20
Sodra	Sweden	5.0	-	-	-
VärmlandsMetanol AB	Sweden		-	-	-
Woodland biofuels	Canada	-	-	-	1.6

'Current capacity' covers plants which are operational and in commissioning, 'planned capacity' covers plants which are planned and under construction

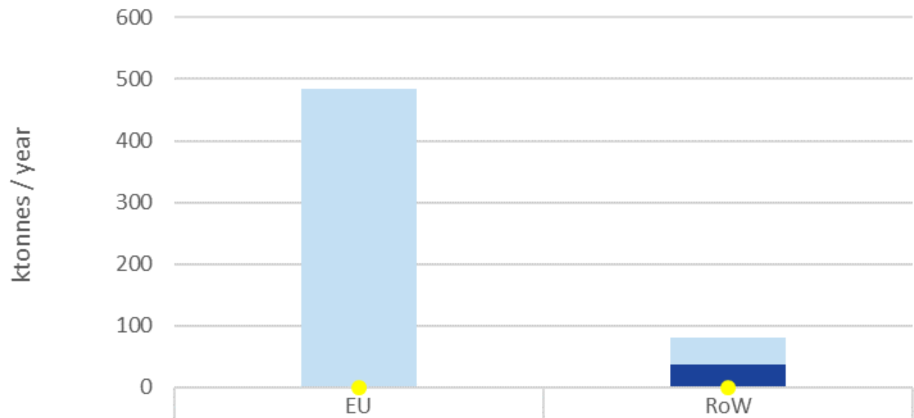
4.9.2.1 Strengths and weaknesses of key players

Whilst Enerkem have a strong track record and an expanding pipeline of projects, and Sodra are also planning a gasification to methanol plant, there are only a few players actively developing this technology pathway. Some, such as Woodland Biofuels, Biofuels Energy Corporation and Mitsubishi have done work on this technology in the past, but do not seem to be actively developing and scaling-up plants at the moment CORE biofuels is aiming to produce gasoline from DME via gasification + catalysis. Large diversified engineering firms such as Thyssen Krupp or Andritz may be involved in projects in order to provide the methanol production unit, and there are other large diversified actors with experience of the technology components from fossil methanol production pathways, for example through coal gasification, which may have the expertise to get involved in this technology route if it proved profitable. However in general the players most active in developing this technology are not particularly large and are fairly specialised.

4.9.3 Current and planned production capacity

Existing production capacity in gasification + catalytic synthesis is dominated by Enerkem, which operates in Canada and the USA. There is also a small contribution to current production capacity from pilot plants built by Woodland Biofuels and Mitsubishi, although the status of these is unclear. The planned production capacity outside the EU is also dominated by Enerkem.

Within the EU, the planned capacity is dominated by only two plants, in the Netherlands and Spain, both of which are being planned by Enerkem. It should be noted however that in the Rotterdam plant Enerkem is aiming to produce methanol for the chemicals sector and not for the fuels sector. Värmlands Methanol had another larger planned plant of 100 ktonnes/year capacity in Sweden. However it was put on-hold by a change in biofuel taxation policy in Sweden in 2012, and no developments have occurred since this date so it is not included here.



	EU	RoW
Planned production capacity	484	43
Current production capacity	0.041	37
Known production volumes	-	-

Figure 30 Gasification + catalytic synthesis: current installed capacity, planned capacity and production volumes for the EU28 compared to the rest of the world

A breakdown by EU Member state is given in Figure 31, showing the dominance of the planned Enerkem plants in The Netherlands and Spain. There is a very small pilot plant in Austria run by the Bioenergy 2020+ consortium, which is assumed to be still operational.

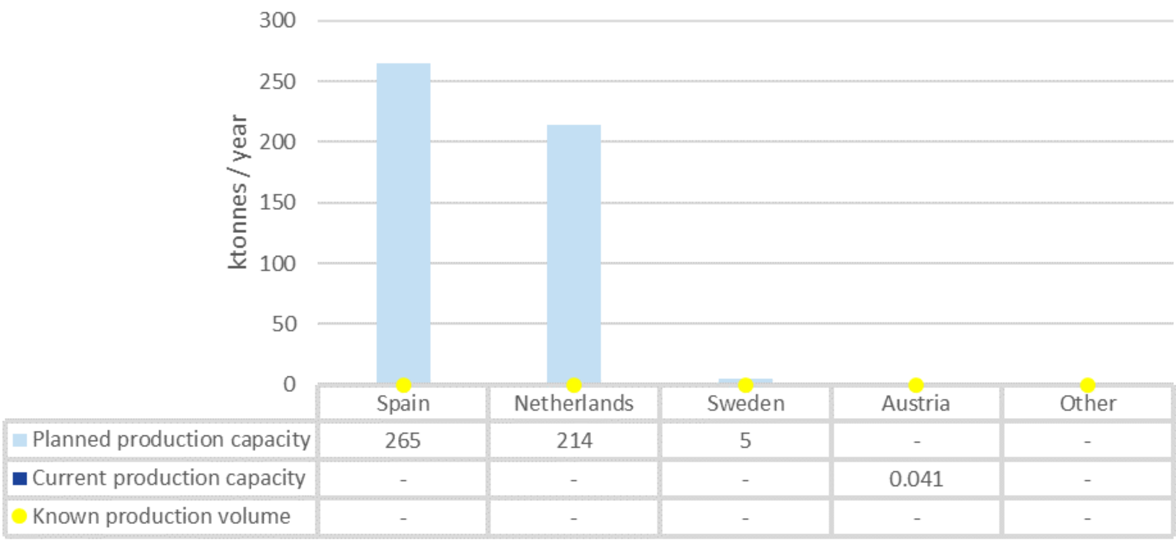


Figure 31 Gasification + catalytic synthesis: current installed capacity, planned capacity and production volumes by EU Member State, covering top 6 MSs by installed capacity

4.9.4 Plant and production costs

Capex costs for gasification + catalytic synthesis plants were available across a range of technology states, from pilot to commercial (Table 25). Two commercial plants were included in the database, both in the planning state from Enerkem. The smaller plant uses MSW as a feedstock, which is generally a limited feedstock in any region, therefore this plant is classified as 'commercial' despite its limited size. Meanwhile the very large first commercial plant (413 ktonnes/year) refers to a plant which is now no longer being developed.

Table 25: Capex and opex costs for gasification + catalytic synthesis plants

Technology status	Plant capacity (ktonnes/year)	Capex cost (million $€_{2016}$)	Opex cost (million $€_{2016}$ / year)
Pilot	0-1.5	N/A	N/A
Demonstration	1.6-120	8.3-303	N/A
First Commercial	30-413	81-511	N/A
Commercial	30-214	89-173	N/A

Data is based on all plants, whether planned, operating or shut; note that the min and max of the cost range do not necessarily correspond to the min and max plant capacity within that range

4.9.5 EU market share

The EU has a reasonable market share in the gasification + catalytic synthesis industry, however it should be noted that the high percentage of production capacity is due mainly to two very large planned plants (see section 0).

Table 26: EU28 market share of gasification + catalytic synthesis industry

	Number of companies (HQ)	Number of plants*	Production capacity *(ktonnes/year)	Known economic value** (million €)
EU	4	4	484	-

	Number of companies (HQ)	Number of plants*	Production capacity *(ktonnes/year)	Known economic value** (million €)
Rest of World	5	10	80	-
Global total	9	14	564	-
% EU	44%	29%	86%	-

**Number of plants and production capacity refers to plants which are currently operational, in commissioning, under construction or planned; **Known economic value was calculated based on known production volumes and estimated 2G biofuel prices. For prices and methodology see Appendix C.*

4.10 Fast pyrolysis with catalytic upgrading

4.10.1 Technology overview

Pyrolysis is the controlled thermal decomposition of (typically dry) biomass at moderate temperatures, in the absence of oxygen, to produce liquid oil, pyrolysis gases and charcoal (biochar). Catalytic fast pyrolysis maximizes the production of the liquid pyrolysis oil fraction (instead of the char), with the gas produced typically used to heat the system and dry the biomass.

Crude pyrolysis oil is a complex mix of oxygenated compounds, such as carboxylic acids, phenols, sugars and water, and is an energy dense intermediate. Crude pyrolysis oil can be upgraded by directly blending with fossil vacuum gas oil at up to 10-20% within an existing oil refinery fluid catalytic cracker (FCC) unit. Alternatively, crude pyrolysis oil can undergo hydro-deoxygenation (HDO), which involves adding hydrogen at high pressure to remove oxygen and other trace elements before hydrocracking – which can all be located onsite with the pyrolysis unit.[30]

Upgrading processes are usually done in a series of separate catalytic steps of increasing severity to reduce the oxygen content while minimising catalyst deactivation. Both upgrading options produce a combination of light, medium and heavy products, which can be distilled to produce diesel, jet and gasoline streams.

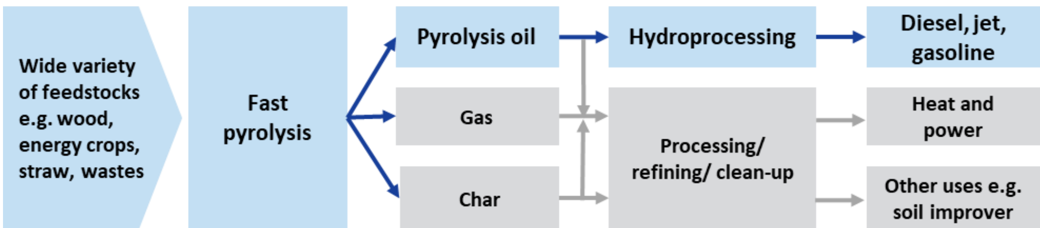


Figure 32: Value chain for fast pyrolysis with catalytic upgrading

Fast pyrolysis to crude pyrolysis oil is at TRL 8 (CRL 2), with several first commercial facilities selling the pyrolysis oil for heating applications. However, refinery FCC upgrading to a finished fuel product is only at early demonstration scale with batch production in limited trial runs, so is currently at TRL 6 (CRL 1). Upgrading via hydrodeoxygenation is currently at TRL 3 (CRL 1), with pilot activities ongoing

[30] Jones *et al*. (2016) "Fast Pyrolysis and Hydrotreating: 2015 State of Technology R&D and Projections to 2017", Pacific Northwest National Laboratory (PNNL). Available at www.pnnl.gov/main/publications/external/technical_reports/PNNL-25312.pdf

such as the H2020 4Refinery project. Therefore the overall route from pyrolysis to liquid transport fuel is at maximum TRL6.

4.10.2 Major players in this technology

Worldwide there are many companies and plants producing pyrolysis oil for heat and power, but given the scope of this report for advanced biofuels, the plants and companies included in the databases, and therefore within this section, are those specifically targeting the production of transport fuel. Nevertheless for the majority of the plants, the capacity of the plant is provided in terms of amount of bio-oil produced and not in terms of amount of finished fuel produced. Therefore the capacity figures provided in Table 27, Figure 33 and Figure 34 likely over-estimate the production capacity of fuel.

The major players in pyrolysis + catalytic upgrading are mostly based in Europe and North America (Table 27). Ensyn and Envergent (which is a joint venture between Ensyn and UOP) have the highest operational capacity to-date and dominate the planned capacity.

In addition, there are a number of technology developers focussed on the pyrolysis of plastics to produce liquid fuels, including Integrated Green Energy Solutions, PlasticEnergy and Recycling Technologies, which could have technologies relevant to biomass pyrolysis, but which are not within scope of this study on advanced biofuels due to the fossil feedstock used. Producers of pyrolysis oil for heat and power, such as Fortum, could also have relevant capabilities but are also not within scope of this transport biofuels study.

Table 27: Major players in the fast pyrolysis + catalytic upgrading industry

Company name	Location of headquarters (country)	Total capacity in the EU* (ktonnes/year)		Total capacity in the RoW* (ktonnes/year)	
		Planned	Current	Planned	Current
Anellotech	USA	-	-	-	0.12
BTG	Netherlands	-	23*	-	-
CRI Catalyst	UK	-	-	-	0.0072
Ensyn	Canada	-	-	183*	13*
Envergent	USA	-	-	33*	0.15
Green Fuel Nordic	Finland	-	-	-	-
Next BTL LLC / Future Blends	UK	-	0.023	-	-
Proton Power	USA	-	-	-	3.1
Pyreco	UK	-	-	-	-
Resynergi					
Synterra Fuels	USA	-	-	-	0.94

'Current capacity' covers plants which are operational and in commissioning, 'planned capacity' covers plants which are planned and under construction

** Capacity figures refer to intermediate rather than final transport fuel*

4.10.2.1 Strengths and weaknesses of key players

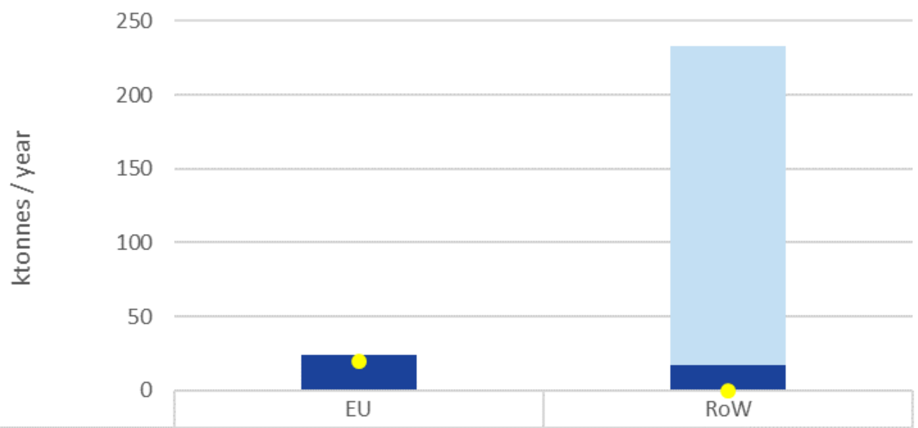
There are a number of companies developing pyrolysis technology, in a range of countries across the world. Many of these companies are small and focussed specifically on developing pyrolysis technology, although there are existing partnerships with larger industrials such as UOP and Shell – which will be particularly important to retain for the required upgrading activities.

A key strength of the pyrolysis industry is that developers typically already have existing supply chains and plants, with pyrolysis oil already being used in various applications for heat and power. There is also continued interest in the pyrolysis of waste plastics (although out of scope as a feedstock of this study) which could support technology development, given the recent concerns with plastic pollution in the environment. However, there are very few companies actually focussing exclusively on advanced biofuel production, which is a weakness of this pathway, given the technical challenges of upgrading pyrolysis oil are significant. Some pyrolysis developers, such as Cool Planet, have stopped focusing on fuels production, and are instead targeting more profitable biochar markets.

4.10.3 Current and planned production capacity

Current production capacity in the EU is slightly higher than that in the rest of the world, although across both EU and RoW the current production capacity is fairly small. It should be noted that for a number of these plants it was only possible to find the production capacity of pyrolysis oil, not of the finished fuel. Therefore, transport fuel production capacity is lower than the figures given in Figure 33.

There are a number of fast pyrolysis plants throughout the world producing pyrolysis oil for heat and power, but as these are not targeting the transport fuel sector they are not within scope of this study and are therefore not included within the capacity figures given in this section.



	EU	RoW
Planned production capacity	-	215
Current production capacity	24	17
Known production volumes	20	-

Figure 33 Fast pyrolysis + upgrading: current installed capacity, planned capacity and production volumes for the EU28 compared to the rest of the world

The operational BTG Empyro plant in the Netherlands dominates fast pyrolysis installed capacity in the EU, and there is also one pilot plant in Germany and one in the UK. However the capacity of the Empyro plant presented here likely overestimates its current capacity to supply the fuels market, as the Empyro plant is mostly aimed at pyrolysis as a fuel for heating / power, with some tests in upgrading to transport fuel.

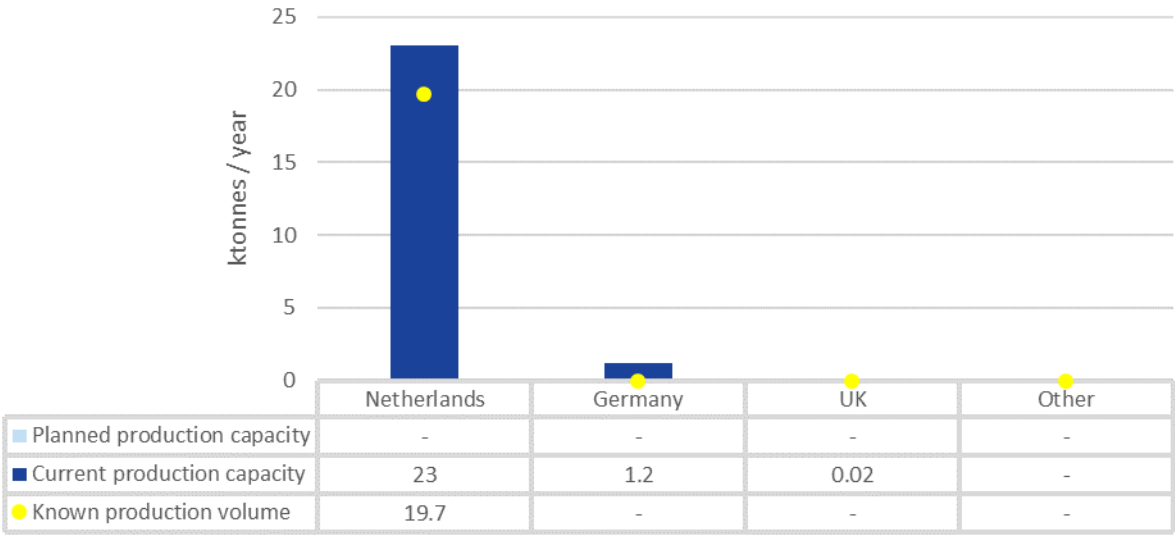


Figure 34 Fast pyrolysis + upgrading: current installed capacity, planned capacity and production volumes by EU Member State, covering top 6 MSs by installed capacity

4.10.4 Plant and production costs

Capex costs are available for demonstration, first commercial and commercial plants (Table 28). These costs for many plants do not include the cost of the catalytic upgrading unit, as this is often done off-site.

Table 28: Capex and opex costs for fast pyrolysis + catalytic upgrading plants

Technology status	Plant capacity (ktonnes/year)	Capex cost (million $€_{2016}$)	Opex cost (million $€_{2016}$ / year)
Pilot	0-1.2	N/A	N/A
Demonstration	3.1-23	22	N/A
First Commercial	19.2-87	69-71	N/A
Commercial	57-96	100	N/A

Data is based on all plants, whether planned, operating or shut; note that the min and max of the cost range do not necessarily correspond to the min and max plant capacity within that range

4.10.5 EU market share

The EU has around 45% of the global market in fast pyrolysis + upgrading (Table 29)

The known biofuel production of pyrolysis oil was provided by developers for one plant. The cost of advanced biodiesel was used in order to estimate the known economic value (see Appendix C), although this likely provides an over-estimation of the value from this plant, as very little of the pyrolysis oil is currently being upgraded to transport fuel.

Table 29: EU28 market share of fast pyrolysis + upgrading industry

	Number of companies (HQ)	Number of plants*	Production capacity *(ktonnes/year)	Known economic value** (million €)
EU	5	5	24	21
Rest of World	6	15	233	-
Global total	11	20	257	21
% EU	45%	25%	9%	100%

**Number of plants and production capacity refers to plants which are currently operational, in commissioning, under construction or planned; **Known economic value was calculated based on known production volumes and estimated 2G biofuel prices. For prices and methodology see Appendix C.*

4.11 Hydrothermal liquefaction (HTL) with catalytic upgrading

4.11.1 Technology overview

Hydrothermal liquefaction (HTL) is a process where biomass (plus a large amount of water) is heated at very high pressures to convert it into an energy dense ‘bio-crude’. The near- or super-critical water acts as a reactant and catalyst to depolymerise the biomass, although other catalysts can also be added. Although the HTL process is related to pyrolysis, HTL oils are notably different[31]. They typically have much lower water contents, higher energy contents, lower oxygen contents and greater stability, hence are expected to be cheaper to transport, and require less extensive upgrading than pyrolysis oils. HTL oil upgrading can happen on or offsite. It is expected that HTL oils would already be able to be used at high blends in refinery FCC units, and with mild hydro-deoxygenation, it might be possible to co-process the bio-crude with fossil crude oil in the front end of existing oil refineries.

Their higher molecular weight distribution makes HTL more suitable for diesel production, but gasoline and jet are possible with more hydro-cracking. HTL is also well suited to process very wet biomass (sewage sludge, manure, micro-algae and macro-algae are commonly used), as well as some ligno-cellulosic feedstocks. The feedstock composition has a significant influence on the yield and quality of the oil (and the co-production of water-soluble organics, chars and gases).

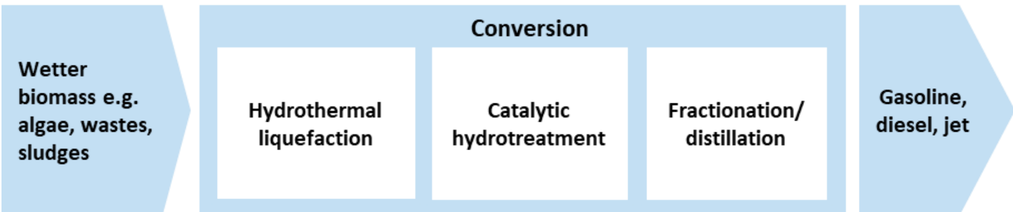


Figure 35: Value chain for HTL with catalytic upgrading

Bio-crude production of HTL oils is currently at TRL 5-6 (CRL 1), with small-scale demonstration activities ongoing. However, upgrading to gasoline, diesel or jet fuels is currently at a much earlier stage and limited to lab-scale reactors, so is currently at TRL 3-4 (CRL 1). However, there are plans for refinery upgrading tests in the coming years such as the H2020 4Refinery project (2017-2021) (once

[31] Elliott *et al*. (2015) “Hydrothermal liquefaction of biomass: Developments from batch to continuous process”, *Bioresource Technology*, vol. 178, no. 1, pp. 147-156

sufficient volumes of HTL oils are available), which is around 5 years behind what pyrolysis oil upgrading achieved.

4.11.2 Major players in this technology

The major players in hydrothermal liquefaction are spread globally, covering Turkey, Europe, North America and Australia. Licella and Steeper Energy are developing major new plants, whilst CWS and Genifuel Corporation Biochemtex also have smaller planned plants. Biochemtex had a planned demonstration plant as part of the Biorefly project, therefore is included in Table 30. However due to the bankruptcy of parent company M&G Group, Biochemtex will be auctioned off in autumn 2018, so it is assumed that this plant will no longer go ahead. In addition to the major companies noted in Table 30, Tübitak MRC Energy Institute in Turkey have also carried out research into HTL, and North West University in South Africa have a small pilot plant. Some companies, such as RenewELP in the UK (licensing Licella technology), are planning to use waste plastics as a feedstock in the HTL process, but these are not within scope of the study.

Table 30: Major players active in the hydrothermal liquefaction industry

Company name	Location of headquarters (country)	Total capacity in the EU* (ktonnes/year)		Total capacity in the RoW* (ktonnes/year)	
		Planned	Current	Planned	Current
Algenol	USA	-	-	-	0.0065
Altaca	Turkey	-	-	-	8.2
Biochemtex	Italy	2	-	-	-
Changing World Technologies	USA	-	-	-	-
Cielo Waste Solutions (CWS)	Canada	-	-	13	-
Genifuel Corporation	USA	-	-	0.24	0.020
Licella	Australia	-	-	66	22
Muradel	Australia	-	-	-	0.29
Steeper Energy	Denmark	-	0.024	118	-

'Current capacity' covers plants which are operational and in commissioning, 'planned capacity' covers plants which are planned and under construction

4.11.2.1 *Strengths and weaknesses of key players*

The hydrothermal liquefaction industry is characterised by small players who have developed several different variations on hydrothermal liquefaction technology. There is little diversification, with most developers focused exclusively on the production of bio-oil, although some developers also have activities in algae production (with this wet feedstock being complementary for HTL oil production). With some new plants planned, and increasing interest from oil refiners in technologies which can produce a higher quality 'bio-oil' with potential for co-processing, interest in the industry is reasonably strong at the moment. There is particular interest in HTL of waste plastics (although out of scope as a feedstock of this study) which could support technology development, given their high calorific value. There seem to be very few companies focusing on HTL oil upgrading, which is known to still be technologically challenging, and there are currently few collaborations with large oil refiners who might be able to do upgrading. These vital upgrading relationships and the volumes of oil being tested and converted are still lagging some way behind those in the pyrolysis + upgrading pathway.

4.11.3 Current and planned production capacity

There is currently only one HTL pilot plant in the EU. Existing HTL capacity outside the EU is dominated by two plants: the Altaca plant in Turkey and the Licella Yarwun Refinery plant in Australia.

Planned production capacity is significantly higher in the rest of the world than in the EU. Within the EU, there is currently one planned HTL plant as part of the BIOREFLY project by Biochemtex. Planned production capacity outside of the EU is dominated by three plants. Two of these, comprising in total 132 ktonnes/year production capacity, are under construction.

It should be noted that the majority of the HTL plants in the database produce bio-crude as a product, therefore the capacities given refer to the production capacity of bio-crude. The total amount of transport fuel that could be produced from this HTL plant capacity is lower, as a catalytic upgrading process is also required. Some of the plants use or are planning to use algae as a feedstock. Use of algae as a feedstock is discussed further in section 4.15.

	EU	RoW
Planned production capacity	-	198
Current production capacity	0	31
Known production volumes	-	0.02

Figure 36 Hydrothermal liquefaction: current installed capacity, planned capacity and production volumes for the EU28 compared to the rest of the world

There is currently a very small HTL pilot plant in Denmark (Figure 37).

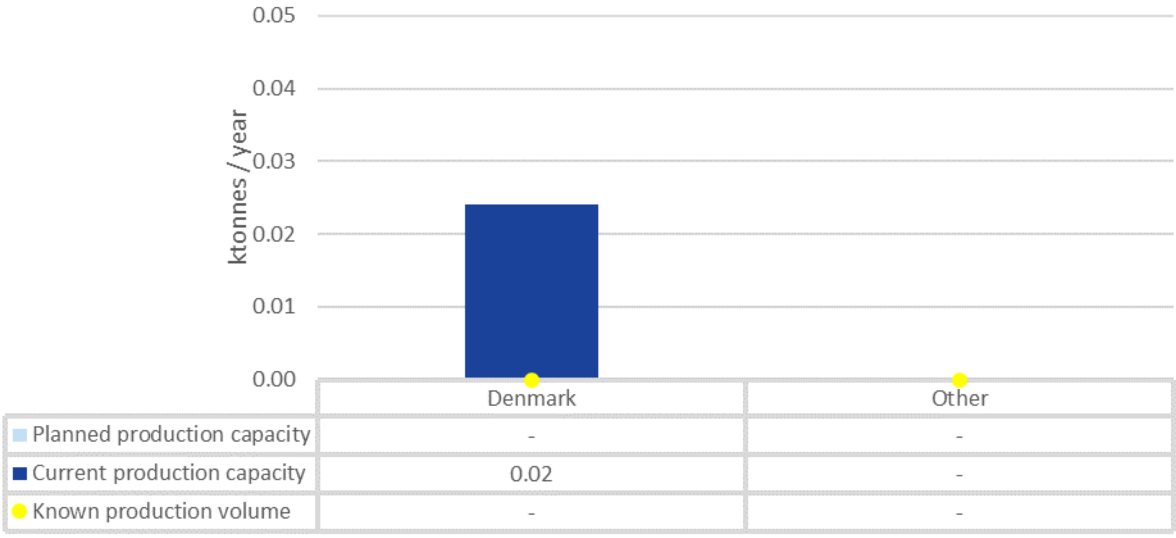


Figure 37 Hydrothermal liquefaction: current installed capacity, planned capacity and production volumes by EU Member State, covering top 6 MSs by installed capacity

4.11.4 Plant and production costs

Capex cost information was available for pilot and demonstration-scale HTL plants (Table 31).

Table 31: Capex and opex costs for hydrothermal liquefaction plants

Technology status	Plant capacity (ktonnes/year)	Capex cost (million €$_{2016}$)	Opex cost (million €$_{2016}$ / year)
Pilot	0-0.41	3.1-9.5	N/A
Demonstration	1.2-24	11	N/A
First commercial	66-118	49	N/A
Commercial	66-118	NA	N/A

Data is based on all plants, whether planned, operating or shut; note that the min and max of the cost range do not necessarily correspond to the min and max plant capacity within that range

4.11.5 EU market share

The EU does not have a significant market share in HTL technology, as there are few companies and only one operating and one planned plant.

Known production volumes were available for one pilot plant. The price of ligno-cellulosic biodiesel (see Appendix C) was used to estimate its known economic value, but this is an over-estimation as the plant is producing biocrude and not diesel.

Table 32: EU28 market share of hydrothermal liquefaction industry

	Number of companies (HQ)	Number of plants*	Production capacity *(ktonnes/year)	Known economic value** (million €)
EU	2	1	0	-
Rest of World	7	17	228	0.2

	Number of companies (HQ)	Number of plants*	Production capacity *(ktonnes/year)	Known economic value** (million €)
Global total	9	18	228	0.2
% EU	22%	6%	0%	0%

**Number of plants and production capacity refers to plants which are currently operational, in commissioning, under construction or planned; **Known economic value was calculated based on known production volumes and estimated 2G biofuel prices. For prices and methodology see Appendix C.*

4.12 Transesterification of residual/waste oil and fats

4.12.1 Technology overview

The transesterification process has triglyceride and methanol as reagents in the presence of an alkaline catalyst, producing FAME (Fatty Acid Methyl Esters). The most common raw materials being used for the production of FAME are rapeseed, sunflower, soybean, palm oils, UCO (used cooking oil) and tallow. Not all production facility is capable of processing waste oil and fats, impurities such as FFA (free fatty acid) and water will lead to soap formation and hydrolysis, so additional steps are needed to process UCO and tallow.

Triglycerides in the feedstock will result in glycerol byproduct, using methanol as a reagent will allow glycerol to be separated simultaneously. If using ethanol, it needs to be free of water to minimise water content in oil and enable glycerol separation. Whilst the glycerol can be used as a chemical for food and chemical industries, it nonetheless reduces biodiesel yield[32].

FAME is a mature technology that has reached industrial scale (TRL 9) where the product is commercially traded (CRL 5). There are continuous efforts to improve the cost and efficiency of the technology:

- Replacing alkaline catalyst with heterogeneous catalyst. Conventional base catalyst such as NaOH and KOH produced soaps and large amount of wastewater which cause separation to be troublesome and costly[33,34]. This approach is at TRL 9. The Esterfip-H process was patented by French Institute of Petroleum and commercialised by Axens, it has been adopted by multiple plants, with the largest more than 250 ktonnes/year[35].
- Pretreatment of UCO with Glycerolysis. By recycling the by-product glycerol to react with FFA before transesterification occurs, this is useful as it converts FFA into glyceride and improves the overall FAME yield when using high FFA feedstock. Glycerolysis also replaces the pre-treatment step of FFA acid transesterification, which is a costly process as the byproduct

[32] European Biofuels Technology Platform (2011), Biofuel fact sheet – Fatty Acid Methyl Esters. Available from http://www.etipbioenergy.eu/images/fame-fact-sheet.pdf
[33] Ikenaga et al. (2017), Biodiesel Production Using Metal Oxide Catalysts under Microwave Heating. International Journal of Biomass & Renewables, 6(2): 23-26, 2017. Available from http://ijbr.utp.edu.my/uploads/71_111_c53ot18-02-23.pdf
[34] Abdullah et al. (2017), A review of biomass-derived heterogeneous catalyst for a sustainable biodiesel production. Renewable and Sustainable Energy Reviews. Available from https://www.sciencedirect.com/science/article/pii/S1364032116310735
[35] Technip (2013), Biofuel plants. Available from http://www.technip.com/sites/default/files/technip/publications/attachments/Biofuels%20plants_December%202013_Web.pdf

methanol needs to be separated via distillation before reusing. Superior Process Technologies has developed the glycerolysis technology and has been using it in a commercial plant, so the technology should be at TRL 8[36]

- Converting glycerol to FAGE (fatty acid glycerol formal ester) for diesel blending[37]. The production process involves waste oils and glycerol as reagents and yields esters of glycerol formal - FAGE, this could reduce glycerol by-product in FAME production and increase the overall biodiesel yield. IUCT (Inkemia IUCT Group) claimed its technology to be at TRL5[38]
- Non-catalytic supercritical transesterification provides another alternative to alkaline catalyst. Under supercritical conditions, the reagent mixtures is a single homogeneous phase, resulting in a shorter reaction time from several hours to minutes[39] and potentially reducing capital and production cost. This is a laboratory concept, indicatively at TRL 3

4.12.2 Major players in this technology

FAME production is a commercially mature route with well-established value chain. Rapeseed oil is the dominant feedstock in the EU (see section 4.12.3).Whilst some producers process only waste oil, most developers use more than one feedstock. Below is a list of key companies compiled from several sources[40,41,42], focusing on waste-oil plant operators. This is a non-exhaustive list and intended to provide representation across the top ten FAME producing Member States.

Three novel technology developers, Axens, Superior Process Technologies, and IUCT, are mentioned in a separate table.

Table 33: Selected FAME plant operators

Company	Year of first operational plant	Location	Total capacity in ownership, ktonnes/year	Feedstock
ecoMotion[43]	2001	Germany	210	Tallow
Argent	2005	UK	53	UCO, tallow, sewage grease
Harvest Energy	2006	UK	250	Primarily waste oils
Greenenergy	2007	UK	194	Waste oils
Ennovor	2010	UK	50	Waste oils
Estener	2013	France	75	UCO, tallow, crude glycerine
Münzer Bioindustrie	2006	Austria	206	UCO, tallow, vegetable oil

[36] Erik Anderson (2014), The Chemical Kinetics of Glycerolysis. Available from http://www.biodieselmagazine.com/articles/76504/the-chemical-kinetics-of-glycerolysis
[37] Lapuerta et al. (2015), Properties of fatty acid glycerol formal ester (FAGE) for use as a component in blends for diesel engines. Biomass and bioenergy 76 (2015) 130-140. Available from https://www.sciencedirect.com/science/article/pii/S0961953415000884
[38] GRAIL (2018) Final Report Summary. Available from https://cordis.europa.eu/result/rcn/226614_en.html
[39] Okoro et al. (2018), Catalyst-Free Biodiesel Production Methods: A Comparative Technical and Environmental Evaluation. Sustainability 2018, 10, 127. Available from www.mdpi.com/2071-1050/10/1/127/pdf
[40] Ecofys (2013), UK biofuels industry overview, 2013
[41] USDA (2018), Indicators of the US biobased economy, 2018
[42] CE Delft (2015), Biofuels on the dutch market, 2015
[43] ecoMotion (2017), What is the future for TME post 2020?. Available from http://efprahamburg2017.com/wp-content/uploads/2017/05/Figgener_Whats-the-future-for-TME-post-2020.pdf

GmbH				
Cargill - Bioro	2005	Belgium	400	Rapeseed, Soybean, Sunflower, Palm*
Eco Fox srl	2009	Italy	131	UCO, tallow, vegetable oil
Biodiesel Aragon, S.L	2008	Spain	100	UCO, tallow, vegetable oil
Bioagra-Oil S.A.	2012	Poland	200	Tallow, Vegetable oil
ENERFUEL, S.A.	2013	Portugal	25	UCO, tallow
Biodiesel Amsterdam	2010	Netherlands	110	UCO, tallow
Eco fuels	2011	Netherlands	50	UCO
SunOil	2011	Netherlands	70	UCO, tallow
Electrawinds Greenfuel	2011	Netherlands	250	UCO, tallow, vegetable oil
SeQuential Pacific Biodiesel LLC	2008	USA	53	UCO
Genuine Bio-Fuel inc	2012	USA	29	Tallow, vegetable oil
HPB-St. Joe Biodiesel LLC	2016	USA	94	Tallow, vegetable oil

** Cargill - Bioro is the only FAME plant in Belgium, but it does not utilise waste feedstock*

Table 34: Novel technology developers related to FAME

Company	First plant operational year	Headquarter Location	Total capacity developed , ktonnes/year	Technology	Feedstock
Axens	2006	France	1085[44]	Heterogeneous catalyst	Vegetable oil
Superior Process Technologies	~2005[45]	USA	63[46]	Glycerolysis	Tallow
IUCT	~2014	Spain	<0.1	Glycerol formal to FAGE	UCO
BDI	2007[47]	Austria	>40[48]	RepCAT	UCO, animal fats, trap grease[49]

4.12.2.1 *Strengths and weaknesses of key players*

FAME production is a mature industry, so many of the companies are well established and operate a number of FAME production plants. This provides strength in terms of existing revenues, supply chains and relationships, and breadth in terms of the number of different countries where these

[44] Øien (2013), Biodiesel Production by the Esterfip-H Process. Available from http://folk.ntnu.no/skoge/diplom/diplom13/oien/masteroppgave.pdf
[45] A 1.6 kton/year pilot plant. Biodiesel magazine (2005), BECOn biodiesel facility starts up. Available from http://www.biodieselmagazine.com/articles/361/becon-biodiesel-facility-starts-up
[46] Planned capacity, as reported by StarTribune (2015), Biofuel innovators look for a breakout. Available from http://www.startribune.com/biofuel-innovators-look-for-a-breakout/285654231/
[47] Realization of the first industrial plant with RepCAT technology in Carinthia, Austria. Available from: https://www.bdi-bioenergy.com/en/company/about-us
[48] Biodiesel magazine (2017) BDI to build RepCat biodiesel plant at Crimson Renewable Energy, Available from: http://biodieselmagazine.com/articles/2516203/bdi-to-build-repcat-biodiesel-plant-at-crimson-renewable-energy (Accessed 11th December 2018)
[49] Available from: https://www.bdi-bioenergy.com/en/technologies-solutions/bdi-biodiesel

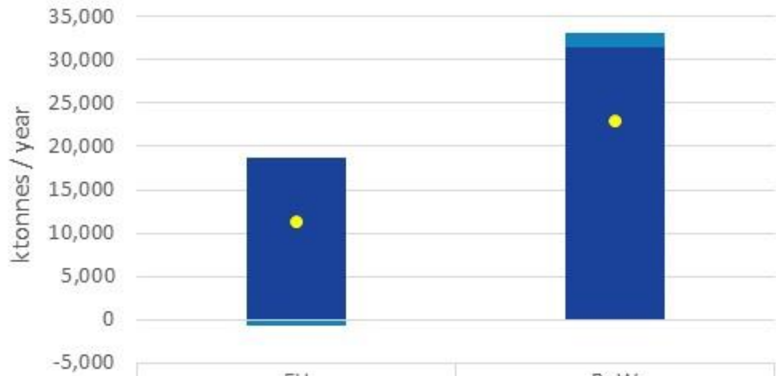
firms are based. Many FAME plants still cannot use waste oils/fats in their process (they can only use virgin vegetable oils). Those FAME plants that can use waste oils/fats were typically very quick to convert their plants (or add upstream pre-processing) in order to access the double-counting subsidies in Europe in the mid-2010s. Europe remains a key focus for producers of FAME from waste fats/oil today, although developer activity levels have slowed somewhat in the last few years.

More FAME plants globally could be retrofitted to use waste oils/fats, if there was sufficient feedstock supply. However, access to sufficient volumes of sustainable waste oil/fat feedstocks – at a reasonable price – is a key challenge for the industry, and has contributed to reasonably low utilisation rates in Europe and elsewhere in the world (section 4.12.3). Increasing demand for sustainable waste feedstocks from other pathways (e.g. HVO plants, or the biochemicals industry) will likely exacerbate this problem. With the low utilisation rates, there have been profitability issues in the wider FAME market, and consolidation of actors as a result. Given profit margins between the feedstock price and biodiesel price are typically very thin, it remains challenging for novel technology developers to enter the market – many existing plants are focused on maximising utilisation and profits, and not necessarily on novel and potentially risky technologies.

4.12.3 Current and planned production capacity

Total global FAME production capacity is presented in Figure 38. Although this is substantially higher than all other routes presented in this study, it should be noted that only a small percentage of this overall capacity processes waste oils and fats. About 18% of EU production is UCO and tallow-based, 16.5% for RoW production.

Moreover, utilisation rates of FAME plants tend to be low, around 68% globally and only 60% in the EU. Combined with increased competition for sustainable waste-based feedstock, this likely contributes to the relatively low volume of planned additional capacity the RoW and negative volumes in the EU, reflecting anticipated plant closures.

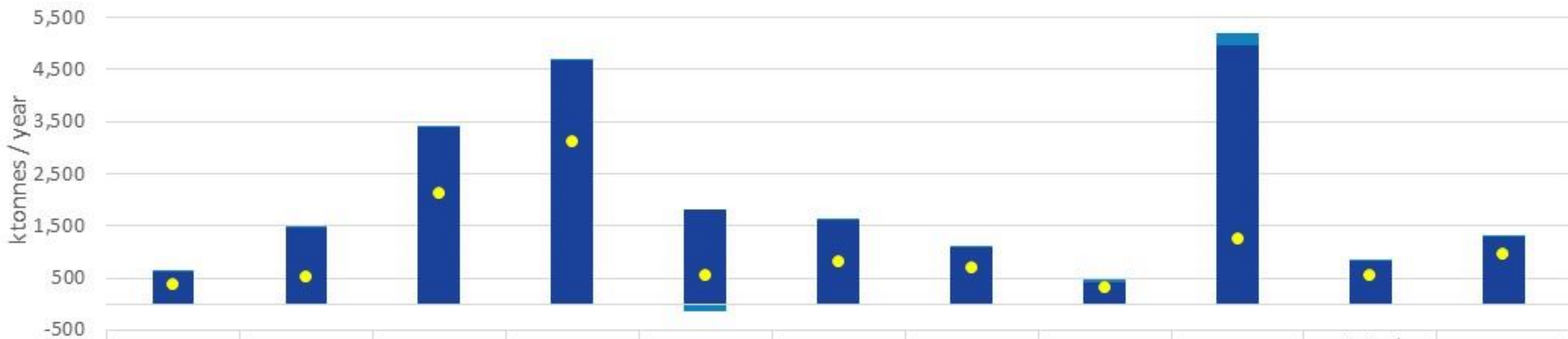


	EU	RoW
Planned production capacity	-730	1,730
Current production capacity	18,612	31,388
Current production volume	11,198	22,882

Figure 38 Capacity (planned and current) and production volumes for EU28 compared to the rest of the world[50,51,52,53]

The increase in production capacity in Spain is a result of higher consumption mandates. With the exception of Finland, Luxemburg, and Malta, every EU member state has at least one FAME production facility.

[50] The current capacity and production volume are based on 2017 data, while the planned capacity is based on 2018 data minus the 2017 data. Much of this planned capacity data may already have been built.
[51] UFOP (2018), Biodiesel 2017/2018. Available from https://www.ufop.de/english/news/updated-ufop-report-global-market-supply-published/
[52] GAIN (2017), EU Biofuels Annual 2017. Available from https://www.fas.usda.gov/data/eu-28-biofuels-annual
[53] F.O.Lichts (2018), World Ethanol & Biofuels Report



	Austria	Belgium	France	Germany	Italy	Netherlands	Poland	Portugal	Spain	United Kingdom	EU-Others
Planned production capacity	4	10	9	31	-148	11	7	63	244	6	9
Current production capacity	609	1,457	3,390	4,664	1,803	1,611	1,088	420	4,954	824	1,283
Current production volume	361	502	2,121	3,099	550	801	700	313	1,250	550	955

Figure 39 Breakdown of planned and current capacity and production volumes by EU Member State[54,55]

It is interesting to note that in the EU (Figure 39) and in the rest of the World (Figure 38) utilisation rates of FAME capacity are low: in some cases well under 50%. This possibly represents the challenge of acquiring sufficient volumes of feedstock, particularly waste feedstock.

[54] Data insufficiency means different data sources and summation method has to be used, leading to discrepancy on figure 1 and figure 2

[55] EU data from GAIN (2017) and UFOP (2017). Current production volume based on 2017 data (GAIN). Current capacity is production volume divided by individual MS utilisation rate, where MS utilisation rate is calculated from dividing 2014 MS volume with capacity (UFOP), and subsequently adjusted to 2017 with 2017 EU utilisation rate (GAIN) . Planned capacity is 2018 forecast MS production volume (GAIN) divided by individual MS utilisation rate (UFOP) then adjusted to 2018 forecast EU utilisation rate (GAIN), with current capacity deducted

Rapeseed oil is the dominant feedstock in EU, whilst palm oil and soybean oil make up the majority of feedstock consumption globally. The relative contribution of waste/residue feedstocks (UCO and Tallow) is about the same in the EU as it is worldwide, with 18% and 17% shares respectively.

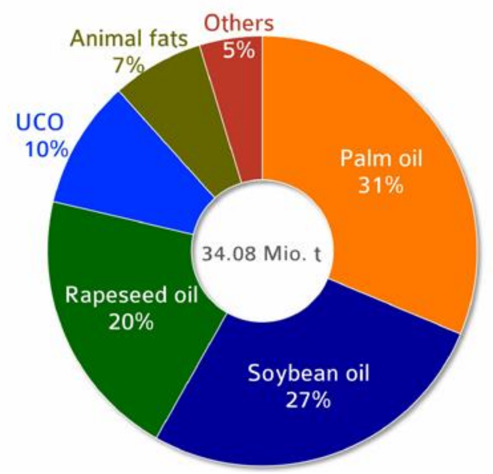


Figure 40 Feedstock use in biodiesel production, worldwide, in 2016[56]

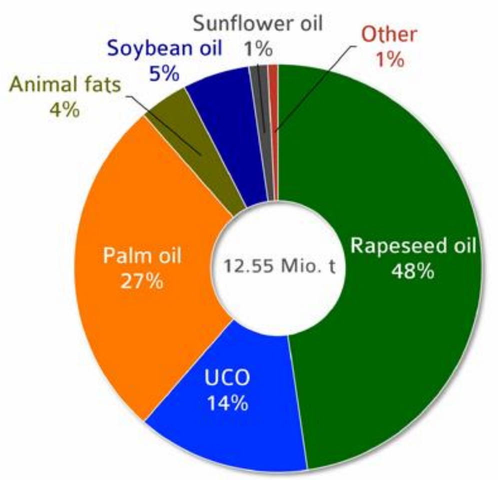


Figure 41 Feedstock use in biodiesel production in the EU-28, in 2016

4.12.4 Plant and production costs

Feedstock is the dominant component of FAME production costs. Economy of scale is not a significant factor for FAME production, as plant capital investment contributes less than 18% on a levelised basis. As a result of this, currently operating FAME plant capacities range between ~10kton/year to ~800kton/year. The ownership of these plants is related to scale, a smaller plant could be owned by a farming village or cooperative, while a larger plant is more likely to be owned by a large multi-national company, due to the capital outlay, labour, and supply-chain requirements. Revenue from by-product is about 140% of operational expenditure and can offset some part of capital depreciation. Feedstock availability and downstream demands are generally the determining factors for the plant scale.

[56] Global and EU-28 charts from UFOP (2018)

Table 35: Plant capex and opex costs according to production capacity[57]

Plant capacity (thousand tonnes / year)	Capex cost (million €, 2017)	Opex cost (million € / year)
200	14	5
100	9	2
50	6	1

Note: assumes UCO feedstock

4.12.5 EU market share

EU has only 33% of the FAME plants in the world, but 37% of production capacity. This is due to a higher average capacity per plant of 95ktonnes/year in the EU compared to 78ktonnes/year in the rest of the world. However, EU production is only 33% of global production, this is due to a lower utilisation rate at 60%, compared to RoW 73%.

Table 36: EU market share of this technology[58]

	Number of plants	Production capacity, ktonnes/yr	Total capex of plants located in this region, million EUR	Economic value, million EUR
EU	201	18,612	22936	8,751
RoW	401	31,388	38681	17,882
Global	602	50,000	61,617	26,634
% EU	33%	37%	37%	33%

4.13 Hydroprocessing of residual /waste oil and fats

4.13.1 Technology overview

The hydrotreatment of bio-based oils involves the conversion of vegetable or waste oils and fats into diesel and jet fuel, generally referred to as hydrotreated vegetable oil (HVO) when converted to diesel, or hydroprocessed esters and fatty acids (HEFA) when converted to jet (Synthetic Paraffinic Kerosene, SPK).

Hydroprocessing uses hydrogen to convert unsaturated compounds such as alkenes and aromatics into saturated alkanes (paraffins) and cycloalkanes, which are more stable and less reactive. The conversion is usually a two-staged process.

[57] Data from Joanneum research (2016), Improving the sustainability of Fatty Acid Methyl Esters. Available from https://ec.europa.eu/energy/sites/ener/files/documents/Technical%20report.pdf. E4tech analysis using UCO feedstock and 0.65 capacity scaling factor for 200kta production cost calculations. Capex per year assume 5% interest payment over the plant lifetime of 25 years

[58] EU plants data from GAIN (2017), RoW plants from various sources, including GAIN (2017) Biofuel annuals for Australia Australia, Russia, Philippines, China, Thailand, Peru, India, Indonesia, Colombia, Malaysia, Brazil, Japan, and Argentina; ISCC (2018) Valid certificates for biodiesel plants for South Africa, Turkey, United Arab Emirates, Singapore, New Zealand, Egypt, Korea, Pakistan, South Africa, Tunisia, and United Arab Emirates, available from https://www.iscc-system.org/certificates/valid-certificates/. EU production data from GAIN (2017), Global production data from F.O. Licht (2018). CAPEX data from Section 1.1.4. Biofuel price assumed to be EUR 781.5/tonne, from PRIMA (2018), PRIMA Low Carbon Fuels and Feeds Report

In the first stage, hydrotreatment, hydrogen is added to saturate the double bonds of the unsaturated oil triglycerides, and to remove the propane backbone to cleave the saturated oil triglycerides to fatty acids. The fatty acids either undergo hydro-oxygenation (by addition of more hydrogen the oxygen leaves as H_2O) or decarboxylation (oxygen leaves as CO_2 without further addition of hydrogen), or a combination of the two. The result is a mixture of straight chain, branched chain, and cyclic paraffinic hydrocarbons.

The second stage involves alkane isomerisation and cracking, bringing the biofuel to a quality that equals or surpasses specifications for conventional petroleum fuels.

Depending on the plant configuration, the facility can be a dedicated HVO plant or a co-production plant with different yields of HEFA and HVO as products, as well as other co-products such as bio-naphtha and bio-propane. The plant can either be located as a separate unit at an existing oil refinery (allowing for the symbiotic use of hydrogen) or be built as a dedicated standalone plant.

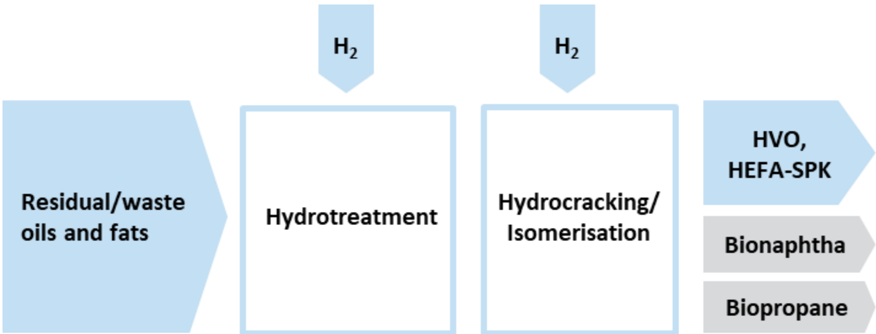


Figure 42 Value chain for hydroprocessing of residual / waste oils and fats

The hydroprocessing of non-food and non-feed biogenic feedstocks into HVO has been commercialised by many companies, with many examples of operating plants in the US, Europe and Asia. The technology is at TRL 9 (CRL 3).

The demand for renewable jet fuel is currently low but increasing. Therefore whilst technically few modifications to HVO plants are required in order to produce HEFA, only one plant worldwide is currently optimised to produce HEFA. HEFA-SPK is therefore slightly less mature than HVO at TRL 8 (CRL 2).

4.13.2 Major players in this technology

The majority of the major players active in hydroprocessing are either in the USA or Europe (Table 37). Neste is the largest single player, with four operational plants. Apart from Neste, the other players operate one plant each, and ENI has one further plant under construction. Alt Air Fuels developed a HVO plant in the USA, but the company and all its assets have recently been sold to World Energy, so is not included as a separate entry in the database. It should be noted that in other publications hydro-processing and co-processing of oils through a refinery are considered as one fuel category as the process is similar. In this report co-processing is considered separately in section 4.1.4.

HVO plants can usually accept both waste and virgin oils, therefore the capacities given in Table 37, Figure 43 and Figure 44 are for the plant as a whole, representing the amount of waste-based HVO that could be produced, although in reality many plants do not use 100% waste-based feedstock.

Where available, the percentage of feedstock that is currently waste or residue is provided in the database, although this can fluctuate over time.

Table 37: Major players active in the hydroprocessing industry

Company name	Location of headquarters (country)	Total capacity in the EU* (ktonnes/year)		Total capacity in the RoW* (ktonnes/year)	
		Planned	Current	Planned	Current
Aemetis	USA	-	-	-	-
Diamond Green Diesel	USA	-	-	-	812
Emerald Biofuels	USA	-	-	325	-
ENI	Italy	1000	421	-	-
Neste	Finland	-	1648	-	910
Renewable Energy Group (REGI)	USA	-	-	-	221
SG Preston	USA	-	-	354	-
Sinopec	China	-	-	30	-
Total S.A.	France	650	-	-	-
UPM Biofuels	Finland	-	100	-	-
World Energy	USA	-	-	-	128

'Current capacity' covers plants which are operational and in commissioning, 'planned capacity' covers plants which are planned and under construction

4.13.2.1 Strengths and weaknesses of key players

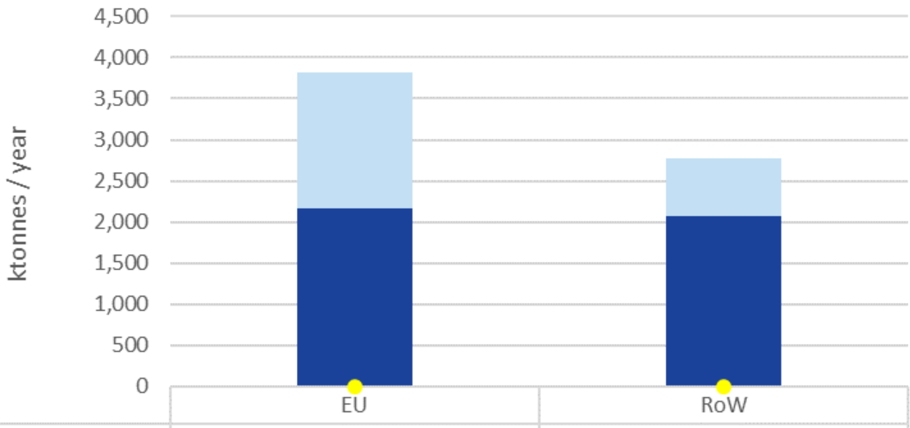
Although the number of players in the HVO market is not large, the plant capacities they have developed and their revenues are large in comparison to most other pathways. Some companies are reasonably small and only focused on running one plant, whereas others have multiple facilities and are more active in developing new projects. Neste has long been a strong player in HVO production, and has shifted over time from virgin vegetable oils to focus increasingly on waste oils/fats. Other players have not spread globally as Neste have done, and have remained in the US or Europe. Nevertheless, it is a sign of strength in the industry that an increasing number of very large oil companies (such as ENI, Total and Sinopec) are beginning or increasing their HVO production – although the exact mix of feedstocks that will be used in their new plants is not yet certain.

4.13.3 Current and planned production capacity

There is around 2000 ktonnes/year current installed hydroprocessing capacity in the EU, and a similar amount outside the EU. As noted above, Figure 44 reflects all hydro-processing capacity regardless of the feedstock used. The actual production of HVO from waste fats and oils is likely to be substantially lower.

The majority of the existing EU installed capacity is run by Neste, with additionally one plant run by ENI and one plant by UPM. The total 1650 ktonnes/year of planned capacity in the EU is comprised of one plant by ENI and one by Total, both of which are currently under construction.

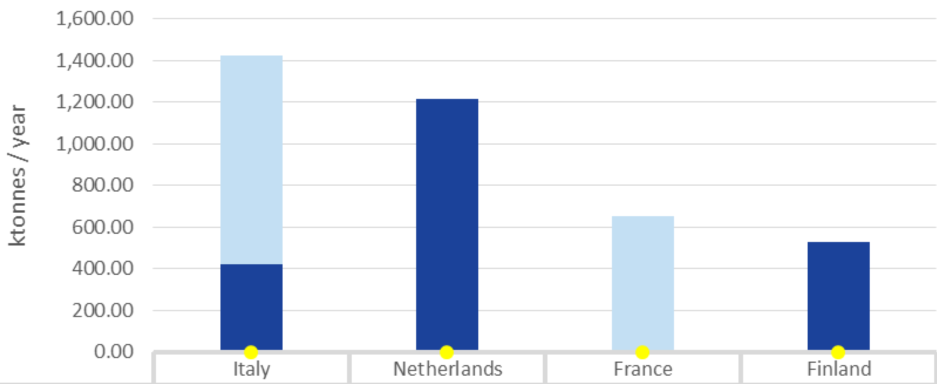
Outside of the EU the current installed capacity is operated by Neste, Renewable Energy Group and Diamond Green Diesel. There may in addition be HVO production in Brazil, but production capacity could not be verified. Whilst it is implied in Figure 43 that there is no planned capacity outside of the EU, Aemetis do have a plant in commissioning but it is not included in the figure as the capacity is not known.



	EU	RoW
Planned production capacity	1,650	709
Current production capacity	2,169	2,071
Known production volumes	-	-

Figure 43 Hydroprocessing: current installed capacity, planned capacity and production volumes for the EU28 compared to the rest of the world

The split of capacity between EU Member States is largely determined by where the key companies are based. ENI has one operating plant and one very large planned plant in Italy, Total operate in France, and Neste and UPM operate predominantly in Finland. In addition Neste has a very large operational plant in Rotterdam in the Netherlands.



	Italy	Netherlands	France	Finland
Planned production capacity	1,000	-	650	-
Current production capacity	421	1,218	-	530
Known production volume	-	-	-	-

Figure 44 Hydroprocessing: current installed capacity, planned capacity and production volumes by EU Member State, covering top 6 MSs by installed capacity

4.13.4 Plant and production costs

Capex costs were available for first commercial and commercial hydroprocessing plants. First commercial plants range from 100 to 421 ktonnes/year. These are larger than some of the commercial plants, because they represent first commercial plants for a given company. Because of this large capacity range, the capex cost range is also large. In general the lower end of the capex cost range corresponds to the smaller capacity and the upper end corresponds to a higher plant capacity.

Similarly for the commercial plants, those at with lower capacity tend to have lower costs, as would be expected from a fairly mature technology.

Table 38: Capex and opex costs for hydroprocessing plants

Technology status	Plant capacity (ktonnes/year)	Capex cost (million €$_{2016}$)	Opex cost (million €$_{2016}$ / year)
Pilot	N/A	N/A	N/A
Demonstration	N/A	N/A	N/A
First Commercial	30-421	74-388	N/A
Commercial	215-1218	98-707	N/A

Data is based on all plants, whether planned, operating or shut; note that the min and max of the cost range do not necessarily correspond to the min and max plant capacity within that range

4.13.5 EU market share

In terms of number of companies, the EU market share in hydroprocessing is roughly similar to that of the rest of the world, but considering number of plants, capacity and capex of those plants, the EU is currently the dominant region globally.

Table 39: EU28 market share of hydroprocessing industry.

	Number of companies (HQ)	Number of plants*	Production capacity *(ktonnes/year)	Known economic value** (million €)
EU	4	7	3,819	-
Rest of World	7	8	2,780	-
Global total	11	15	6,599	-
% EU	36%	47%	58%	-

**Number of plants and production capacity refers to plants which are currently operational, in commissioning, under construction or planned; **Known economic value was calculated based on known production volumes and estimated 2G biofuel prices. For prices and methodology see Appendix C.*

4.14 Co-processing of residual / waste oils and fats in refineries

4.14.1 Technology overview

Co-processing is the simultaneous transformation of biogenic feedstocks and intermediate petroleum distillates in existing petroleum refinery process units to produce renewable hydrocarbon fuels. Co-processing therefore largely utilises existing refining, transport and storage infrastructure, avoiding the need for investment in new bio-refinery units and the infrastructure to support them.

Biogenic oils and fats require pre-treatment prior to co-processing, and solid biomass requires conversion to a liquid (bio-oil). The converted biomass needs to meet a defined specification and composition to ensure compatibility with the co-processed fossil feedstock and operational conditions of the refinery conversion and treatment process units. These limits are defined by process simulations and pilot testing, but major uncertainties remain. Several feedstocks may need to be combined to provide the required feedstock availability and specification for direct co-processing, to obtain the optimal refinery product slate.

Upstream solid biomass pre-treatment options include fast pyrolysis and hydrothermal liquefaction (HTL), both of which have technical challenges to provide commercial scale biogenic feedstock for direct co-processing through fluidised catalytic cracking and residual catalytic cracking units, and hydrotreatment/hydrocracking units. These supply chains allow decentralised investment in pre-treatment facilities to minimise biomass transport costs, and high-efficiency centralised conversion.

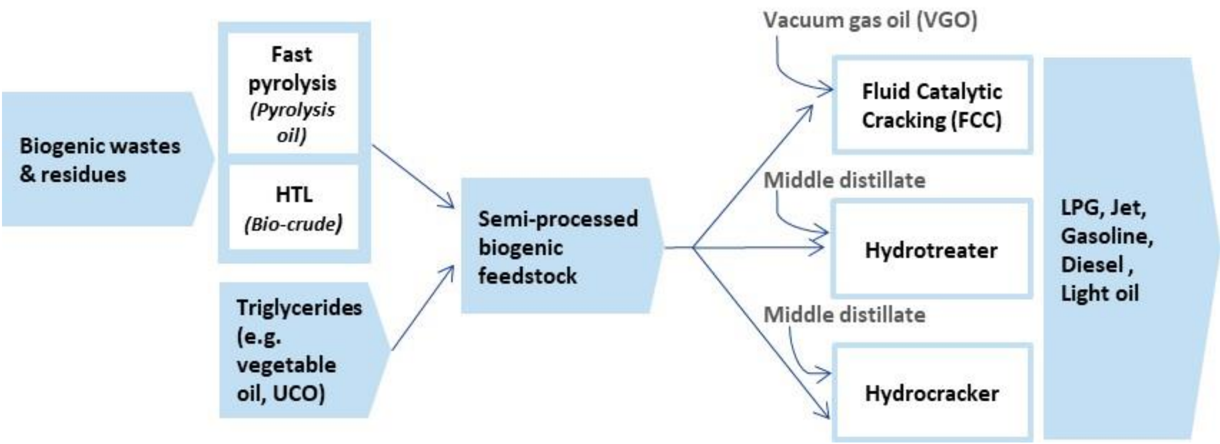


Figure 45 Value chain for co-processing of residual / waste oils and fats

TRL and CRL assessments for upstream fast pyrolysis and HTL to produce biogenic feedstocks for refinery co-processing are provided in Section 4.10.1 and 4.11.1 of this document.

The fast pyrolysis and HTL co-processing pathway through FCC and Hydrocracker units is at TRL 3-4 (CRL 1). Whilst there are commercial plants processing biogenic feedstocks through fast pyrolysis, there is no evidence of the co-processing of feedstocks from these pathways through oil refineries.

Co-processing virgin vegetable oils through a hydro-treater is at TRL 8-9 (CRL 4), and there are several examples of this being carried out in commercial refineries. However there is no evidence of any commercial scale co-processing from used cooking oil (UCO) or from animal fats, and no pilot or demonstration plans were identified.

Co-processing of tall oil[59] through a hydrotreater is at TRL 8-9 (CRL 3), based on the commercialised co-processing conducted by Preem in Sweden.

4.14.2 Major players in this technology

Several major oil refiners have trialled vegetable oil co-processing in their refineries, including REPSOL, GALP and Total. However, concrete plans for co-processing residual / waste oils and fats have only been announced by two players: Andeavor and Preem. The figures given for production capacity in Table 40 and Figure 46 refer to the capacity of the refinery to co-process biogenic oils, not to the overall capacity of the refinery. However some portion of these units may run off non-waste vegetable oils, so the actual amount of advanced biofuel produced is lower than the capacity

[59] It should be noted that tall oil is categorised as a waste / residue by some Member States but as a co-product by others.

provided here. It was not possible to confirm this with data on the precise feedstocks used by these plants.

Table 40: Major players active in the co-processing industry

Company name	Location of headquarters (country)	Total capacity in the EU* (ktonnes/year)		Total capacity in the RoW* (ktonnes/year)	
		Planned	Current	Planned	Current
Andeavor (previously Tesoro)	USA	-	-	905	-
Preem	Sweden	-	172	-	-

'Current capacity' covers plants which are operational and in commissioning, 'planned capacity' covers plants which are planned and under construction

4.14.2.1 Strengths and weaknesses of key players

There are currently very few players actively involved in co-processing waste oils and fats, which means direct knowledge and supply chains are limited. Expressions of interest from several oil companies suggests this may improve in the future. The high staffing, large revenues and available blending capacity of existing oil refineries (and their associated oil majors) suggests that very large volumes of waste fats/oils could be co-processed within a relatively short period of time, with minimal capital expenditure – which is a key strength of this pathway. Refiners also have some flexibility to change feedstocks or vary product slates in response to market movements. However, the development of this pathway depends on securing sufficient waste/residue feedstocks at sufficiently low prices – and with a consistent enough quality to avoid refinery operational issues (or perceived risks). Increasing demand for sustainable waste feedstocks from other pathways (e.g. HVO plants, or the biochemicals industry) will likely exacerbate supply problems.

4.14.3 Current and planned production capacity

Current and planned co-processing capacity illustrated in Figure 46 refers to only two plants. The existing co-processing capacity is operated by Preem in Gothenburg, whilst the 905 ktonnes/year planned co-processing plant is being constructed by Andeavor (previously Tesoro) in the USA. As noted above, production capacity refers to the capacity of the refinery to co-process biogenic oils, not to the overall capacity of the refinery.

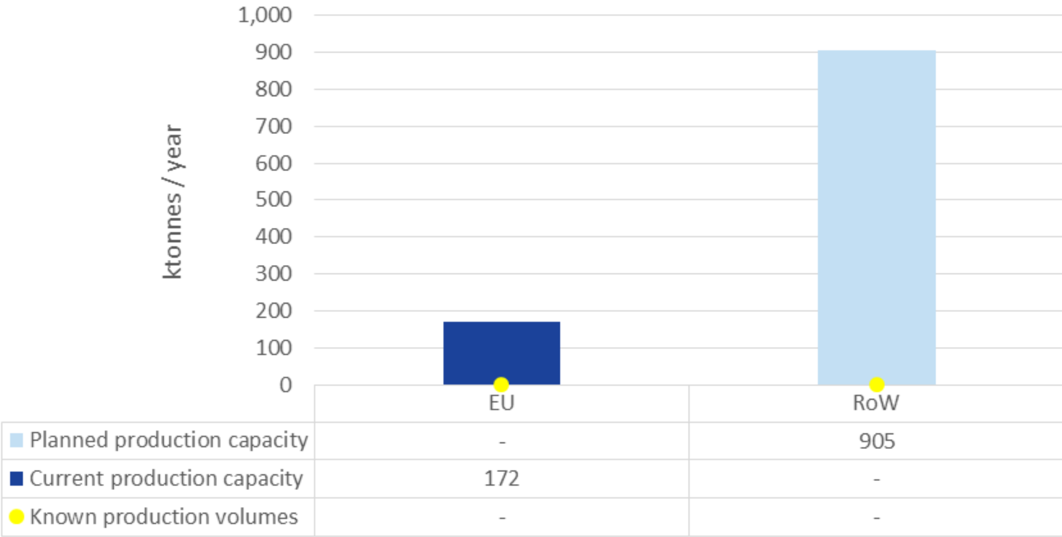


Figure 46 Co-processing: current installed capacity, planned capacity and production volumes for the EU28 compared to the rest of the world

As the only operational or planned co-processing capacity in the EU is that operated by Preem in Sweden, no further breakdown is given of EU capacity by Member State. Note there may be other plants in the EU which are co-processing raw vegetable oils, but these are not within scope of this study.

4.14.4 Plant and production costs

Capex cost data was only available for the larger of the two first commercial co-processing plants (Andeavor). When implementing co-processing at an existing refinery there is generally very little additional capital cost, other than for pre-treatment of the feedstock where required. Therefore considering the large capacity of the co-processing unit, the capex cost for introducing co-processing at an existing refinery is generally low (Table 41)

Table 41: Capex and opex costs for co-processing plants

Technology status	Plant capacity (ktonnes/year)	Capex cost (million €$_{2016}$)	Opex cost (million €$_{2016}$ / year)
Pilot	N/A	N/A	N/A
Demonstration	N/A	N/A	N/A
First Commercial	172-905	4.6	N/A

Data is based on all plants, whether planned, operating or shut; note that the min and max of the cost range do not necessarily correspond to the min and max plant capacity within that range

4.14.5 EU market share

The EU currently has a minority share in the global co-processing market for waste oils in terms of production capacity (Table 42).

Table 42: EU28 market share of co-processing industry

	Number of companies (HQ)	Number of plants*	Production capacity *(ktonnes/year)	Known economic value** (million €)

	Number of companies (HQ)	Number of plants*	Production capacity *(ktonnes/year)	Known economic value** (million €)
EU	1	1	172	-
Rest of World	1	1	905	-
Global total	2	2	1,077	-
% EU	50%	50%	16%	-

**Number of plants and production capacity refers to plants which are currently operational, in commissioning, under construction or planned; **Known economic value was calculated based on known production volumes and estimated 2G biofuel prices. For prices and methodology see Appendix C.*

4.15 Microalgae

Microalgae is only a biomass feedstock and not a conversion route, so the analysis presented in this section is not in the same format as the advanced biofuel conversion routes given in the other sections of this chapter.

4.15.1 Technology overview

4.15.1.1 Microalgae cultivation

There are four main categories of microalgae, namely photo-autotrophic, heterotrophic, photo-heterotrophic, and mixotrophic. Photo-autotrophic microalgae grow similar to land-based plants by fixing dissolved inorganic carbon (CO_2) and absorbing energy from light. Heterotrophic microalgae on the other hand use organic compounds, such as glucose, as their energy source, and so do not need light to grow. As a result, heterotrophic microalgae are actually a process in themselves rather than feedstock since they use a carbon source to grow. These are covered in the section on aerobic fermentation (section 4.4) and will therefore not be discussed any further in this chapter. Mixotrophic microalgae are capable of simultaneously using inorganic CO_2 and organic carbon sources and/or light in different combinations, making these species the most flexible of microalgae. Photo-heterotrophic microalgae require both organic carbon and light in order to grow, and so are usually not selected for commercial production of microalgae given high costs of production.[60]

There are two main cultivation techniques available for mass production of photo-autotrophic microalgae. These are:

- Open (raceway) ponds
- Photobioreactors (PBRs)

Other more novel techniques have been investigated, but not yet scaled up.[61]

Open (raceway) ponds

[60] Bashan, Y., Perez-Garcia, O., 2015. Microalgal Heterotrophic and Mixotrophic Culturing for Bio-refining: From Metabolic Routes to Techno-economics. Available from: https://www.researchgate.net/publication/283489490_Microalgal_Heterotrophic_and_Mixotrophic_Culturing_for_Bio-refining_From_Metabolic_Routes_to_Techno-economics

[61] Estime, B., Ren, D., Sureshkumar, R. (2017). Cultivation and energy efficient harvesting of microalgae using thermoreversible sol-gel transition. Available at: https://www.nature.com/articles/srep40725

This technique involves the cultivation of microalgae in large shallow open ponds that are usually in the shape of a raceway. These are ~30 cm deep closed loop flow channels with a central dividing wall and paddlewheels to circulate the water and mix CO_2 which is added to enhance microalgae growth[62]. Harvesting is done through continuous settling followed by solid-liquid separation techniques, then natural drying[63].

Open ponds have lower capital costs compared to other microalgae cultivation methods. However, the risk of contamination is high as it is difficult to protect the algal broth from pests and grazers. Further, intensity of light varies in open ponds leading to variation in temperature and photosynthetic rates.[64]

Photobioreactors (PBRs)

Closed photobioreactors are used for the cultivation of photosynthetic microalgae. A typical PBR design is tubular, consisting of arrays of transparent tubes of rigid and/or flexible plastic in which algae grow and flow in the presence of nutrients, water, CO_2 and light.[65] Microalgae are harvested by draining the PBR and separating the algae from liquid media till a thick de-watered algal paste is obtained.[66] The reactors protect the algae from pests and grazers and provide a potentially more controlled environment. However, the reactor material can add significantly to the cost. Further, microalgae can stick to the inner walls of the PBR blocking light.[67]

4.15.1.2 Microalgae to transport fuel routes[68]

Microalgae can be converted to transport fuels via a large number of potential pathways, as shown in **Figure 47**. However, the following thermochemical/biochemical/chemical processes are currently seen as the most likely pathways, due to having ongoing industry or academic interest:

Solvent based extraction refers to the process where algae cell walls are mechanically ruptured and the lipid content of the algae is extracted using a solvent. The lipids are subsequently separated from the solvent with a centrifuge, and the lipids then converted to FAME or HVO liquid fuels in downstream processing plants. Solvent extraction is a proven technology, widely used for conventional vegetable oil extraction, and can reach oil extraction efficiencies of up to 90%. The main drawback is that with the current algae feedstock production costs, the algae oil is not cost competitive with other vegetable oils such as rapeseed and palm oil. Pulsed electric field extraction techniques have been investigated as an alternative to using solvents.[69]

[62] Chisti, Y., 2016. Large-Scale Production of Algal Biomass: Raceway Ponds. In: Algae Biotechnology. Available from: https://www.springer.com/cda/content/document/cda_downloaddocument/9783319123332-c2.pdf?SGWID=0-0-45-1551972-p177034897
[63] Kalaitzidis, T., 2013. Harvesting, thickening and dewatering microalgae biomass. Available from: https://www.researchgate.net/publication/266146908_Harvesting_Thickening_and_Dewatering_Microalgae_Biomass
[64] Chisti, Y., 2016. Large-Scale Production of Algal Biomass: Raceway Ponds. In: Algae Biotechnology. Available from: https://www.springer.com/cda/content/document/cda_downloaddocument/9783319123332-c2.pdf?SGWID=0-0-45-1551972-p177034897
[65] Lutzu, G., A., 2011. Analysis of the growth of microalgae in batch and semi-batch photobioreactors. Available from: http://veprints.unica.it/797/1/PhD_Lutzu_Giovanni.pdf
[66] EnAlgae (n.d.). Growing and harvesting algae. Available from: http://www.enalgae.eu/getfile.php?type=site_documents&id=CSF%20Poster%203%20growth%20and%20harvesting.pdf
[67] Oilgae (n.d.). Materials used in photobioreactor design. Available from: http://www.oilgae.com/ref/downloads/materials_used_in_PBR_construction.pdf
[68] E4tech, 2014. Study on 'Prospects of algal energy for Switzerland' conducted for the Paul Scherrer Institute (PSI).
[69] Kumamoto University, 2017. Fast, low energy, and continuous biofuel extraction from microalgae. Available from: https://www.sciencedaily.com/releases/2017/04/170428093906.htm

Anaerobic Digestion (AD) can be used to break down the whole algae or the residues after lipid extraction. The technology is well-established and has the advantage that it can be deployed at small scale (for example to generate electricity for the algae cultivation process), but the disadvantage is creation of a relatively lower-value biogas that requires further clean-up before use in transport.

Hydrothermal liquefaction (HTL), in which the whole algae is processed into liquid fuel, has the advantage of being feedstock flexible and tolerant to high water contents, reducing the need for high lipid contents and drying steps. However, HTL is not a mature technology and development needs include improving the efficiency and scaling-up of the bio-crude upgrading process – see Section 0 for more details.

Hydrothermal gasification, in which whole algae are converted into biomethane, using a catalytic reaction process at higher temperatures and pressures than with HTL. Plants could also be configured so that hydrothermal gasification and HTL processes are combined, producing both liquid and gaseous fuels from algae. Hydrothermal gasification refers to technologies such as catalytic hydrothermal gasification (CHG) and catalytic supercritical water gasification (SCWG) – both are tolerant to high water content feedstocks and can have relatively high yields[70], but have high capital costs and generate a relatively lower-value fuel from a high cost feedstock. Development needs include scale-up out of the lab, and system integration (making use of the nutrients in the waste streams for algae cultivation).

[70] Brandenberger, M., *et al.*, 2013. Producing synthetic natural gas from microalgae via supercritical water gasification: A techno-economic sensitivity analysis. *Biomass and Bioenergy.* Available from: https://pdfs.semanticscholar.org/f721/3100b24888e587614c388fd5b775d914e74f.pdf?_ga=2.208627985.280228281.1531312988-1090785791.1530628382

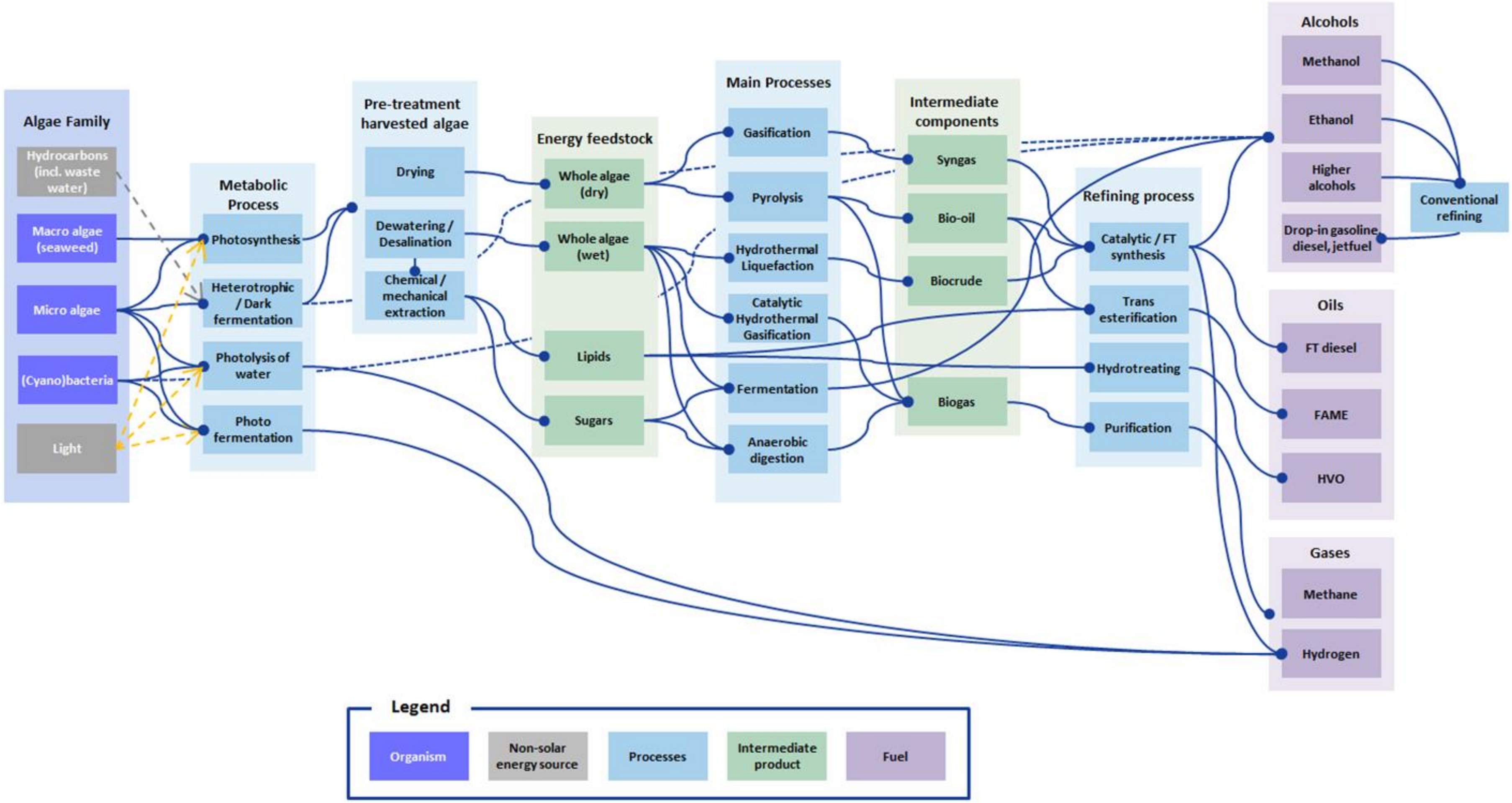


Figure 47: Potential pathways from microalgae (and macroalgae) to transport fuel[71]

[71] E4tech, 2014. Study on 'Prospects of algal energy for Switzerland' conducted for the Paul Scherrer Institute (PSI).

4.15.2 Major players

Several companies and research groups around the world have been engaged in developing technologies for microalgae cultivation and conversion of algae feedstocks to energy and bioproducts. The majority of these companies are based in the US. The following gives a brief description of some of the leading companies.

Table 43: Major players active in the microalgae industry

Company name	HQ (country)	Technology	Business focus	Known activities/ other comments
Global Algae Innovations	US	Open pond	Microalgae production using flue gas CO_2; improving algae oil yields for fuels and bioproducts[72,73]	Own an algae farm in Hawaii, co-located with a power plant.[74] $11 mn funding from the US DoE since 2013.
Cellana	US	PBR + open pond	Producing microalgae for food, nutrition and biofuels sectors using seawater[75,76]	Demo plant in Hawaii.[77] Conditional off-take agreement with Neste for algae oil feedstock for biodiesel.[78,79]
Sapphire Energy	US	Open pond	Microalgae production for food, nutrition and biofuels sectors[80]	Completed US DoE project in 2017; demonstrated algae production for a year in Las Cruces, New Mexico[81]
BioProcess Algae	US	Biofilm-based system	Mixotrophic algae production for fuels using CO_2, LC sugars and waste heat from corn ethanol plant in Iowa[82]	Recently completed a US DoE funded project (2013-2017)[83]

[72] US DoE, 2016. Energy Department Announces $15 Million to Advance Algae-based Biofuels and Bioproducts. Available at: https://www.energy.gov/eere/articles/energy-department-announces-15-million-advance-algae-based-biofuels-and-bioproducts
[73] Casey, T., 2017. $8 Million for Algae Biofuel from U.S. Department of Energy. Available at: https://www.triplepundit.com/2017/07/8-million-algae-biofuel-u-s-department-energy/
[74] US DoE, 2016. Algae hard at work in Hawaii. Available at: https://www.energy.gov/eere/articles/algae-hard-work-hawaii
[75] Cellana, 2018. Cellana and POS Bio-Sciences Sign Letter of Intent for the Joint Development and Commercialization of High-Value Algae Biomass for EPA Omega-3s. Available from: http://cellana.com/news-events/news/
[76] Cellana (n.d.). Microalgae – A versatile crop. Available from: http://cellana.com/products/products-overview/
[77] Cellana (n.d.). A US leader in algae production. Available from: http://cellana.com/production/kona-demonstration-facility/
[78] Neste, 2014. Algae oil is a promising raw material for renewable diesel – Neste Oil ensures its supply with conditional purchase agreements. Available from: https://www.neste.us/algae-oil-promising-raw-material-renewable-diesel-%E2%80%93-neste-oil-ensures-its-supply-conditional
[79] Cellana, 2013. Cellana and Neste Oil Enter Into Multi-Year, Commercial-Scale Off-Take Agreement for Algae Oil Feedstock for Biofuels. Available from: http://cellana.com/press-releases/cellana-and-neste-oil-enter-into-multi-year-commercial-scale-off-take-agreement-for-algae-oil-feedstock-for-biofuels/
[80] Sapphire Energy, 2016. The Sapphire story. Available from: https://www.sapphireenergy.com/
[81] Lane, J., 2017. Crossing the 3K threshold: The Digest's Multi-Slide Guide to Sapphire Energy's algae biofuels productivity. Available from: http://www.biofuelsdigest.com/bdigest/2017/08/23/crossing-the-3k-threshold-the-digests-multi-slide-guide-to-sapphire-energys-algae-biofuels-productivity/
[82] Bioprocess algae (n.d.). Technology. Available from: http://www.bioprocessalgae.com/technology/
[83] Biofuels Digest, 2017. Mixotrophic Algae: The Digest's 2017 Multi-Slide Guide to BioProcess Algae. Available from: http://www.biofuelsdigest.com/bdigest/2017/02/08/mixotrophic-algae-the-digests-2017-multi-slide-guide-to-bioprocess-algae/4/

Company name	HQ (country)	Technology	Business focus	Known activities/ other comments
Synthetic Genomics & ExxonMobil	US	Open ponds; GM algae	GM microalgae production for fuels	Doubled lipid content of microalgae sp. while sustaining growth.[84] 2025 target: 10k barrels of algae fuels/day[85]
Heliae	US	Open pond + PBR	Microalgae production, extraction, and processing for neutraceuticals, agri and aquaculture sectors[86]	Research and demonstration facilities in Arizona, USA
Solix Algredients	US	PBR	Microalgae production for nutrition and personal care sectors[87]	Formerly Solix BioSystems[88]
Eldorado biofuels LLC	US	Open pond	Industrial wastewater treatment (used for algae growth) + algal-derived biofuel and bioproducts[89]	Demo facility in New Mexico. Current products include algae oil, whole algae paste and lipid-extracted algae.[90]
AlgaSpring	Netherlands	PBR	Microalgae production using seawater for the food, feed and aquaculture sectors[91]	Part of an ongoing Wageningen University & Research (WUR) programme (2015-2019)[92]
Algaenergy	Spain	Open pond + PBR	Develop microalgae-based products for food, nutrition, energy sectors.[93] Aim to use flue gas CO_2.[94]	
Algaetech International	Malaysia	Open pond + PBR	Microalgae production for neutraceuticals sector[95]	Two production facilities in Technology Park Malaysia
Algae. Tec Ltd	Australia	PBR	Microalgae production for neutraceuticals and aqua feed sectors[96]	Supplied PBR to Reliance Industries in India which uses CO_2 from oil refinery for microalgae production.[97]

[84] Synthetic Genomics, 2017. Algae biofuels. Available from: https://www.syntheticgenomics.com/cell-factories/#algae_biofuels
[85] Peters, A., 2018. Exxon Thinks It Can Create Biofuel From Algae At Massive Scale. Available from: https://www.fastcompany.com/40539606/exxon-thinks-it-can-create-biofuel-from-algae-at-massive-scale
[86] Heliae (n.d.). Bridging lab to market. Available from: https://heliae.com/technology/
[87] Solix Algredients (n.d.). Introduction. Available from: http://www.solixalgredients.com/who-we-are/
[88] Collins, F., 2015. Solix BioSystems rebrands itself as Solix Algredients, adds two board members. Available from: http://csuventures.org/solix-biosystems-rebrands-itself-as-solix-algredients-adds-two-board-members/
[89] Eldorado biofuels (n.d.). About Us. Available from: http://eldoradobiofuels.com/about/
[90] Eldorado biofuels (n.d.). Available products. Available from: http://eldoradobiofuels.com/available-products/
[91] AlgaSpring (n.d.). Marine phytoplankton *Nannochloropsis gaditana* micro-algae. Available from: http://www.algaspring.nl/nannochloropsis-gaditana-micro-algae/
[92] Wageningen University & Research (n.d.). Robust cultivation of marine microalgae species for the aquaculture industry in Zeeland. Available from: https://www.wur.nl/en/project/Robust-cultivation-of-marine-microalgae-species-for-the-aquaculture-industry-in-Zeeland-.htm
[93] Algaenergy (n.d.). Sectors & Products. Available at: http://www.algaenergy.es/en/sectors-products/
[94] Algaenergy (n.d.). Technology & Facilities. Available from: http://www.algaenergy.es/en/technology-facilities/
[95] Algaetech International (n.d.). Our vision. Available from: https://algaetech.com.my/about/#vision
[96] Algae. Tec (n.d.). About us. Available from: http://algaetec.com.au/index.php/about-us/the-company
[97] Oil Capital, 2015. Algae.Tec dispatches first algae photobioreactor for Reliance Industries. Available from: http://www.oilcapital.com/companies/news/148304/algaetec-dispatches-first-algae-photobioreactor-for-reliance-industries--62165.html

Company name	HQ (country)	Technology	Business focus	Known activities/ other comments
Algae for future (A4F)	Portugal	Range of technologies	Facility design, scale-up and operation	Project coordinator of the BioFAT project

In summary, there are a few companies that have demonstration level projects ongoing for bioenergy production from microalgae, while several microalgae companies have set their focus exclusively on the food, feed and neutraceuticals markets, given the much higher product prices achievable in these markets. Although microalgae production via open ponds is at commercial-scale, the microalgae to biofuels technology route is still at TRL 6-7 (CRL 1).[98,99]

4.15.3 Production cost of fuels from microalgae feedstock

This section provides a summary of the production costs of microalgae using open pond or PBR methods, based on a review of recent reports by NREL, EnAlgae, and AlgaePARC. Production cost estimates vary widely, depending on the production facility scale, location and capital cost assumptions.

4.15.3.1 Cultivation using open ponds

NREL's study (2016) on the economics of algal biomass production pathway, using ~20km^2 of open pond system, estimated a cost of 0.54 $/kg of dry matter given in 2011$ (or ~0.51 €/kg in 2018€).[100,98] Although the cost is high, it is relatively low in comparison to the following EU studies, as the NREL study already assumes scale-up to large commercial production volumes, as well as a number of yield, process and downstream processing improvements.

The **EnAlgae** project (2011-2015) involved 19 EU-based partners and covered research on micro and macroalgae production and subsequent conversion to bioenergy or bioproducts. The cost price for *Chlorella vulgaris* algae biomass (15% dry matter) produced in a 1,000m^2 (0.001km^2) open pond is calculated as 35.92 €/kg of dry matter[101]. Capital costs make up 72% of this cost, with labour (16%), electricity (8 %) and water (3 %) the other key cost factors.[101] When scaled to 1 km^2, the cost drops to 6.27 €/kg of dry matter.

AlgaePARC is a large multidisciplinary research program based in Wageningen University & Research (WUR) in the Netherlands. As part of an evaluation of technology development at AlgaePARC in 2016, six different locations around the world were compared as potential locations for an algal biomass production facility, with microalgae production costs using 1 km^2 open ponds calculated to vary between 4 €/kg and 11 €/kg.[102]

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[98] IEA Bioenergy, 2017. State of Technology Review – AlgaeBioenergy. Available from: http://www.ieabioenergy.com/wp-content/uploads/2017/01/IEA-Bioenergy-Algae-report-update-20170114.pdf
[99] Brutyan, M., M., 2017. Foresight of microalgae usage for the production of third-generation biofuel. Indian Journal of Science and Technology, Vol. 10 (16). Available at: http://www.indjst.org/index.php/indjst/article/viewFile/111621/79797
[100] NREL, 2016. Process Design and Economics for the Production of Algal Biomass: Algal Biomass Production in Open Pond Systems and Processing Through Dewatering for Downstream Conversion. Available from: https://www.nrel.gov/docs/fy16osti/64772.pdf
[101] EnAlgae, 2015. AlgaEconomics: bio-economic production models of micro-algae and downstream processing to produce bio energy carriers. Available from: http://www.enalgae.eu/getfile.php?type=site_documents&id=WP2A7.10%20report%20Business%20economics%20microalgae%20and%20DSP.pdf
[102] Ruiz, J., et al., 2016. Results of AlgaePARC. Towards industrial products from microalgae. Energy & Environmental Science. Available from: http://pubs.rsc.org/-/content/articlepdf/2016/ee/c6ee01493c

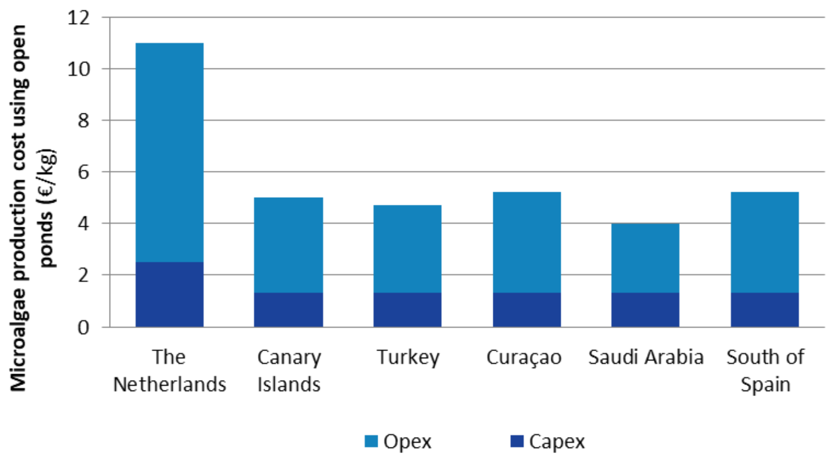

Figure 48: Comparison of production costs of microalgae using 1km^2 open algae ponds[102]

4.15.3.2 Cultivation using PBRs

The **AlgaePARC** study also considered microalgae production costs using PBRs, comparing the costs for different types of PBRs in six different locations.[102]

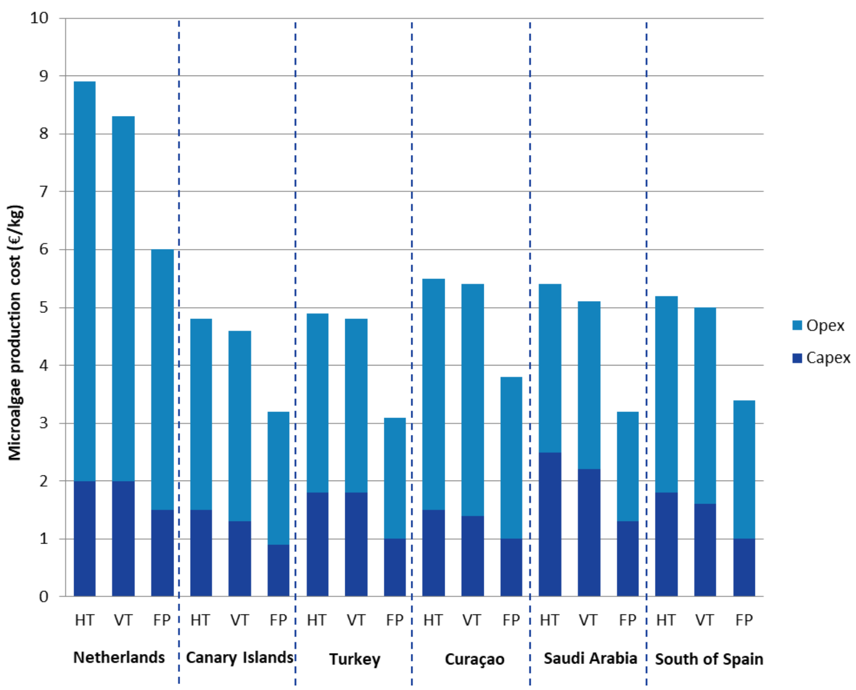

Figure 49: Comparison of microalgae production costs using 1km^2 PBRs (HT = Horizontal tubular PBR, VT = Vertically stacked horizontal tubular PBR, FP = Flat panel PBR)[102]

At a scale of 1 km^2, microalgae production costs using horizontal tubular PBR could vary from 4.8-8.9 €/kg, with vertically stacked horizontal tubular PBR costs varying from 4.6-8.3 €/kg, and flat panel PBR costs varying from 3.1-6.0 €/kg.

The **EnAlgae** study calculated the cost of algae biomass (15% dry matter) produced in a 1,000m^2 (0.001km^2) tubular PBR as 19.07 €/kg of dry matter. This cost mainly consists of capital costs (66%), with electricity (18%) and labour (15%) featuring as the other key cost factors.[103] When scaled to 1 km^2, the cost drops to 4.57 €/kg of dry matter. On the other hand, the cost of algae biomass (15% dry matter) produced in a 1,000 m^2 (0.001km^2) flat panel PBR is 12.52 €/kg of dry matter. This cost mainly consists of capital costs (55%), with electricity (31%) and labour (14%) featuring as other important costs factors. When scaled to 1 km^2, the cost drops to 4.53 €/kg of dry matter.

4.15.3.3 Economics of producing fuels from microalgae

Overall costs involved in deriving biofuels from microalgae include the cost of feedstock production (discussed above), plus the cost of converting it into a final fuel product. This section therefore focuses on specific studies carried out by **NREL** and the **EnAlgae** research project.

The **EnAlgae** study covered the costs involved in conversion of microalgae to biodiesel, ethanol or methane. For the **biodiesel** route, the cost price of 1L of biodiesel made from 10,000kg algae dry mass is calculated as €69.38, while the market price is only 0.52 €/kg biodiesel. Algae feedstock makes up 68% of the cost price, supercritical CO_2 extractor capital costs and the energy used in drying the algae paste also contributing significantly.[103]

For the **ethanol** route, the cost price with dry milling is calculated as 85.08 €/kg ethanol, and 99.43 €/kg ethanol with wet milling, compared to a market price of 0.41 €/kg ethanol.[103]

For the **methane** route, the cost price is 20.05 €/Nm^3 methane, compared to a market price of 0.22 €/Nm^3 methane. The costs for the algae paste form the major part of the cost price, but even the algae downstream processing costs (0.98 €/Nm^3) by themselves are higher than the fossil methane selling price.[103]

NREL's study (2014) on the process design and economics for the conversion of algal biomass to biofuels estimated an overall renewable diesel blendstock production cost of 4.35 $/gallon gasoline equivalent (gge) given in 2011$ (1.15 $/L or 1.1 €/L in 2018€).[104,98] Further R&D is needed to reduce fuel production costs to meet the US DoE target of 3 $/gge (or 2.6 €/gge)[105]. At the time this study was published in 2014, algal feedstock cost was assumed to be 0.47 $/kg (or 0.44 €/kg in 2018€), i.e. less than the more recent NREL study from 2016.

Overall, given the high cost of microalgae production, it is very unlikely to be economically feasible to pursue routes to biofuel production at present.

4.15.4 In summary

Overall, little progress has been made in the past decade in commercialising algal oil-based biofuels despite the number of operating algae companies.[106] The efficiency of converting solar energy into organic energy remains low, despite concerted efforts by academics and companies. Costs of

[103] EnAlgae, 2015. AlgaEconomics: bio-economic production models of micro-algae and downstream processing to produce bio energy carriers. Available from: http://www.enalgae.eu/getfile.php?type=site_documents&id=WP2A7.10%20report%20Business%20economics%20microalgae%20and%20DSP.pdf

[104] NREL, 2014. Process Design and Economics for the Conversion of Algal Biomass to Biofuels: Algal Biomass Fractionation to Lipid and Carbohydrate-Derived Fuel Products. Available from: https://www.nrel.gov/docs/fy14osti/62368.pdf

[105] US DoE, 2016. Energy Department Announces $11.3 Million Available for Mega-Bio: Bioproducts to Enable Biofuels. Available from: https://www.energy.gov/eere/bioenergy/articles/energy-department-announces-113-million-available-mega-bio-bioproducts

[106] IRENA, 2016. Innovation Outlook: Advanced Liquid Biofuels. Available from: http://www.irena.org/-/media/Files/IRENA/Agency/Publication/2016/IRENA_Innovation_Outlook_Advanced_Liquid_Biofuels_2016.pdf

production, especially algae feedstock, remain significantly higher than other advanced biofuels.[107] Given the continued high costs of production, and fall in crude oil prices in 2014-2015, several companies switched from focusing on biofuels production to producing microalgae for high value products such as neutraceuticals and pharmaceuticals.

5 Comparison of current capacity with advanced biofuel targets

5.1 Biofuel and advanced biofuel targets in the EU

5.1.1 Biofuel Mandates in EU-28 Member States

The Renewable Energy Directive sets a 2020 target for a minimum of 10% of each Member State's transport energy consumption to come from renewable energy sources. In 2016, EU-28 consumed 14,047 ktoe of biofuels, accounting for 5.8% of total energy used in transport, and of which 3,842 ktoe[108] (without including double counting) were advanced biofuels produced from Annex IXA feedstocks.

26 Member States have chosen to implement biofuel blending mandates (Table 44). Two countries – Sweden and Germany – have chosen to promote the use of biofuels through alternative measures. Sweden has opted to use biofuel tax exemptions[109] (see more detail in Appendix D). Between 2009 and 2014, Germany had a biofuel mixing rate mandate, but since 2015, Germany has set greenhouse gas saving targets to be achieved compared to a fossil only baseline (see more detail in Appendix D).

Table 44: Biofuel blend mandates in EU-28 Member States, as a percentage of total fuel consumption by either energy or volume

<table>
<tr><th></th><th>Bioethanol</th><th>Biodiesel</th><th>Double-counting of advanced biofuel?</th></tr>
<tr><td>Austria[110]</td><td>3.4% (energy)</td><td>6.3% (energy)</td><td>Yes</td></tr>
<tr><td></td><td colspan="2">5.75% (energy)</td><td></td></tr>
<tr><td>Belgium[110]</td><td>8.5% (volume)</td><td>6% (volume)</td><td>Yes</td></tr>
<tr><td>Bulgaria[110]</td><td>8% (volume)</td><td>6% (volume)</td><td>No</td></tr>
<tr><td>Croatia[110]</td><td>0.97% (energy)</td><td>5.75% (energy)</td><td>Yes</td></tr>
<tr><td></td><td colspan="2">6.92% (energy)</td><td></td></tr>
<tr><td>Cyprus[111]</td><td colspan="2">2.4% (energy)</td><td>Yes</td></tr>
<tr><td>Czech Republic[110]</td><td>4.1% (volume)</td><td>6% (volume)</td><td>Yes</td></tr>
</table>

[107] NREL, 2017. A perspective on renewable bioenergy from photosynthetic algae as feedstock for biofuels and bioproducts. Algal Research. Available from: http://www.ieabioenergy.com/wp-content/uploads/2013/09/Laurens-2017-Renewable-energy-from-algae-perspective.pdf
[108] All references to biofuel consumption in 2016 (most recently released year of data) comes from Eurostat (2018) "SHARES 2016 detailed results". Available at: http://ec.europa.eu/eurostat/web/energy/data/shares
[109] Since 2016, E-85 (bioethanol blended at 85% by volume in petrol) is no longer tax exempt.
[110] Global Agricultural Information Network (2018) "Biofuel Mandates in the EU by Member State in 20118" Available at: https://gain.fas.usda.gov/Recent%20GAIN%20Publications/Biofuel%20Mandates%20in%20the%20EU%20by%20Member%20State%20in%202018_Berlin_EU-28_6-19-2018.pdf
[111] ePure (2016) "Overview of the biofuel policies and markets across the EU-28". Available at: https://epure.org/media/1369/overview-of-the-biofuel-policies-and-markets-across-the-eu-28-final.pdf

	Bioethanol	Biodiesel	Double-counting of advanced biofuel?
Denmark[110]	5.75%(energy)		Yes
Estonia[112]	3.1%(volume)		Unknown (presumed no)
Finland[110]	15%(energy)		Yes
France[110]	7.5%(energy)	7.7%(energy)	Yes[113]
Germany[110]	No longer has a blending target. Germany now has GHG reduction targets for transport, with a 4% reduction for 2018.		
Greece[110]	7%(energy)		Yes
Hungary[110]	4.9%(energy)	4.9%(energy)	Yes
Ireland[114]	8%(volume)		Yes
Italy[115]	7%(energy)		Yes
Latvia[116]	5%(volume)	6%(volume)	No
Lithuania[111]	5%(volume)	7%(volume)	No
Luxembourg[111]	5.15%(energy)		Yes
Malta[111]	8.5%(energy)		Yes
Netherlands[110]	8.5%(energy)		Yes
Poland[110]	7.5%(energy)		Yes
Portugal[110]	9%(energy)		Yes
Romania[117]	4.5%(energy)	6%(energy)	Yes
Slovakia[110]	5.8%(energy)		Yes
Slovenia[110]	7.5%(energy)		Yes
Spain[110]	6%(energy)		Yes
Sweden[110]	Sweden uses tax exemptions to promote the use of biofuels.		
United Kingdom[118]	7.25%(volume)		Yes

The iLUC Directive from 2015 suggests that Member States should promote the use of advanced biofuels by setting a non-legally binding target for their use in transport fuel. However, this was not

[112] ePure (2017) "Estonian parliament approves biofuel mandate". Available at: https://epure.org/news-and-media/news/estonian-parliament-approves-biofuel-mandate/

[113] In France, only a small portion of biofuels produced from advanced feedstocks can be double-counted. Up to 0.3% of bioethanol and 0.35% of biodiesel can be double-counted.

[114] National Oil Reserves Agency (2018) "The Biofuels Obligation Scheme Annual Report 2017". Available at: http://www.nora.ie/_fileupload/457-18X0074%20-%20BOS%20Annual%20Report%20for%202017.pdf

[115] Decreto 10 ottobre 2014 – Aggiornamento delle condizioni, dei criteri e delle modalita' di attuazione dell'obbligo di immissione in consumo di biocarburanti compresi quelli avanzati. Available at: http://www.gazzettaufficiale.it/eli/id/2014/10/27/14A08212/sg

[116] Ministru kabineta noteikumi Nr. 45 (2018) "Grozījumi Ministru kabineta 2000. gada 26. septembra noteikumos Nr. 332 'Noteikumi par benzīna un dīzeļdegvielas atbilstības novērtēšanu'". Available at (https://likumi.lv/ta/id/296656).

[117] Global Agricultural Information Network (2017) "Romania Biofuels Market Overview" Available at: https://gain.fas.usda.gov/Recent%20GAIN%20Publications/Romania%20Biofuels%20Market%20Overview_Bucharest_Romania_6-14-2017.pdf.

[118] Department for Transport (2018) "Renewable Transport Fuel Obligation Guidance Part One Process Guidance" Available at: https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/694277/rtfo-guidance-part-1-process-guidance-year-11.pdf

mandatory. As of 2018, six Member States – Bulgaria, France, Italy, Luxembourg, Netherlands, Croatia – have adopted legally binding targets for advanced biofuels.

While most MSs do not have sub-targets for advanced biofuels, 22 MSs are promoting the use of advanced biofuels by allowing them to double-count towards their national targets (therefore allowing advanced biofuel producers to claim double rewards). However the exact scope of double-counting legislation varies between MSs. The iLUC Directive (Annex IX) provides a detailed list of feedstocks for advanced biofuel production, and thus eligible for double counting, but MSs do not have to use this definition, and the exact criteria for fuels to double-count varies between MSs. Though MSs cannot add feedstocks to this list for double-counting, only remove. For example, Italy only considers Part A of Annex IX as advanced feedstocks for double counting, whereas France has selected a few feedstocks in both Part A and B. Alternatively, Spain has transposed the entire list (i.e. all of Part A and B of Annex IX), although until mid-2018 did not allow any double-counting. Furthermore, France only allows for a small amount of double counting, since only a maximum of 0.3% (energy content) of petrol and 0.35% (energy content) of diesel can come from advanced feedstocks eligible for double counting[119]. This is compared to overall French bioethanol and biodiesel targets of 7% and 7.7% by energy content, respectively. Bulgaria and Lithuania have also not implemented double counting measures, likely due to concerns over competition to their crop-based biofuel producers, and additional concerns over actual (vs. accounted for) renewable energy consumption in transport[120].

5.1.2 Biofuel targets compared to capacity

Figure 45 compares current advanced biofuel capacity to the overall biofuel required to achieve the existing biofuel targets of all Member State. This overall volume target is calculated based on each MS's current target and their current transport energy requirements. As Germany does not have an advanced biofuels mandate, the volume of advanced biofuel required was estimated based on achieving their current GHG reduction target. For Sweden, the target level was estimated based on the requirement for 10% renewable energy in transport in order to meet the RED[121].

Advanced biofuel capacity in Europe is determined using the data collected in the database of industrial-scale demonstration and/or first-of-kind commercial plants (Section 4). For advanced biofuels excluding FAME and HVO, the total production capacity is illustrated in Figure 46. For FAME and HVO, it is likely that their ability to produce advanced biofuel is limited primarily by feedstock. Therefore for these fuels, the estimated production of ***advanced*** FAME and HVO is used (i.e. that produced from wastes and residues), rather than total FAME and HVO capacity, which is substantially higher. For HVO this breakdown is done on a plant-by-plant basis, based on information captured in the database. An average figure is used for FAME: across the EU 18% of all FAME production is from advanced feedstocks.

[119] This is likely limited to promote the use of national biofuels over potentially imported advanced biofuels.
[120] EURACTIV (2018) "Joint declaration of Visegrad 4 plus Bulgaria, Latvia and Lithuania biofuels associations on the new Renewable Energy Directive Recast (RED II)". Available at: https://www.euractiv.com/section/energy/opinion/the-v4-countries-appeal-to-politicians-for-stable-biofuels-policy-to-fight-the-climate-change/
[121] The volume of biofuel supplied in Sweden is actually greater than this 'target' as in 2016 Sweden had already achieved over 30% renewable energy in transport.

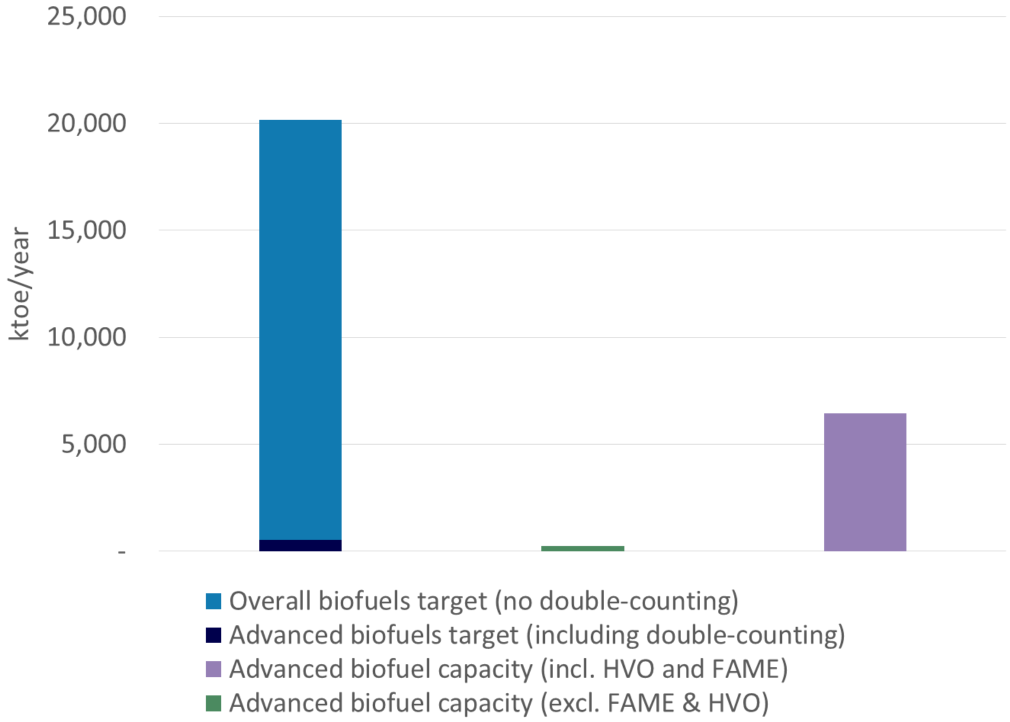

Figure 50: Advanced biofuel current capacity compared to biofuel requirements to achieve targets in the EU

The comparison between current biofuel targets and advanced biofuel capacity (Figure 50) demonstrates that current advanced biofuel capacity within the EU, including estimates of advanced biofuel capacity from HVO and FAME plants, is sufficient to fulfil the advanced biofuel targets implemented by the six member states noted above.

However the advanced biofuel capacity is very small in comparison to the overall biofuel targets of Member States. To achieve MS biofuel targets, over 20,000 ktonnes/yr of biofuels are required, whereas there is only 250 ktonnes/year of advanced biofuel capacity, rising to 6,500 ktonnes/yr when FAME and HVO are included. It is important to note that if the overall biofuel target is met by advanced biofuels, the required capacity would nearly halve, as most MS allow for double counting. However there would still be insufficient capacity to meet biofuel targets, even if advanced HVO and FAME are included.

6 Current incentives and support policies for advanced biofuel technologies

In this section advanced biofuel incentives and support policies from around the World are reviewed and analysed. The following countries or regions are considered in detail: Brazil, United States, EU-28 (including individual Member States), China, India, Malaysia and Indonesia. In section 6.1 the policies in each specific country or region are reviewed in detail, and in 6.2 a comparison is drawn between the different countries and types of support provided.

Across these regions there is no single definition of advanced biofuels. The EU defines advanced biofuels as biofuels produced from wastes, residues, non-food cellulosic and ligno-cellulosic feedstocks. The United States classifies a biofuel as 'advanced' if it produces a greater than or equal to 50% GHG savings compared to a 2005 petroleum fuel baseline. It has a further classification for 'cellulosic biofuel', requiring a greater than or equal to 60% GHG saving and that it is produced from approved feedstocks, which are broadly aligned with the Annex IX advanced feedstocks in the EU. In China, an advanced biofuel is defined as being produced from non-grain feedstocks, ensuring that fuel production does not compete with food production. In India, in their recent Biofuels Policy, advanced biofuels are defined as fuels originating from ligno-cellulosic feedstocks, non-food crops or industrial waste and residue streams. In the remaining countries, no formal definition of advanced biofuels was found. However, fuels produced in these countries are sold into EU and USA markets as advanced biofuels. All of the policies included within this section apply to advanced biofuels as defined in the EU, and are therefore within scope of this report, but it is inevitable that some policies support a narrower or wider pool of fuels than the EU considers to be advanced. Where relevant to the overall conclusions this is discussed within the text, and for specific information on the scope of each policy, see Appendix E.

The support mechanisms investigated can be grouped into six types: loans, grants (including R&D, demonstration and investment grants), price subsidies, tax incentives, blending mandates[122], and double counting[123]. Some countries or regions will have (advanced) biofuel plans, which will drive the types of support mechanisms they offer.

6.1 Country-specific Support Mechanisms

The following sections will provide a high-level overview of the available support in each country. Appendix E provides detailed information on the operation, key actors, compliance requirements and cost of each support mechanism mentioned in the subsequent sections.

6.1.1 European Union

Table 45: Support policies for advanced biofuels in the European Union (including both Community and Member State policies)

Support Mechanism Type	Policy Name	Jurisdiction
Blending Mandate	- iLUC Directive 2015/1513 - Directive of the European Parliament and of the Council on the promotion of the use of energy from renewable resources (recast) - Thirty-eighth Ordinance on the Implementation of the Federal Pollution Control Act - Renewable Transport Fuel Obligation – Development Fuels	- All MS - All MS - Germany - UK
Double counting	- Directive 2009/EC/28 of 23 April 2009 on the promotion of the use of energy from renewable sources and amending subsequently repealing Directives 2001/77/EC and 2003/30/EC	- All MS
Tax incentives	- Act 1994/1472 on liquid fuels excise duty	- Finland

[122] This includes both physical blending mandates (e.g. 1% of transport fuels are advanced biofuels) and as well greenhouse gas emission mandates which specifically promoted advanced biofuels (e.g. transport fuels must reduce emissions by 10% by 2020).
[123] This refers to double counting the advanced biofuel content to count towards mandates.

	- The Law of 3 February 2004 on the excise of mineral oil, as amended	- Slovakia
Grant	- New Entants' Reserve 300 (NER300) - Horizon 2020 – Societal Challenge 2: Food security, sustainable agriculture and forestry, marine, maritime and inland water research and the bioeconomy - Horizon 2020 – Societal Challenge 3: Secure, clean and efficient energy - Advanced Biofuels Demonstration Competition - Fuels for Flight and Freight Competition	- EU - EU - EU - UK - UK
Loan	- InnovFin Energy Demonstration Projects Facility	- EU
Subsidy	- State Aid: Support scheme for the production and distribution of advanced biofuels, incl. advanced biomethane	- Italy

In the EU, there are six types of support policies, with some implemented at the Community-level and others implemented within certain Member States (Table 45). In the Union, the promotion of advanced biofuels is supported via the Renewable Energy Directive (RED) (including the recast) and the Indirect Land Use Change (iLUC) Directive. The RED has targets for renewable energy use in transport, and has a 'double-counting mechanism' to specifically support advanced biofuels. Under this double-counting mechanism the energy content of biofuels from waste, residue, non-food cellulosic and ligno-cellulosic feedstocks is double counted towards the overall renewable energy in transport target[124]. The implementation of double-counting in each Member State is described in Appendix E. All but six countries – Bulgaria, Germany, Latvia, Lithuania, Slovenia and Sweden – have transposed the double counting mechanism. Germany and Sweden have not included double counting, as they do not have overall biofuel blending mandates, choosing to promote renewable energy in transport with other mechanisms (see section 5.

The iLUC Directive builds on the RED by providing a defined list of advanced feedstocks that are double counted. It also introduced a voluntary blending mandate for advanced biofuels at 0.5%[125]. Twenty-one Member States have formally introduced advanced biofuels mandates into their respective country laws, with some already in effect while others will begin as late as 2020 (see Appendix D for details). The recast RED, however, makes advanced biofuel mandates compulsory, suggesting that the remaining seven countries will also have mandates once this has been transposed[126].

The UK has introduced a blending mandate for 'development fuels' rather than 'advanced biofuels'. Development fuels are a subset of fuels produced from double-counted sustainable wastes and residues (excluding segregated oils such as UCO and tallow), and renewable fuels of non-biological origin. The produced fuel must either be hydrogen, aviation fuel or a natural gas substitute.

[124] Directive 2009/28/EC. Available at: https://eur-lex.europa.eu/legal-content/EN/ALL/?uri=CELEX%3A32009L0028
[125] Directive 2015/1513. Available at: https://eur-lex.europa.eu/legal-content/EN/ALL/?uri=CELEX%3A32009L0028
[126] Council of the European Union (2018) "Proposal for a Directive of the European Parliament and of the Council on the promotion of the use of energy from renewable resources: Analysis of the final compromise text with a view to agreement". Available at: http://data.consilium.europa.eu/doc/document/ST-10308-2018-INIT/en/pdf

Alternatively, a fuel may qualify as a development fuel if it can be blended such that the final blend has a renewable fraction of at least 25% whilst still meeting the relevant fuel standard. Development fuels will be rewarded with double 'development fuel' Renewable Transport Fuel Certificates (RTFCs), essentially double-counting their contribution. The blending mandate is set to begin in 2019, with a target of 0.1% of total fuel by volume (including double-counting).[127]

The iLUC Directive also introduced a cap on crop-based biofuels, in which they can contribute up to 7% of transport energy. This cap could indirectly support advanced biofuel production, as advanced biofuels, along with electricity in transport, can make up the difference to achieve the 10% renewable energy in transport target. Six countries have not transposed the crop cap, though this is in some cases because they are still in the process of transposing the iLUC Directive e.g. Latvia, Cyprus. The Netherlands, Germany and the UK have set more stringent crop caps than proposed by the iLUC Directive.

Member States have also implemented mechanisms to support advanced biofuel production in their respective countries. In Finland, advanced biofuels are exempt from paying the carbon aspect of the excise tax[128,129]. Italy has introduced a scheme to support the production and distribution of advanced biofuels, by offering advanced biofuel producers a premium to cover the additional costs, making advanced biofuels more cost competitive with traditional biofuels and fossil fuels[130]. In Slovakia, producers are given tax breaks if they meet advanced biofuel blending targets[131]. Lastly, the United Kingdom has introduced competitions – the Advanced Biofuels Demonstration Competition (ABDC)[132] and the Future Fuels for Flight and Freight Competition (F4C)[133] – to provide financial support for new plants.

6.1.2 USA

Table 46: Support policies for advanced biofuels in the United States (including both federal and state policies)

Support	Policy Name	Jurisdiction

[127] Department for Transport (2018) "Renewable Transport Fuel Obligation Guidance Part One Process Guidance – Year 11: 15/4/18 to 31/12/18". Available at: https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/694277/rtfo-guidance-part-1-process-guidance-year-11.pdf

[128] Vero Skatt (2018) "Nestemäisten polttoaineiden verotaulukot". Available at: https://www.vero.fi/yritykset-ja-yhteisot/tietoa-yritysverotuksesta/valmisteverotus/valmisteverolajit/nestemaiset_polttoaineet/nestemaisten_polttoaineiden_verotaulukk/

[129] Vero Skatt (2018) "Energiaverotus". Available at: https://www.vero.fi/syventavat-vero-ohjeet/ohje-hakusivu/56206/energiaverotu/

[130] European Commission (2018) "State Aid: Commission approves €4.7 billion public support scheme for advanced biomethane and biofuels in Italy". Available at: http://europa.eu/rapid/press-release_IP-18-1441_en.htm

[131] ZÁKON z 3. februára 2004 o spotrebnej dani z minerálneho oleja (The Law of 3 February 2004 on the excise of mineral oil, as amended). Available at: https://www.slov-lex.sk/pravne-predpisy/SK/ZZ/2004/98/20160601#paragraf-4.odsek-7.pismeno-a

[132] Arup URS Consortium (2014) "Advanced Biofuel Demonstration Competition Feasibility Study". Available at: https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/383577/Advanced_Biofuel_Demonstration_Competition_-_Feasibility_Study_FINAL_v3.pdf

[133] Ricardo Energy and Environment (2017) "Future Fuels for Flight and Freight Competition (F4C)". Available at: http://www.ieabioenergy.com/wp-content/uploads/2016/09/iea-bioenergy-countries-report-13-01-2017.pdf

Mechanism Type		
Blending Mandate	- Renewable Fuel Standard - Low Carbon Fuel Standard - Oregon Clean Fuels Program - Washington State House Bill 2338	- Federal - California - Oregon - Washington
Tax incentives	- Second Generation Biofuel Producer Tax Credit - Special Allowance for Second Generation Biofuel Plant Property	- Federal - Federal
Grant	- Biomass Research and Development Initiative - Algal Biomass Yield, Phase 2 - BioEnergy Engineering for Products Synthesis - Efficient Carbon Utilization in Algal Systems - Process Development for Advanced Biofuels and Biopower - Affordable and Sustainable Energy Crops - Project Definition for Pilot- and Demonstration-Scale Manufacturing of Biofuels, Bioproducts, and Biopower - MARINERS - TERRA - Defense Production Act (DPA) Title III Advanced Drop-in Biofuels Production Project (ADBPP) Biofuels 2 - Community-Scale Advanced biofuels Production Facilities - North Dakota Industrial Commission's Renewable Energy Program - Biofuel Production Grant Program	- Federal - Federal - Federal - Federal - Federal - Federal - Federal - Federal - Federal - Federal - California - North Dakota - Minnesota
Loan	- Biorefinery Assistance Program (Section 9003)	- Federal
Subsidy	- Advanced Biofuel Production Payments in Bioenergy Program for Advanced Biofuels - Biomass Crop Assistance Program	- Federal - Federal
Other	- Support for Advanced Biofuel Deployment	- The State of California to the US Federal government

The United States offer six types of support mechanisms to promote advanced biofuels, including mechanisms introduced at state level[134] (See Appendix E for further information on each policy). Further, the support mechanisms are offered along the entire supply chain from R&D grants to feedstock development payments to fuel production and supply incentives.

At the Federal level, the Renewable Fuel Standard (RFS) has likely had the greatest impact on advanced biofuel promotion in the United States. The RFS mandates the quantity of advanced biofuels, which in 2018 was 4.29 billion gallons. A fuel is classified as advanced not based on its feedstock, but rather on its lifecycle GHG savings, which need to be at least 50% when compared to fossil fuels. This means that some fuels, notably sugar-cane ethanol, are classified as 'advanced' in the USA but not in the EU. The standard is administered using Renewable Identification Numbers (RINs). These RINs are used to track the amount of advanced biofuels produced and mixed into fossil fuels. Fuel suppliers are obligated to blend a certain amount of advanced biofuels based on the

[134] Due to the number of states, a high-level investigation of state-level support mechanisms was done. This allows for a general understanding of the types of support available within states, and does not attempt to provide a comprehensive list of all state-level policies.

amount of fuel they are projected to sell in the year. As the RFS has targets for multiple advanced biofuel subcategories (e.g. cellulosic biofuel), targets for each subcategory need to be fulfilled by the appropriate RIN. Note that a RIN generated from a fuel produced in one year must be retired to demonstrate compliance in either that same year or the following, after which the RIN expires and can no longer be used.[135]

The Californian Low Carbon Fuel Standard (LCFS) is the most successful state-based legislation. In fact the Pacific Coast Collaboration, between California, Oregon, Washington State and British Columbia[136], directly addressed the Low Carbon Fuel Standard to ensure strategic alignment among the states on policies to reduce GHG emissions. The LCFS is a market-based cap and trade mechanism that aims to reduce transport emissions. The mechanism requires that fuel suppliers reduce the lifecycle emissions of their supplied fuels. Each year, a target carbon intensity is set, and fuels with lifecycle emissions below the target generate credits and those above the target generate deficits. The size of the credit and deficit is a function of the difference between the target carbon intensity and the lifecycle emissions of the produced fuels. Fuel suppliers will aim to balance these credits and deficits to ensure they meet the targeted GHG emissions for supplied fuels. Of the approved feedstocks, biofuels produced from used cooking oil, technical corn oil and tallow have the lowest lifecycle emissions and thus generate the largest number of credits, supporting the production of advanced biofuels[137].

6.1.3 China

Table 47: Support policies for advanced biofuels in China

Support Mechanism Type	Policy Name
Blending Mandate	- Implementation plan for expanding biofuel ethanol production and promoting vehicle ethanol use (unofficial target)
Tax incentives	- Various tax exemptions
Subsidy	- Various subsidies
Other	- Implementation plan for expanding biofuel ethanol production and promoting vehicle ethanol use (National Biofuel Plan)

Advanced biofuels in China are supported via three mechanisms: subsidies, tax exemptions and a biofuel plan (Table 47). In 2014, a subsidy was introduced for cellulosic ethanol, where each ton of cellulosic ethanol produced receives RMB 600 (~€75.42/ton[138]). This subsidy is expected to be phased out by the end of 2018. The ethanol market in China is heavily regulated, where facilities can only be built with direct approval from the government, whereas the biodiesel market is mostly unregulated with many small, private producers. Biodiesel produced from used cooking oil receives a tax

[135] United States Environmental Protection Agency (2018) "Renewable Fuel Standard Program". Available at: https://www.epa.gov/renewable-fuel-standard-program
[136] British Columbia (2018) "Renewable & Low Carbon Fuel Requirements Regulation". Available at: https://www2.gov.bc.ca/gov/content/industry/electricity-alternative-energy/transportation-energies/renewable-low-carbon-fuels
[137] Green Plains (2018) "U.S. Biofuel Policies". Available at: https://www.iscc-system.org/wp-content/uploads/2017/02/12_Hahn_GreenPlains_ISCC-Conference_200218.pdf

[138] 10 October 2018 exchange rate

exemption of RMB 0.8 per litre (€0.10/L[139]). Further, 1.5G[140] and 2G ethanol[141] from non-grain feedstocks are fully exempt from paying VAT and excise tax. These tax exemptions only apply to ethanol produced in China, and not imported fuels[142,143].

In 2017, the National Development and Reform Commission, the National Energy Administration and the Ministry of Finance released a plan that set an indicative target to produce, by 2020, over 3.8 billion litres of cellulosic and non-grain-based ethanol[144]. The plan also targets the roll-out of large-scale cellulosic ethanol production technologies by 2025[145]. The Ministry of Agriculture estimates that there are potentially 687 million tons of crop residues which can be collected every year. If only a third of this was converted into biofuels, 50.7 billion to 63.4 billion litres of cellulosic ethanol could be produced in a year[146], well above the 2020 target. When this policy was announced, by the central government, the stock prices of advanced biofuel producers increased[147], demonstrating the importance of strong government support for the industry even if the mechanism behind achieving those targets is currently unclear.

Until 2015, the government only offered financial and policy support for cellulosic ethanol development to state-owned enterprises (SOE). In 2015, the government began to offer private industry subsidies and partnerships with SOEs. This policy shift resulted in leading advanced biofuel technology companies, such as Novozymes and LanzaTech, investing in plants and scaling up their technology in China. Some of these advanced cellulosic ethanol plants are moving from demonstration scale to commercial scale.

6.1.4 India

Table 48: Support policies for advanced biofuels in India

[139] 10 October 2018 exchange rate
[140] Defined as biofuels produced from non-grain sugar or starch crops (e.g. cassava, sweet sorghum, sweet potato, sugarcane or ligno-cellulosic feedstocks) (http://www.etipbioenergy.eu/images/liping-kang.pdf)
[141] Defined as biofuels produced from cellulosic feedstocks (e.g. corn cobbs, corn stover, forage sorghum, wood chips and other fibre materials)
[142] IEA Bioenergy Task 39 (2016) "The Potential of Biofuels in China". Available at: http://task39.sites.olt.ubc.ca/files/2013/05/The-Potential-of-biofuels-in-China-IEA-Bioenergy-Task-39-September-2016.pdf
[143] USDA Foreign Agricultural Service (2017) "China – Peoples Republic of: Biofuels Annual – Biofuels Demand Expands, Supply Uncertain". Available at: https://gain.fas.usda.gov/Recent%20GAIN%20Publications/Biofuels%20Annual_Beijing_China%20-%20Peoples%20Republic%20of_1-18-2017.pdf
[144] Comparatively, in 2018, forecasts expect advanced biofuel production to be 395 million litres.
[145] China Daily (2017) "China planning nationwide use of biofuel by 2020". Available at: http://www.chinadaily.com.cn/business/2017-09/14/content_31972205.htm
USDA Foreign Agricultural Service (2017) "China – Peoples Republic of: Biofuels Annual – Biofuels Demand Expands, Supply Uncertain". Available at: https://gain.fas.usda.gov/Recent%20GAIN%20Publications/Biofuels%20Annual_Beijing_China%20-%20Peoples%20Republic%20of_1-18-2017.pdf
[146] USDA Foreign Agricultural Service (2017) "China – Peoples Republic of: Biofuels Annual, Growing Interest for Ethanol Brightens Prospects". Available from: https://gain.fas.usda.gov/Recent%20GAIN%20Publications/Biofuels%20Annual_Beijing_China%20-%20Peoples%20Republic%20of_10-20-2017.pdf
[147] Financial Times (2017) "Biofuel-linked stocks jump as China said to plan 2020 ethanol roll-out". Available at: https://www.ft.com/content/31c68837-9eb2-3f22-b10b-7611f7960606

Support Mechanism Type	Policy Name
Grant	- Programme on Energy from Urban, Industrial and Agricultural Wastes/Residues
Other	- National Policy on Biofuels

There has been limited formal government support for advanced biofuels in India (Table 48). In June 2018, India released their National Policy on Biofuels[148]. With regards to advanced biofuels, the policy aims to promote the 2G ethanol technologies and advanced drop-in fuels, through the use of support mechanism such as offtake agreements and investment support. Further, the policy stipulates that a National Biofuel Fund could be created to provide financial incentives, in the form of grants and subsidies, for new and advanced biofuel technologies. As the policy has only recently been approved, these support mechanisms have yet to be implemented. There is, however, an additional government support program, Waste-to-Energy, which has a budget of approximately €12 billion and supports some advanced biofuel production[149].

Generally speaking, advanced biofuel development in India is fairly early stage, with ongoing trials with MSW, micro-algae and photosynthetic organisms as feedstock[150]. However, according to the oil minister, India is planning a 2G ethanol plant with a production capacity of 1 billion litres per year[151]. Further the government is planning to build 12 more biorefineries in 11 states, all of which will be producing 2G ethanol[152,153].

The Indian government and the European Union have been working closely on promoting advanced biofuels in the country. The EU and India have listed commodities and technologies they want to cooperate more closely on, including advanced biofuel technologies. Nevertheless the aim is not to export the advanced biofuel produced to the EU, but to use it for domestic consumption[154].

6.1.5 Malaysia

Advanced biofuel technologies do not benefit from direct support mechanisms in Malaysia, possibly influenced by the large existing palm oil industry in Malaysia. Since 2002, there has been research on developing advanced biofuels, but a lack of investment and low oil prices have hindered the progress

148 The Gazette of India (2018) "National Policy on Biofuels – 2018".
149 USDA Foreign Agricultural Service (2018) "India: Biofuels Annual 2017". Available at: https://gain.fas.usda.gov/Recent%20GAIN%20Publications/Biofuels%20Annual_New%20Delhi_India_6-27-2017.pdf
150 USDA Foreign Agricultural Service (2017) "India – Biofuels Annual". Available from: https://gain.fas.usda.gov/Recent%20GAIN%20Publications/Biofuels%20Annual_New%20Delhi_India_6-27-2017.pdf
151 Energy Census (2018) "India's cabinet to soon examine advanced biofuel strategy". Available at: https://www.energycensus.com/Article/India-s-cabinet-to-soon-examine-advanced-biofuels-strategy-1039.html
152 USDA Foreign Agricultural Service (2017) "India – Biofuels Annual". Available at: https://gain.fas.usda.gov/Recent%20GAIN%20Publications/Biofuels%20Annual_New%20Delhi_India_6-27-2017.pdf
153 Press Information Bureau – Government of India, Ministry of Petroleum & Natural Gas (2016) "First 2G (Second Generation) Ethanol Bio-refinery in India to set up a Bathinda (Punjab); Foundation Stone laying to be held on 25th December, 2016". Available at: http://pib.nic.in/newsite/PrintRelease.aspx?relid=155782
154 Energy Census (2018) "India's cabinet to soon examine advanced biofuel strategy". Available at: https://www.energycensus.com/Article/India-s-cabinet-to-soon-examine-advanced-biofuels-strategy-1039.html

of this research. Further, the feedstocks available for advanced biofuels have high economic value in other industries such as to produce pharmaceutical grade sugar[155].

Despite the general legislative focus on conventional palm oil biodiesel, there have been some advances in Malaysia to promote advanced biofuel production. A consortium of local companies (e.g. Hock Lee Group), international companies (e.g. Biochemtex & Beta Renewables) and the Malaysian government are investing in an advanced biofuel plant in the Malaysian province of Sarawak that will use the by-products of the palm-oil plantations to generate biofuels[156]. Another project is being developed at the University of Nottingham Malaysia that seeks to transform the palm oil industry into being effectively zero-waste. The technological advancements would transform various palm wastes and residues into advanced biofuels[157].

During the talks to recast the Renewable Energy Directive, a proposal to ban biofuels produced from palm oil by 2021 was suggested. Malaysia strongly opposed this ban, suggesting that it would lead to higher costs for meeting the RED. It was further argued by Malaysia that this would not be in line with WTO free trade regulation[158], an assertion the EU disagreed with[159]. In the most recent version of this legislation, which is still undergoing ratification by the EU, the palm oil ban does not feature. Latest developments suggest that a ban is unlikely before 2030[160]. Limited constraints on the use of palm oil for biofuel in Europe and in the large Chinese market [161] is not likely to speed up advanced biofuel development in Malaysia.

6.1.6 Indonesia

No governmental support mechanisms specifically for advanced biofuels were identified in Indonesia. However, advanced biofuel production is being explored by the Indonesia Institute of Science (LIPI), where research focuses on the biofuel production from wastes and residues from palm oil plantations and palm solid wastes. The institute operates a small-scale plant capable of using empty palm fruit bunches to produce fuel-grade ethanol[162].

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[155] USDA Foreign Agricultural Service (2017) "Malaysia – Biofuels Annual". Available at: https://gain.fas.usda.gov/Recent%20GAIN%20Publications/Biofuels%20Annual_Kuala%20Lumpur_Malaysia_10-24-2017.pdf

[156] McKinsey & Company (2016) "The future of second-generation biomass". Available at: https://www.mckinsey.com/business-functions/sustainability-and-resource-productivity/our-insights/the-future-of-second-generation-biomass

[157] Phys (2018) "Zero-waste palm oil industry on the horizon with new technology". Available at: https://phys.org/news/2018-05-zero-waste-palm-oil-industry-horizon.html

[158] New Straits Times (2018) "Spain backs Malaysia's palm oil biofuel stand". Available at: https://www.nst.com.my/news/nation/2018/02/335111/spain-backs-malaysias-palm-oil-biofuel-stand

[159] EurActiv (2018) "Commission Tells Malaysia Proposed Biofuel Policy Respects WTO Rules". Available at: https://www.euractiv.com/section/agriculture-food/news/commission-tells-malaysia-proposed-biofuel-policy-respects-wto-rules/

[160] Borneo Post (2018) "MPOC elated on EU palm biofuel ban". Available at: http://www.theborneopost.com/2018/06/20/mpoc-elated-on-eu-palm-biofuel-ban/

[161] Malaysian Biodiesel Association (2018) "China offers a huge market for M'sian biodiesel producers". Available at: http://www.mybiodiesel.org.my/index.php/mba-news/mba-news/57-china-offer-huge-market-for-malaysian-biodiesel-producers

[162] USDA Foreign Agricultural Service (2018) "Indonesia Biofuels Annual 2018". Available at: https://gain.fas.usda.gov/Recent%20GAIN%20Publications/Biofuels%20Annual_Jakarta_Indonesia_8-13-2018.pdf

6.1.7 Brazil

Table 49: Support policies for advanced biofuels in Brazil

Support Mechanism Type	Policy Name
Blending Mandate	- RenovaBio
Loan	- PAISS Program (Support Program for Industrial Technology Innovation in the Sugarcane and Sucrochemistry Sectors) - PAISS Program (Agriculture)

Advanced biofuels in Brazil have been promoted through the use of loans and will be promoted through a new blending mandate (Table 49). In 2019, a new programme, RenovaBio, will come into effect and aims to decrease transport emissions by 10% in the next 10 years, resulting in 600 million tonnes of cumulative emission savings. The programme is modelled after the US Renewable Fuel Standard and the California Low Carbon Fuel Standard, whereby it favours fuels with lower carbon intensities, rather than a specific fuel. Biofuel producers will receive credits (CBios) based on the lifecycle emission savings of their fuel compared to petrol. These CBios will then be traded on the open market, where fuel suppliers will purchase them to meet mandated yearly targets[163]. However, there are concerns over whether this will stimulate 2G biofuel generation, as currently 1G ethanol produces 90% emission savings compared to around 95% savings for advanced biofuels. As the programme is still being fully developed, there is potential that the certification, required to receive credits, will be tied to other sustainability criteria, e.g. land use changes or water consumption. If these are included this could increase the support towards advanced biofuels, especially those produced from wastes and residues[164].

The PAISS Program, through the Agriculture and Industrial Technology Innovation schemes, provide loans to increase the presence of advanced biofuel technologies in Brazil. The Industrial Technology Innovation scheme provides BRL 2 billion (€470 million[165]) in funding to produce cellulosic ethanol from sugarcane bagasse. As a result of this scheme, 7 new commercial and demonstration plants are being built. The Agriculture scheme has a budget of BRL 1.56 billion (€370 million[166]) for the 2014-2018 period. This scheme resulted in one pilot and two commercial sized plants with a combined

[163] Ministério de Minas e Energia (n.d.) "RenovaBio: Principal". Available at: http://www.mme.gov.br/web/guest/secretarias/petroleo-gas-natural-e-combustiveis-renovaveis/programas/renovabio/principal
[164] J. Moss (2018) "What to expect from Brazil's RenovaBio Programme". Available at: https://knect365.com/energy/article/e5560843-78a9-4034-81f7-25319afe103c/what-to-expect-from-brazils-renovabio-programme
[165] 10 October 2018 exchange rate
[166] 10 October 2018 exchange rate

capacity of 140 million litres[167,168]. Investment in 2G technologies is also a response to stagnating industrial and agricultural yields in conventional biofuels[169].

No other advanced biofuel support mechanisms were found for Brazil. The National Program of Biodiesel Production and Use (NPBP) has the remit to promote advanced biodiesel production, but there is some suggestion that this could contradict other aims of the NPBP to foster the social inclusion of farmers, if promoting biodiesel production from wastes reduces demand for conventional oil crops[170]. Combined with Brazil's strong focus on ethanol as a gasoline fuel replacement, this may explain why there has been limited deployment of advanced biodiesel technologies in Brazil to-date.

Brazil does not have a target for 2G ethanol consumption, so the production of second-generation biofuels in Brazil is driven by policies in the United States[171] as well as the Renewable Energy Directive in the EU.

6.2 Analysis

6.2.1 Advanced biofuel supply chain

Support mechanisms used to promote advanced biofuels can be offered at different points of the supply chain, including feedstock supply, plant construction, fuel production and fuel supply. Support can also be provided for research and development of feedstocks, technologies and infrastructure, and the construction of refuelling infrastructure, but these were not the focus of this analysis. Table 50 outlines which steps of the supply chain have policies within each country.

Table 50: Presence of policies at each step of the supply chain

	Feedstock supply	Plant construction	Fuel production	Fuel supply
United States	✓	✓	✓	✓
European Union	×	✓	✓	✓
China	×	×	✓	✓
India	×	×	×	×
Indonesia	×	×	×	×
Malaysia	×	×	×	×
Brazil	×	✓	×	×

[167] The Brazilian development bank (2014) "BNDES and Finep launch a R$1.48 bn program to encourage innovation in the sugar-based ethanol sector". Available at: https://www.bndes.gov.br/SiteBNDES/bndes/bndes_en/Institucional/Press/Noticias/2014/20140217_PAISS.html

[168] Ethanol Producer Magazine (2013) "Financing complete on Brazil's first commercial 2G ethanol plant". Available at: http://www.ethanolproducer.com/articles/9876/financing-complete-on-brazils-first-commercial-2g-ethanol-plant

[169] United Nations Conference on Trade and Development (2016) "Second Generation Biofuel Markets: State of Play, Trade and Developing Country Perspectives". Available at: http://unctad.org/en/PublicationsLibrary/ditcted2015d8_en.pdf

[170] Cardoso et al. (2017) "Development of Brazilian Biodiesel Sector from the Perspective of Stakeholders". Available at: http://www.mdpi.com/1996-1073/10/3/399

[171] Current ethanol production in Brazil qualifies as advanced under the US Renewable Fuel Standard and the Californian Low Carbon Fuel Standard, due to its 61% GHG savings compared to gasoline.

The United States is the only country/region examined that has implemented a support mechanism that benefits the entire advanced biofuel supply chain. Further, it is also the only region that has a direct policy to support feedstock development, with the Biomass Crop Assistance Program and the Affordable and Sustainable Energy Crops policy. Support policies in the European Union also cover most of the value chain. Apart from Brazil, the emerging economies tend to focus their policies on fuel production and supply. However, China and India have implemented national biofuel policies that could lead to additional support mechanism for advanced biofuels, which could cover more elements of the value chain.

6.2.2 Advanced biofuel plant development

Figure 51 illustrates the number of different types of support mechanism present in each country investigated (illustrated by coloured shading), along with the number of planned and operational advanced biofuel plants (illustrated by the size of the markers). The support mechanisms are classified into the following types: loans, grants, price subsidies, tax incentives, blending mandates and double counting.

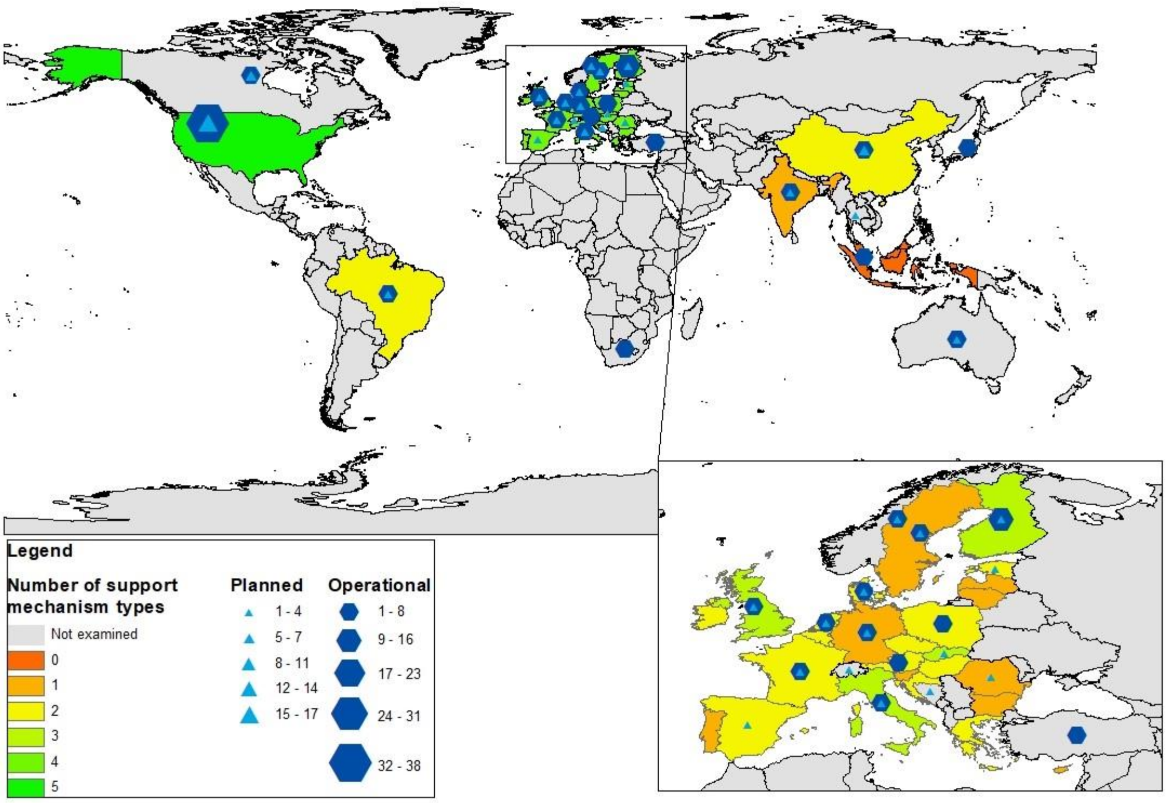

Figure 51 Number of different types of advanced biofuel support mechanism available in each country reviewed, and number of planned and operating plants

In most cases advanced biofuel plants at demonstration scale and above are present in countries which have some form of support mechanism. Those countries which have a number of different types of support mechanisms generally have the largest number of installed or planned plants. Such regions include China, the USA considering both federal and state support, and the EU when both Community-level and MS policies are considered. Conversely, Malaysia and Indonesia currently have no specific support mechanisms for advanced biofuels and no operating plants. China and India have developed national biofuel plans that address advanced biofuels, but do not provide direct support mechanisms specifically for advanced biofuels. Despite this there are a number of planned plants in these regions.

As a whole country, the United States has the greatest number, of advanced biofuel plants, with 55 plants that are either planned or operational, whereas the European Union, as a whole region has the greatest number of plants with 65. Both regions have opted to promote supply of advanced biofuels through mandates. Mandates are relatively simple to impose, and place the cost burden on the supplier (likely passed on to the consumer) rather than on the government. They create a demand for advanced biofuels by attributing to them a greater value in the market than conventional fuels, due to the requirement for suppliers to meet blend targets. These mandates are further complemented with a range of supply-side support schemes, such as grants, loans and subsidies. These are particularly important given the early stage of some of the technology routes, as a mandate alone may not provide sufficient incentive to get the investment required for new plants, given the risks associated with technology scale-up. The range of mechanisms across the supply chain have helped the development of the large number of advanced biofuel plants.

Countries like Malaysia and Indonesia, and to a lesser extent Brazil, do not have strong national policy support for advanced biofuels. As key suppliers to the USA and European Union, their biofuel industry is impacted by the policies of these regions, such as the RFS in the USA and the RED in the EU. For example, the advanced biofuel requirements to fulfil the RFS in the USA has led to increased sugarcane ethanol imports from Brazil, as it provides a 61% emission reductions compared to conventional gasoline[172]. The RFS has likely supported the 8 operational and planned advanced biofuel plants in Brazil. It is clear therefore that demand-side policies in one region can impact advanced biofuel production in countries which wish to supply into that market, but without more developed supply-side support it remains challenging for early-stage technologies to develop in countries like Malaysia and Indonesia: there are no known advanced biofuel plants in Indonesia and only one plant in Malaysia which is now shut.

6.2.3 Policy recommendations for the EU

The European Union is one of the leading regions with regards to the promotion of advanced biofuels, offering a range of support mechanisms both at the EU level but also within respective Member States. The RED mandates the increased use of renewable energy in transport, which it is assumed will decrease greenhouse gas emissions, and up to 2020 the Fuel Quality Directive (FQD) aims to directly reduce greenhouse gas emissions by 6%. However after 2020 there is no specific target to reduce the GHG intensity of transport fuel, and there has been some concern that the RED will not achieve additional GHG emissions reductions in transport, notably with the double counting mechanism, which allows for a smaller portion of fossil fuels to be displaced than the target suggests. A mechanism similar to the Californian LCFS could be implemented in parallel to the RED, as is the case in California in parallel to the federal-level RFS. This would ensure that GHG targets are met, which arguably is the main driver for increased renewability in transport. Agreement on the REDII

[172] Ethanol Producer Magazine (2016) “US, Brazil Demonstrate What’s Possible”. Available at: http://ethanolproducer.com/articles/13519/us-brazil-demonstrate-whatundefineds-possible

and a harmonised approach to its implementation across MSs will also provide certainty to producers and a better functioning single market for advanced biofuels.

7 Market outlook to 2030

7.1 Barriers and actions affecting deployment

This section reviews non-technical barriers that impact the deployment of advanced biofuel technologies.

Barriers impacting the supply of advanced biofuels are presented in section 7.1.1, and fall into one of four key areas:

- Project finance
- Feedstock
- Infrastructure
- Environmental and social impacts

Barriers to increased demand for advanced biofuels are presented in section 7.1.2, and can be grouped as either market barriers or policy and regulation barriers. Each of these broad areas is covered by a table enabling clear identification of the specific nature of the barrier, impact, geographic specificity (within the EU), and the actions that could be adopted to overcome it.

Many of these barriers are common across more than one of the conversion pathways within scope, and some apply to all of the technology pathways. Therefore to avoid repetition each barrier is discussed once and we note, using the acronyms defined in Table 1, which routes are primarily affected.

The market outlook for advanced biofuels is assessed based on the methodology outlined in section 7.2, with results and discussion in section 7.3. Finally in section 7.4 we highlight and discuss the key barriers which must be overcome in order to facilitate deployment of advanced biofuels.

7.1.1 Non-technical supply side barriers

Table 51: Project financing barriers which limit the deployment of advanced biofuels

Barriers	Explanation	Impact	Geographic specificity	Routes most affected	Mitigation measures
i. High capital cost and capital risk	Especially impacts high capital pathways	High	EU-wide	Gasif. routes (6,7,8,9), HTL (11), S2D (4)	Use of insurance schemes (e.g. GCube); Gov loan guarantees or capital grants (e.g. US DOE)
ii. Shortage of long-term strategic investors	Limited pool of investors, even with multiple sources of capital being combined	High	EU-wide, particularly in some MSs without big industry	All except for FAME (12) and Co-process (14)	Encourage exploitation of existing instruments such as the Green for Growth Fund Southeast Europe (GGF). Ensure that such initiatives are available across Europe to advanced biofuel developers, either through existing institutions or new institutions dealing specifically with green investments. Foster understanding of the sector amongst strategic investors and provide strong policy direction from government to reduce perception of risk.
iii. Negative investor perception because of past developer failures	Deters investment or significantly increases hurdle rates/project costs	Medium	EU-wide	2G alcohol (1), gasif. routes (6,7,8), HTL (11), Pyrolysis (10), S2D (4)	Greater Gov grant support in demo and 1st commercial stages to lower risk; investor education on differences to past developer failures
iv. Investors unwilling to scale-up & simultaneously use new feedstocks and/or components	Switching to new feedstocks, e.g. 2G sugars or MSW, usually requires multiple development stages – taking more time and /or money	Medium	EU-wide	APR (3), S2D (4)	Technology performance insurance (e.g. New Energy Risk)

v. Low and volatile oil prices	If off-take agreement is based on oil price, it will affect plant profitability. Reduced interest from investors & policy makers	Medium	EU-wide	All	Off-takes with floor prices; market hedging (esp. for short-term); Gov set up CfDs[173]; diversify revenue streams (e.g. gate fees, power, CO_2)
vi. Currency risk	Impacts profitability if importing feedstock or exporting fuel, may impact equipment capital cost	Low	EU-wide, particularly outside Euro	All	Agreements priced in domestic currency; forex hedging

Table 52: Barriers concerning feedstock which limit the deployment of advanced biofuels

Barriers/sensitivities	Explanation	Impact	Geographic specificity	Routes most affected	Mitigation measures
i. Variable feedstock quality (lack of specifications/ standards)	May impact plant performance and guarantees. Reduces amount of feedstock available and increases price	Medium - particularly for MSW	EU-wide	All	Gov or industry to create feedstock specifications/ standards
ii. Feedstock availability	Abundance of feedstock relative to project needs, and supply variation over time. Tight or seasonal supply increases project risk, and impacts production security	Medium - highly site & feedstock specific	Some EU MSs	All	Projects can invest upstream; Gov infrastructure grants and lending (e.g. for storage facilities); regional availability studies
iii. Feedstock accessibility	Supply chain logistics and required quality of feedstocks dictates infrastructure investment requirements	Medium - highly site & feedstock specific	Some EU MSs	All except FAME (12), Co-process (14), HVO (13)	Some projects invest upstream to secure supplies, others partner with logistics or biomass/waste firms
iv. Feedstock competition	Increased feedstock competition may limit availability and increase feedstock price.	Medium - but increasing (esp. with long-term	EU-wide	All	Projects can invest upstream; Gov support for infrastructure grants

173 CfDs are Contract for Differences. This is a market mechanism that guarantees producers a fixed product price, via subsidies that vary inversely to the market fossil price.

	Severely limited access (e.g. supplies locked into 25 year waste contracts) deters investment	waste contracts)			and lending; clearer Gov direction on desired long-term use of feedstocks
v. Feedstock cost variability	Feedstock forms a major part of production costs, esp. for HVO, FAME and co-processing, and catalysis routes that arbitrage alcohol and diesel/jet spot prices. Volatility impacts operating hours and profits	Low - unless outside of a supply contract	EU-wide	Especially 2G catalysis (2) but also HVO (13), FAME (12), Co-process (14)	Tie in part of feedstock supply to a contract; use market hedging; Gov set up CfDs

Table 53: Barriers concerning infrastructure which limit the deployment of advanced biofuels

Barriers/sensitivities	Explanation	Impact	Geographic specificity	Routes most affected	Mitigation measures
i. Immature supply chain for feedstocks	Increases project risk as well as costs. Impacts ability to procure sufficient feedstock volumes. Supply logistics will become more important as development accelerates & feedstock competition increases	Medium – particularly for energy crops, or cleaner feedstocks with greater competing uses	Some EU MSs	All except FAME (12), HVO (13), Co-process (14)	Develop regional feedstock exploitation plans to raise awareness about supply, mobilisation and use of currently under-utilised feedstock; Gov investment/loans for harvesting, collection, storage in order to increase available feedstock.
ii. Immature supply chain for technology components	Increases project risk if large items of equipment are not available on time, need to be imported from abroad, or end up costing much more than first budgeted	Medium	EU-wide	All except FAME (12), HVO (13), Co-process (14)	Delivery contracts with penalties for delay, insurance, forex hedging; Gov support to address weakest links in supply chain

iii. For some fuels, vehicle homologation/compatibility with fuels limits uptake	Sales of vehicles using natural gas as fuel are limited. Limits to alcohol blends.	Medium	EU-wide	Routes producing alcohols (1, 8, 9) + gaseous fuels (5,7)	Gov can improve demand by direct subsidy, sales tax/VAT exemptions, toll or parking waivers, access to priority lanes or zones; standards for higher alcohol blend levels
iv. Batch supply of intermediate products from multiple locations could be problematic for refiners	Processing multiple batches together (to form a homogenous fuel product) requires additional time/cost for individual batch testing	Low	EU-wide	HTL (11), Pyrolysis (10), Co-process (14) as rely on refinery upgrading	Gov or industry to create intermediate product specifications/standards
v. Lack of appropriate refuelling infrastructure (for various fuels)	There is limited natural gas refuelling infrastructure in most MSs, and within the EU very little refuelling infrastructure for high alcohol blends (e.g. E85). Impacts willingness of customers to pay for alternative or flex-fuel vehicles, therefore limits penetration of these fuels	Low – for most fuels does not limit uptake	EU-wide	Routes producing alcohols (1,8,9) + gaseous fuels (5,7)	Establish case for high biofuel blends such as E85; Customer education campaign; effective implementation of the EC Action Plan on Alternative Fuels Infrastructure covering a range of alternative fuel types and with coherence between EU MSs.
vi. Lack of space at forecourts for introducing new biofuel blends	Introducing new fuel types or blends (e.g. E20 or natural gas) requires well-coordinated changes to national infrastructure to change out a fuel grade, due to lack of space/storage at forecourts	Low – for most fuels does not limit uptake	Varies between EU MSs	Routes producing alcohols (1,8,9) + gaseous fuels (5,7)	As above

	for adding new fuel grades				
vii. Lack of CO_2 distribution and sequestration infrastructure	Several routes generate CO_2 that could be captured, and sequestered to improve fuel GHG savings. But modest volumes compared to coal/gas plants means fuels facilities cannot pay for the CO_2 infrastructure themselves	Low – few developers focusing on CO_2 capture currently, but could increase in future	EU-wide	2G alcohol (1), gasif. routes (6,7,8), APR (3), HTL (11), Pyrolysis (10), S2D (4), Pretreat+AD (5)	Government investment in early CCS projects to de-risk the technology; coordination of different stakeholders; CO_2 price (e.g. in ETS) reflective of CCS costs

Table 54: Environmental and social barriers which limit the deployment of advanced biofuels

Environmental and social factors can limit both supply and demand for advanced biofuels, but are included here together in one table for consistency.

Barriers/sensitivities	Explanation	Impact	Geographic specificity	Routes most affected	Mitigation measures
i. Unclear sustainability characteristics of feedstocks (e.g. soil quality, water, forestry carbon debt, biodiversity)	Some feedstocks may not be sustainable in the long-term in certain regions as industry scales-up and better data becomes available, or as counterfactual uses or land-use patterns change. Policymakers may change categorisations/accounting rules	Medium - depending on feedstock.	Varies between EU MSs	All	Investment in sustainability research (e.g. field trials, modelling) to reduce uncertainties and understand key drivers and competing uses
ii. Lack of factual knowledge about advanced biofuels (public awareness & perception)	Public opinion may change, or not realise the benefits compared to 1G biofuels, and press policymakers to change rules	Medium	EU-wide	All	Public education campaigns, via ads, forecourts, and address mis-conceptions. Use of voluntary schemes to certify feedstock in order to demonstrate

					sustainability
iii. Limited customer understanding of new blends or fuel types	Introduction of new fuel blends has not always proven successful in the past (e.g. with E10 in several MSs), causing confusion and concern amongst motorists	Medium – particularly in those MSs where E10 introduction failed	Likely to vary between EU MSs	All routes that do not lead to drop-in fuels, i.e. routes producing alcohols (1,8,9) and FAME (12)	Customer education campaigns about vehicle compatibility, engine warranties and fuel availability
iv. Complexity of environmental sustainability standards	Compliance with standards increases operating costs, and may be a barrier to entry for smaller players. Inconsistent approaches globally may lead to poor outcomes & market fragmentation	Low	EU-wide	All	RED II adoption will help harmonise some EU rules; greater collaboration between MSs and voluntary schemes in agreeing double-counting lists; publish policy comparisons to improve market transparency
v. Site planning permission and building permits	Results in delays in project development, and added costs	Low	EU-wide	All	National planning policy guidance
ix. Continued consumer shift away from diesel (post diesel-gate), to gasoline or EVs	Continues to erode diesel vehicle market share, particularly in passenger vehicles, leading to lower demand for diesel and novel low carbon diesel replacements.	Low – mostly car focused, as buses/HGVs have different standards and customers and continue to rely on diesel	EU-wide, but particularly urban drivers	Routes producing diesel fuel replacements (2, 3, 4, 6, 10, 11, 12, 13). Could be a	Further engine and after-treatment design changes to minimise PM, NO_x in real-world driving; promotion of fuels with enhanced combustion properties; customer education campaigns; re-tuning of technologies towards

				benefit to routes producing alcohols (1,8,9)	jet and gasoline production

7.1.2 Non-technical demand-side barriers

Table 55: Market barriers which limit the deployment of advanced biofuels

Barriers/sensitivities	Explanation	Impact	Geographic specificity	Routes most affected	Mitigation measures
i. Lack of understanding of market size and value as a result of policy mechanisms	Value implied by policy mechanisms may not be well understood by investors, if for example policy is a market-based mechanism where the value is dictated by over/under-supply of fuels against targets. If this is not clear then developers and investors will perceive projects as too risky	Medium	EU-wide, and varies significantly across MSs	All	Policies should be designed to send clear pricing and demand signals; pricing regimes and likely actions if there is under/over-supply of fuels should be clearly communicated; publish projections of market sizes and underlying assumptions.
ii. Shift to producing higher value products (e.g. bio-based chemicals) rather than fuels	Limits pool of developers interested in converting waste & residues to advanced biofuels. Chemical outputs may also be a cash-flow positive in co-producing plants, helping with financing	Medium - particularly for sugar based routes	EU-wide	Gasif.+syngas ferm. (8), APR (3), Pyrolysis (10), S2D (4)	Gov to set out vision on desired long term use of biomass resources; prioritise use of resources across different energy sectors or provide clear policy mechanisms that enable producers to determine competition between uses.
iii. Nearer term or lower cost competing opportunities for	Use of e.g. pyrolysis oil in heating, LC ethanol in ICEs without upgrading to jet.	Medium - for some technology routes	EU-wide – although some	2G catalysis (2), HTL (11),	

growth (e.g. using intermediate products in heat, power, gases) rather than making liquid fuels	Limits pool of developers interested in converting waste & residues (or renewable power) to advanced biofuels.		MSs (like UK) are already targeting strategic fuel types	Pyrolysis (10), gasif. routes (6,7,8,9)	Fuels procurement commitments and partnership with fuel suppliers could help to make fuel production more attractive compared to other markets.
iv. Jet fuel specifications either limit blending or are not yet approved for new fuels	Takes a very long time and considerable expense for new fuels to be approved to ASTM standards for aviation, and still limited to a % blend. Particular issue for early TRL fuel pathways that do not yet produce the test volumes required	Medium – for unapproved jet routes	EU-wide	2G catalysis (2), HRJ (13) and S2D (4) are approved pathways; APR (3), HTL (11), Pyrolysis (10) still to be approved	Ongoing development of fast-track ASTM certification process will speed up certification; Gov grant support for lab and jet engine rig testing to accelerate ASTM Tier 1-4 progression; industry actions and flights to demonstrate use

Table 56: Policy and regulation barriers which limit the deployment of advanced biofuels

Barriers/sensitivities	Explanation	Impact	Geographic specificity	Routes most affected	Mitigation measures
i. Lack of clear, long-term policy signals	Venture capital, private equity or strategic investors (e.g. oil majors and refiners) will not make significant investments without policy certainty. 2030 is already very close, and policy needs to start looking beyond	High	EU-wide	All	MSs transpose harmonised REDII rules as soon as possible; delegated acts which postponed some decisions within the REDII legislation should be addressed as soon as

	2030				possible; EU to give clarity on 2050/Paris targets, and importance of low carbon fuels
ii. Uncertainty around policy attractiveness	Difficulty estimating economic value of multiple-counting, as well as proposed 1.2x multiplier for aviation and marine fuels in RED II. Level of policy support needs to be high enough to make sufficient volumes profitable	High	Varies significantly across MSs	All, but particularly 2G catalysis (2) and developers focusing on jet or marine (3,11,6,10,4,13,14)	As above; plus MSs could set support floor prices; consider CfD type support; or grandfather double-counting decisions; greater cooperation between MSs, voluntary schemes and fuel suppliers to agree double-counting lists
iii. Lack of a strong decarbonisation driver for aviation & marine fuels	With few national-level mandates for low-carbon aviation or shipping fuel, uptake driven primarily by international agreements from ICAO and IMO.. However international frameworks and rules to ensure targets are met are yet to be agreed, and rules may not be aligned with EC rules. Aviation and marine sectors often outside of national incentive schemes	High	EU-wide, but with exceptions e.g. Netherlands incentivises aviation and shipping	Routes that can produce jet fuel (2,3,11,6,10,4,13,14)	More national level policies required to drive decarbonisation in aviation and shipping sectors, such as including these sectors within national targets, tax and incentive schemes that support meeting global targets in a competitive way
iv. Subsidies to support fossil fuel exploration, production and/or use	Creates additional price disparity Market signals can deter investors	Medium - indirect impact, varies by MS	EU-wide but varies widely across MSs	All	Major reform and phasing out of government subsidies for fossil fuel exploration, production and consumption
v. Significant variation	Unclear how much fuel could be exported to	Medium	Varies	All	EU to impose greater harmonisation

between national biofuel policies	or imported from other countries; and at what price. Complicates replicability of projects. RED II will only marginally help with harmonisation of policies & regulations		significantly across MSs		in transposing to MS policy; greater cooperation between MSs, voluntary schemes and fuel suppliers; publish policy comparisons to improve market transparency
vi. Clarity of the policy definitions for advanced feedstocks	Process for inclusion / exclusion and definitions of the feedstocks in Annex IX lists are vague.	Medium	EU-wide issue, but expected to vary widely across MSs	All except FAME (12), HVO (13), Co-process (14)	Commission to publish clear definitions with aim of common adoption across MSs; clear rules published for addition of new feedstocks or removal of feedstocks from Annex IX
vii. Diesel bans planned in several EU cities, due to air quality impact on human health	The ban creates uncertainty over use of diesel in light-duty vehicle applications, and reduces resale value/customer demand for diesel vehicles. This in turn impacts demand to develop new low carbon fuels that can be blended with or replace diesel.	Low – but increasing, as urban new EV focus. HGVs less likely to be impacted	Some EU member states, focused on cities	Particularly HVO (13) but also routes that can produce diesel (2,3,11,6,10,4)	Further engine and after-treatment design changes to minimise PM, NO_x in real-world driving; re-tuning of technologies towards jet and gasoline production

7.2 Methodology for assessment of market outlook to 2030

7.2.1 Technology-limited routes

None of the advanced biofuel technology routes within scope of this study, apart from FAME, HVO and co-processing, are currently widely commercially deployed and several are still at pilot-scale. Therefore their deployment to 2030 is likely to be limited by technology development, number of companies developing new technology, how quickly they can build out new plants, and willingness of investors to fund new plants.

For these pre-commercial technology routes their likely deployment to 2030 is assessed using a ‘bottom-up’ method. This relies on the information gathered on existing companies and plants in Task 2 and Task 3 (sections 2 and 3) to provide reliable information on the status and production capacity of each pathway. The likely future deployment of each route is then assessed based on the following key factors that influence how far and how fast a pathway can progress:

- How long it takes to build each plant? (Project timelines)
- How many years each plant operates for? (Lifetime)
- Where are these plants built? (EU or Rest of World)
- How large each plant is? (Plant capacity)
- How many hours per year a plant operates for? (Utilisation rate)
- How many commercial projects can be started each year, e.g. via technology licences? (Initiation rate)
- How soon after a previous project starts is it is feasible for the next project to start? (Launch points)
- How many of these plants and developers might fail/be unsuccessful? (Success rate, compounded)
- How many developers are independently starting projects? (From Tasks 1-3)

More detail is provided on each of these factors in Appendix F. Figure 52 gives a summary of how these different factors fit together, and how they impact the 2030 production volume projections.

Given the large degree of uncertainty in how these factors will vary to 2030, two scenarios, ‘Challenging Growth’ and ‘Technology Success’, are developed to project the potential production volume. A third scenario, RED II stretch is developed specifically to illustrate how the RED II target might be reached, requiring very rapid technology ramp-up.

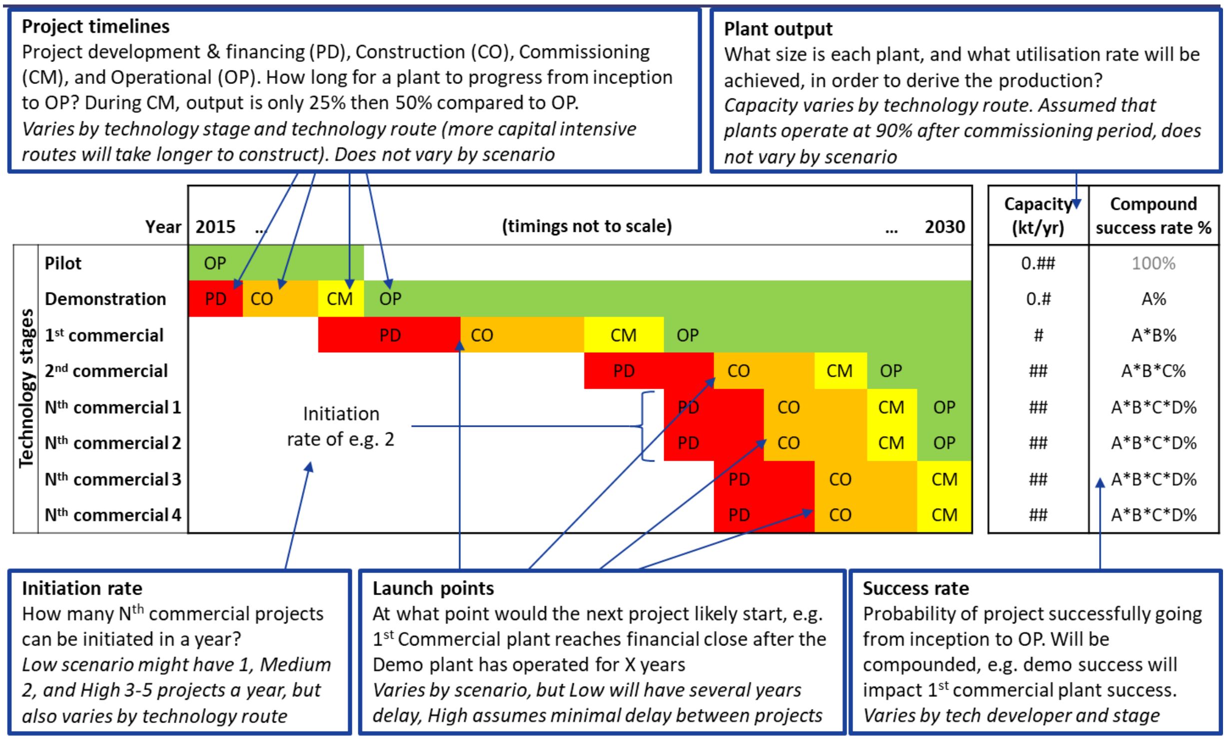

Figure 52 Illustration of the key steps of the ramp-up methodology for a single developer

The scenarios differ in terms of the following assumptions, as summarised in Table 57, with additional detail provided in Appendix F:

- Initiation rate (number of Nth commercial projects that start construction per year (globally), per developer)
- Launch-point (Number of years of operation of plant required before the next scale-up of plant)
- Success rate (probability of any particular project being successful from inception to operation)

In all of these scenarios a supportive policy environment for advanced biofuels is assumed. This supportive policy environment is assumed to provide sufficient support for advanced biofuels to make them cost-competitive with fossil fuels, so that all existing developers of advanced biofuel technologies continue to develop plants and scale-up. Therefore the scenarios for deployment shown here reflect the ***technical ability*** of the industry to scale-up, based on the current number of ***technology developers,*** scale of ***existing plants***, and ***plausible build-rates*** in this industry. Availability of sustainable feedstock is not considered a limiting factor in the scale-up of plants, as both scenarios fit within the currently available feedstock volumes, as demonstrated in section 7.3.4. The actual rate of deployment will depend on a wide range of factors including the cost competitiveness of each technology, the level of policy support available, and infrastructure to access sufficient quantities of sustainable feedstock.

Table 57: Summary of assumptions across the three* scenarios for advanced biofuel deployment to 2030

Scenario:	Challenging growth	Technology success	*RED II stretch*

Scenario:	Challenging growth	Technology success	*RED II stretch*
Initiation rate	1 for all technologies apart from AD, 5 for AD	2 for all technologies apart from AD, 10 for AD	Between 3 and 5 for all technologies apart from AD, 25 for AD
Launch-point	1 – 3 years	0.5 - 2 years	0 – 1 years
Success rate	50-90%	75-95%	100%

Note: RED II stretch illustrates the conditions which would be required in order to meet RED II target.

For each scenario, and for each biofuel production technology, we model the anticipated advanced biofuel capacity deployment in Europe and in the Rest of the World, based on location of existing plants and the assumption that 50% of plants from 2nd commercial scale onwards will be located in Europe.

7.2.2 Feedstock-limited routes

An alternative methodology was used to assess the ramp-up of FAME, HVO and co-processing, as these technologies are more commercially mature and are likely to be limited by the availability of sustainable feedstock rather than technology development, particularly given that waste feedstock is required in order to produce advanced biofuel. The availability of waste fats and oils in the EU and the rest of world was therefore used in order to assess the likely supply of advanced biofuel from these three technology routes together.

Biodiesel production volume from FAME, HVO and co-processing is expected to be significantly higher than other advanced biofuel routes. Feedstock availability will be a limiting factor, due to the challenges of waste oil collection, and competition from non-energy use, limiting the amount of transport fuel that could be produced via these routes. Currently around 20% of globally available waste fats and oils are used for biodiesel production, Therefore across the two scenarios, varying percentages of the feedstock is assumed to be used for biofuels: 25% under the challenging growth scenario and 50% under the technology success scenario.

7.2.3 Future production cost

The cost of advanced biofuel technologies is assessed based on their anticipated first commercial plant costs, obtained from a variety of literature sources including IRENA (2017), Cornell (2017) and input from plant developers. If the first commercial plant is anticipated before 2030 then a 2030 cost is also estimated, using a learning rate approach based on the deployment modelled in the market outlook assessment.

7.3 Results of advanced biofuel market outlook to 2030

7.3.1 Potential supply scenarios to 2030 by pathway (excluding FAME, HVO, and Co-Processing)

The potential global production of advanced biofuels in 2030 under the two scenarios is summarised in Figure 53, broken down between the EU and the rest of the World. The development of this capacity over time is shown in Figure 54 and Figure 55.[174] Results are discussed in detail in sections 7.3.1.1 and 7.3.1.2, where the overall deployment for each scenario is broken down by the individual biofuel technology.[175] The split of deployment between Europe and the Rest of the World is based only on the assumptions outlined in section 7.2.1 and is not intended to reflect the complex mix of factors including policy drivers, government support, infrastructure and feedstock availability, which would impact decisions on where to site plants.

Results are presented as production potential in a given year, corresponding to 90% of capacity, which is assumed to be the maximum production that plants could realistically achieve. In all cases the results are presented in ktonnes of fuel produced, but in order to account for the variable energy content of many of the fuels produced, the same graphs are provided in Appendix G on an energy basis. 'Global' results refer to deployment across the whole world, which is split into deployment in 'EU' (referring to EU 28) and the 'Rest of the World (RoW)'.

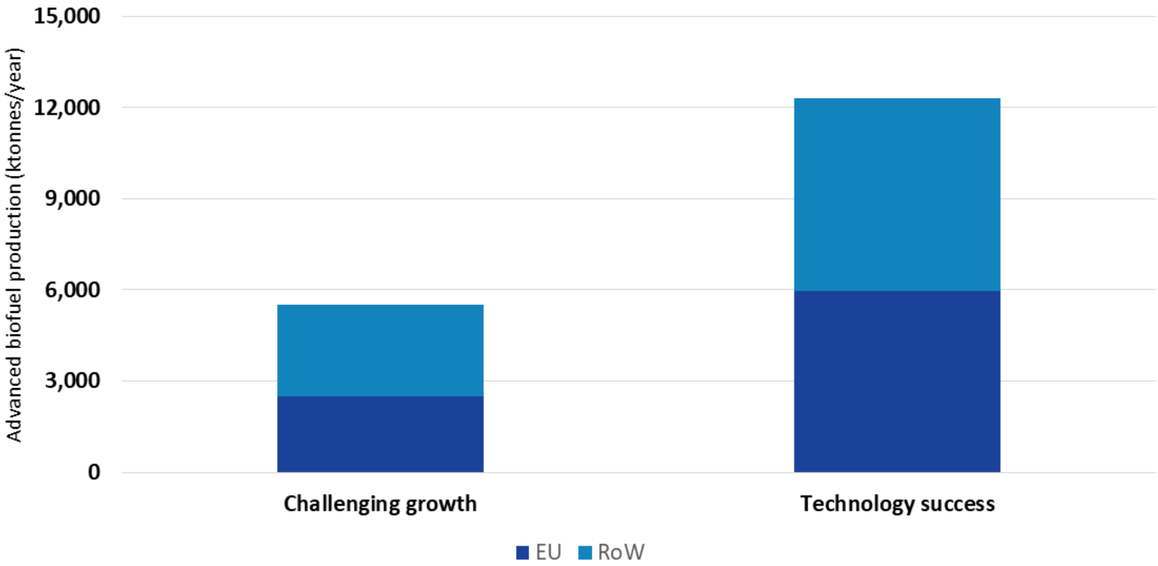

Figure 53 Global advanced biofuel production potential in 2030 across scenarios (excl. FAME, HVO, co-processing and alcohol catalysis)

[174] In these figures the results across all technology routes are summed together, but alcohol catalysis is excluded to avoid double-counting the use of 2G alcohol.
[175] The deployment of individual routes is independent of all other routes, therefore in Figure 53 to Figure 55 where the results are added together, alcohol to jet capacity has been excluded, because it duplicates the LC alcohol capacity.

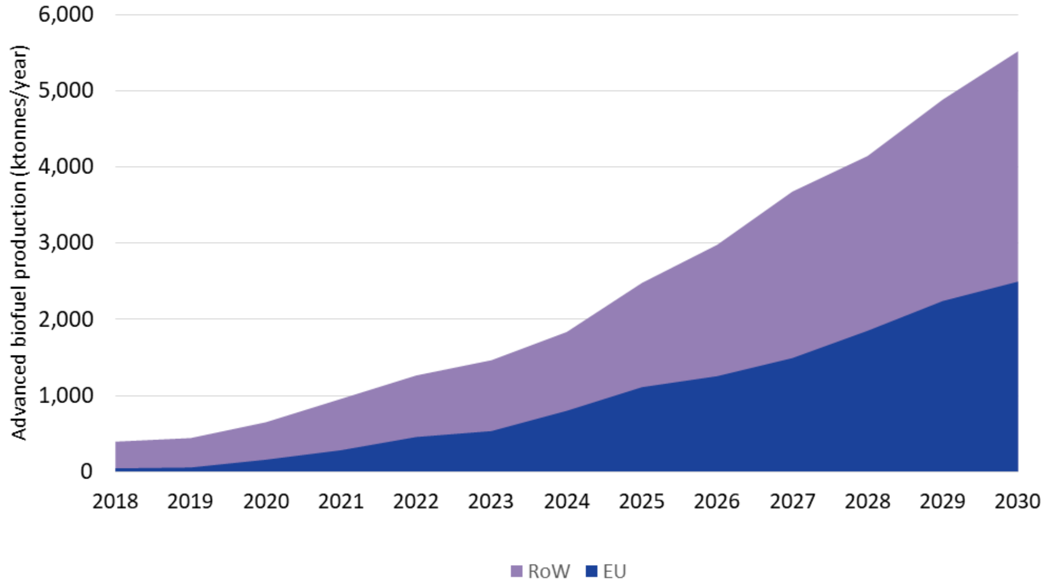

Figure 54 Global advanced biofuel production potential, challenging growth scenario (excl. FAME, HVO, co-processing and alcohol catalysis)

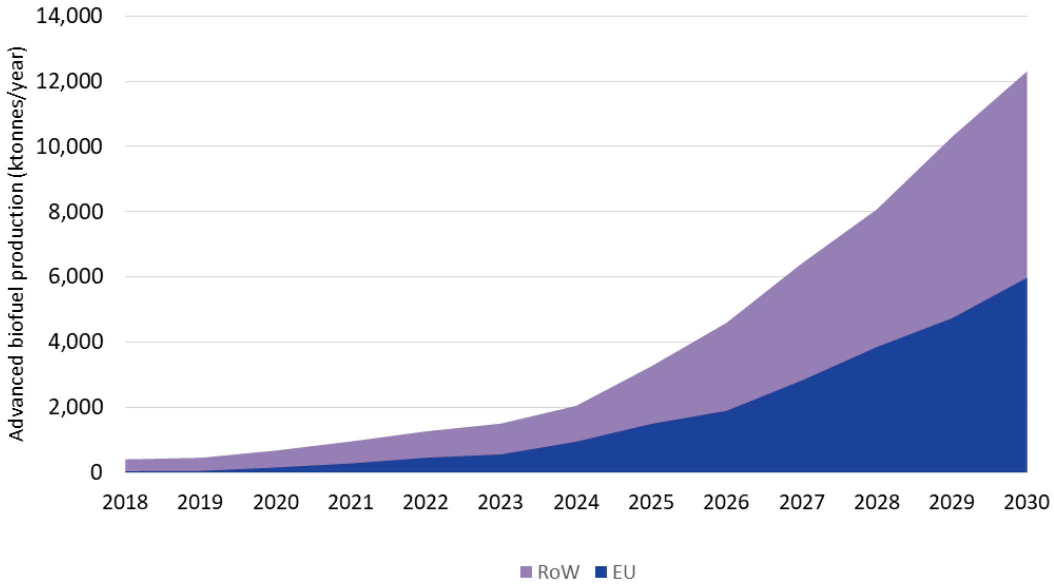

Figure 55 Advanced biofuel production potential, technology success scenario (excl. FAME, HVO, co-processing and alcohol catalysis)

7.3.1.1 Challenging growth scenario

Advanced biofuel production potential to 2030 for each of the different technology routes under the challenging growth scenario is illustrated for Europe in Figure 56 and for the rest of the World in Figure 57. This scenario reflects a situation where companies continue to develop the advanced biofuel technologies which they are developing today, but there are some failures and extended timescales for implementing new plants. See section 7.2.1 and Appendix F for detailed assumptions behind this scenario.

Other than FAME, HVO, and co-processing, LC alcohol is the most technologically mature route considered in this study, therefore across all scenarios it has the highest global deployment of any of the technology-limited advanced biofuel routes by 2030. LC alcohol dominates global production volume throughout the two scenarios, as there are more players in this route than in any of the other advanced biofuel routes assessed, and already several 1st commercial scale plants built – although they are not all operating currently.[176] With commercial-scale operation demonstrated, licensed roll-out could start very soon, and a lot of the developers are assumed to be able to start developing new projects from 2019.

Given the low existing production capacity of gasification+ FT and gasification + methanol synthesis routes, large planned plants such as the Kaidi gasification + FT plant and the Rotterdam methanol plant (both in Europe) can lead to substantial steps in production. Gasification + methanol production is more dominant in the rest of the world compared to Europe, as all operational plants to-date are located outside of the EU.

Meanwhile those routes which are still in the earlier stages of technology development, do not have large-scale operational plants today, or have few developers working on them, do not increase capacity significantly until the late 2020s. These include APR, aerobic fermentation, HTL, and gasification + methanation. Note that methanol production capacity is higher on a mass basis than on an energy basis compared to the other fuels, as it has a lower heating value.

The number of AD + pre-treatment plants grows rapidly in all scenarios, but overall capacity grows more slowly as the plants tend to be smaller, but can be deployed fairly rapidly. Nevertheless the growth is highly dependent on the assumption of how many plants would likely be deployed per year, which provides a significant spread in the projected AD capacity in 2030 across the two scenarios.

[176] The DuPont ligno-cellulosic ethanol plant is excluded from the ramp-up assessment, but the Abengoa and Beta Renewables plants are included, as they have been purchased by companies which could continue to develop the technology, although currently it is unknown whether this development will occur.

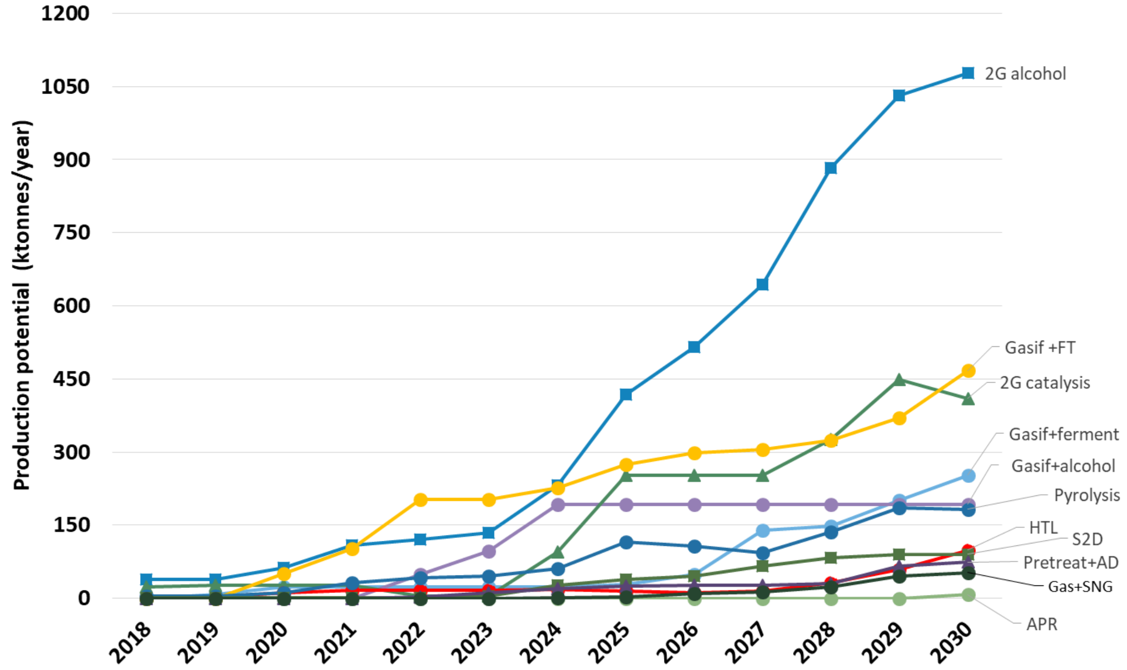

Figure 56 Anticipated EU production potential to 2030 under the challenging growth scenario

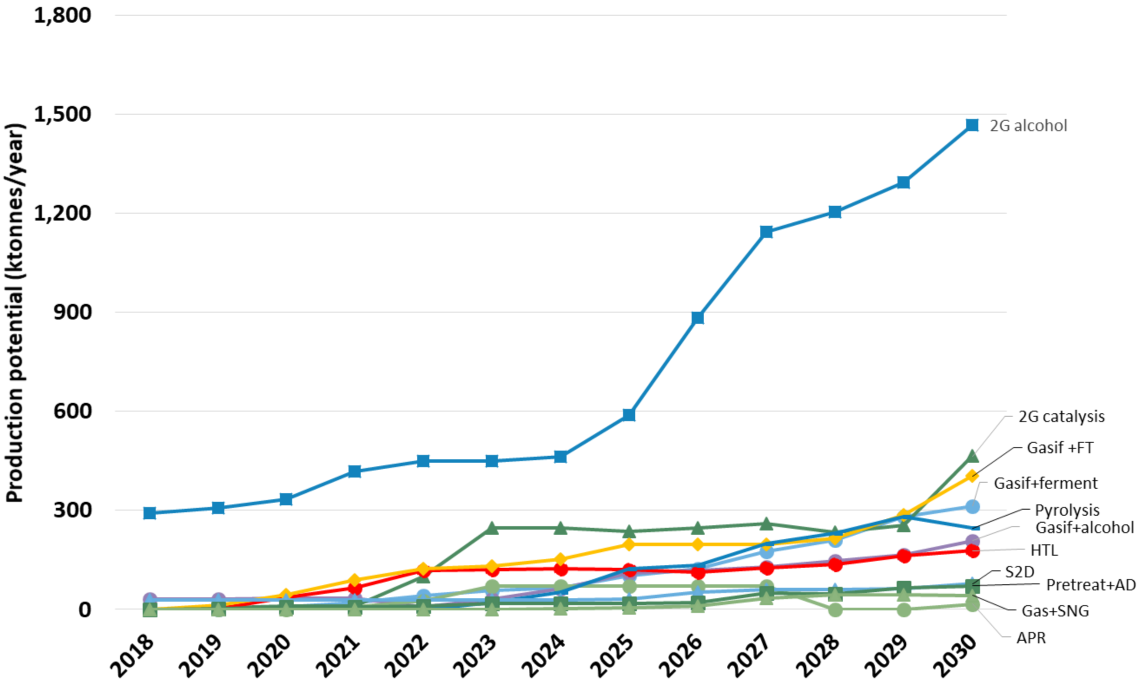

Figure 57 Anticipated RoW production potential to 2030 under the challenging growth scenario

7.3.1.2 Technology success scenario

Advanced biofuel deployment to 2030 for each of the different technology routes under the technology success scenario is illustrated for Europe in Figure 58 and for the rest of the World in Figure 59. This scenario reflects a situation where the majority of plants are successful and new projects can be implemented fairly quickly. See section 7.2.1 and Appendix F for detailed assumptions behind this scenario.

Under this scenario, the overall anticipated production output is over double that of the challenging growth scenario due to the more optimistic assumptions used. Nevertheless, the relative market share of different conversion pathways in this scenarios is similar to that in the challenging growth scenario, with LC alcohol dominating in both cases, and similar launch points for key plants in early or mid-2020s across both scenarios.

As in the challenging growth scenario, , gasification + methanol synthesis and pyrolysis, fall behind the deployment levels of LC ethanol, with 2G alcohol catalysis becoming more significant as well. Other less developed technologies like APR, HTL, and gasification + methanation start to see some output in 2030.

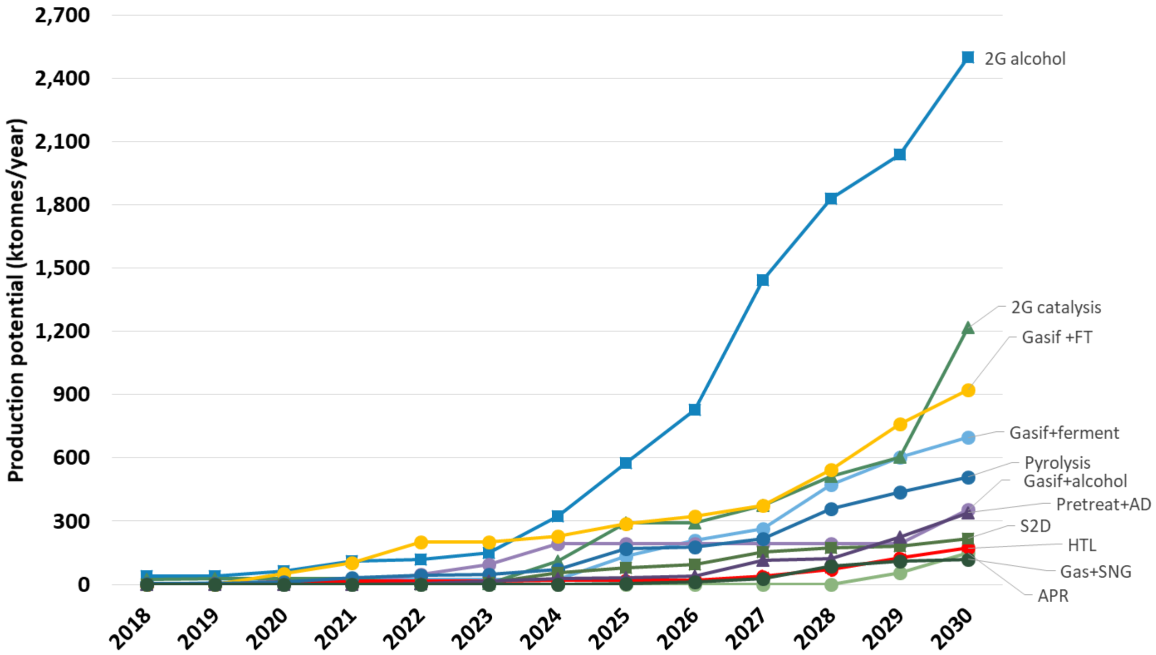

Figure 58 Anticipated EU production potential to 2030 under technology success scenario

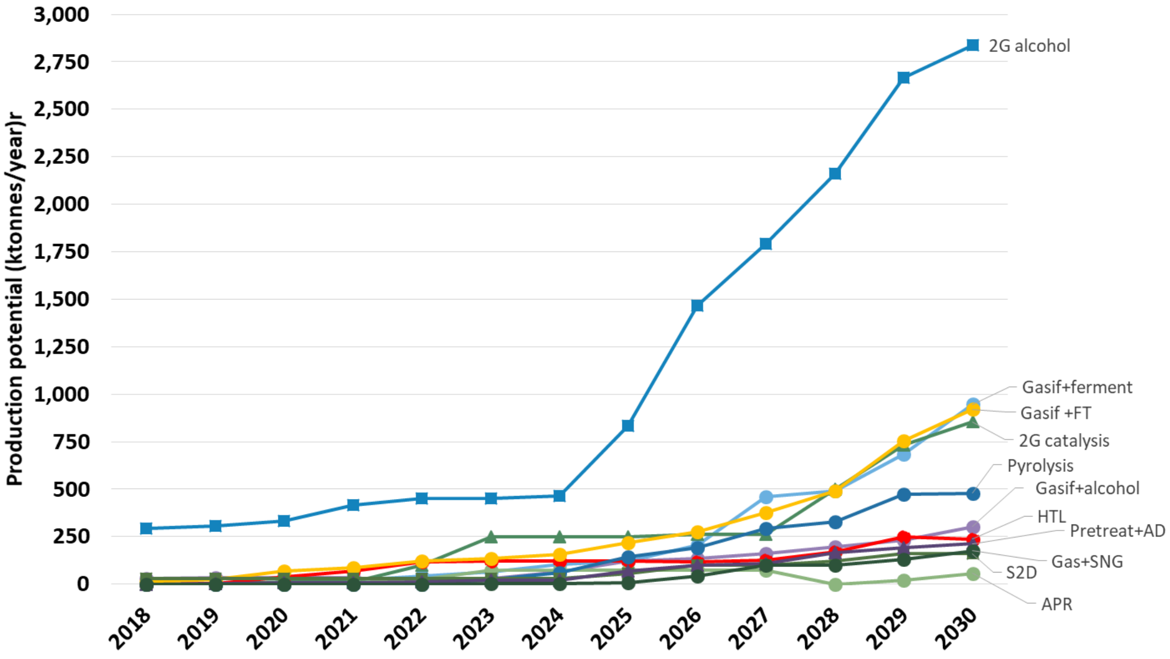

Figure 59 Anticipated RoW production potential to 2030 under technology success scenario

7.3.2 Potential supply scenarios to 2030 by pathway (including FAME, HVO, and Co-Processing)

As described in section 7.2.2, a top-down approach was taken for FAME, HVO and co-processing, limited by the amount of waste fats and oils available. There is significant uncertainty over how much of the available waste oils and fats globally could be used to produce biofuels, due to challenges in collecting it and competition from other industries. Therefore the two scenarios reflect this uncertainty: in the challenging growth scenario 25% of potential waste oils and fats supply is being used for biofuels, and the technology success scenario assumes 50%.

Comparing production between Europe and RoW is not relevant in the case of FAME, HVO and co-processing, as the conversion technology is commercial and the feedstock could generally be traded globally, so production could take place anywhere. Therefore results including FAME, HVO and co-processing are reported on a global basis, and are not split into Europe and Rest of World as for the other technology routes. Global deployment of these three oil-based routes, in the context of global deployment of other advanced biofuel production routes, is provided for the two scenarios in Figure 60 and Figure 61, respectively.

In these scenarios the production of advanced biofuel from FAME, HVO or co-processing is several times higher than from any of the other advanced biofuel routes. The potential for these oil-based biofuels does not overwhelm the other technologies. However even if the ligno-cellulosic biofuels were to develop rapidly, the supply of advanced biofuel from ligno-cellulosic feedstocks will still be less than the level of supply from waste oils and fats by 2030, although the gap is getting smaller.

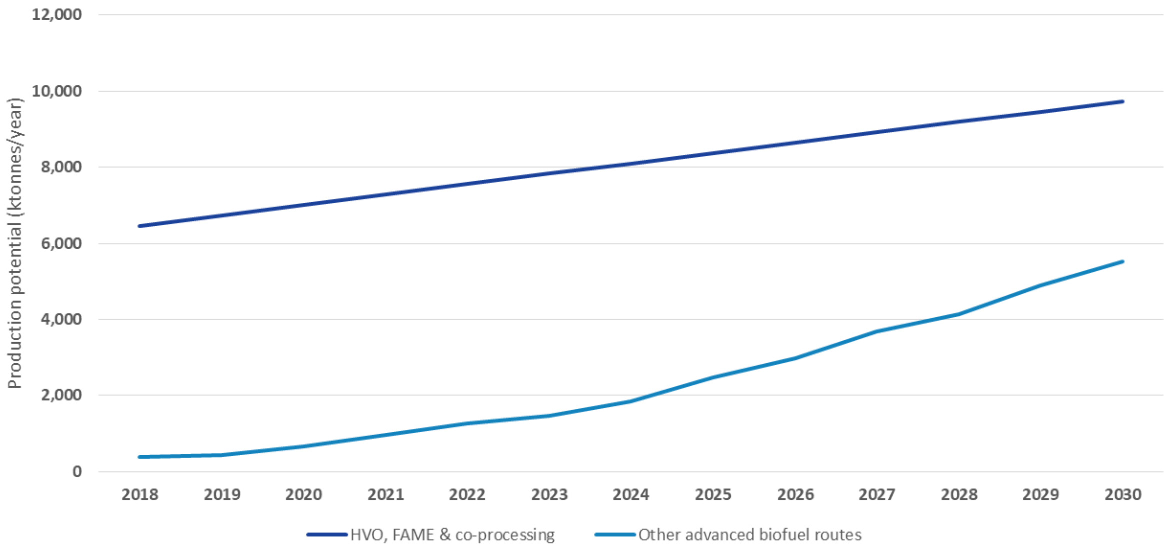

Figure 60 Anticipated global production potential to 2030 of advanced biofuels including FAME, HVO and co-processing, under the challenging growth scenario

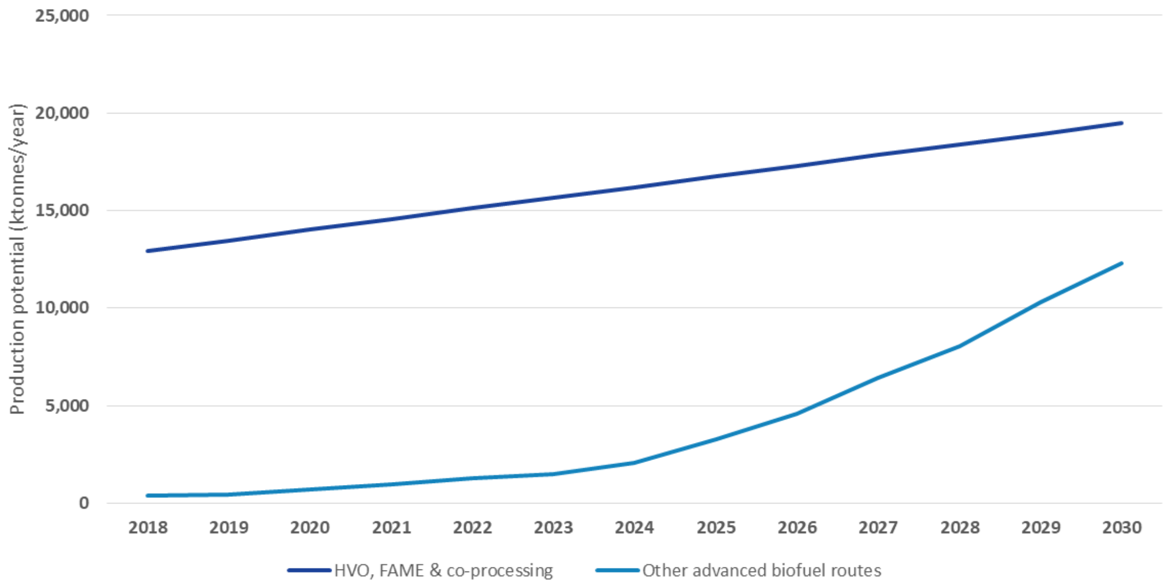

Figure 61 Anticipated global production potential to 2030 of advanced biofuels including FAME, HVO and co-processing, under technology success scenario

7.3.3 Comparison with REDII targets

In this section, the potential supply scenarios for advanced biofuel production are put into the context of the REDII targets. The REDII requires that in 2030 3.5% of transport energy demand be met with Annex IXa biofuels, equivalent to roughly 500PJ/year[177]. The contribution of Annex IXa fuels towards this target can be double-counted if Member States choose to, which would reduce the amount of fuel required to 1.75% of transport fuel demand. In the REDII there is also a multiplier of

[177] 3.5% of total Europe transport fuel demand in 2030, taken from https://data.europa.eu/euodp/data/dataset/energy-modelling

1.2 times for the contribution of fuels used in the aviation and marine sectors towards the target, but for clarity in this section no multipliers are applied.

For the EU this analysis is carried out for two cases to demonstrate two ends of an extreme: assuming that 2G alcohols can be imported so that all of the potential ATJ capacity can be utilised; and assuming that 2G alcohols are not imported, so that only domestically produced LC ethanol provides feedstock for ATJ plants in Europe.

When considering global deployment, the total production of LC ethanol is limited. Figure 63 therefore illustrates two cases: either all of the potential production of LC ethanol is used as ethanol, or some is diverted to alcohol catalysis. The difference between the two cases simply reflects a small conversion efficiency loss of the alcohol catalysis process.

The total Annex IXa biofuel production potential in the EU and globally is compared to the REDII target level in Figure 62 and Figure 63 respectively.

In the EU, under the situation where all ATJ capacity can use imported 2G alcohol, EU Annex IXa biofuel production potential could reach 91GJ/year in the challenging growth scenario, and 229GJ/year in the technology success scenario. The technology success scenario would not be able to meet the RED II target, even considering double counting. The additional scenario, RED II stretch, was created to illustrate a supply evolution that could meet the target, however the rate of deployment that is required under this scenario is very ambitious.

In the technology success scenario, global supply can meet RED II target if double counting is allowed (Figure 63).

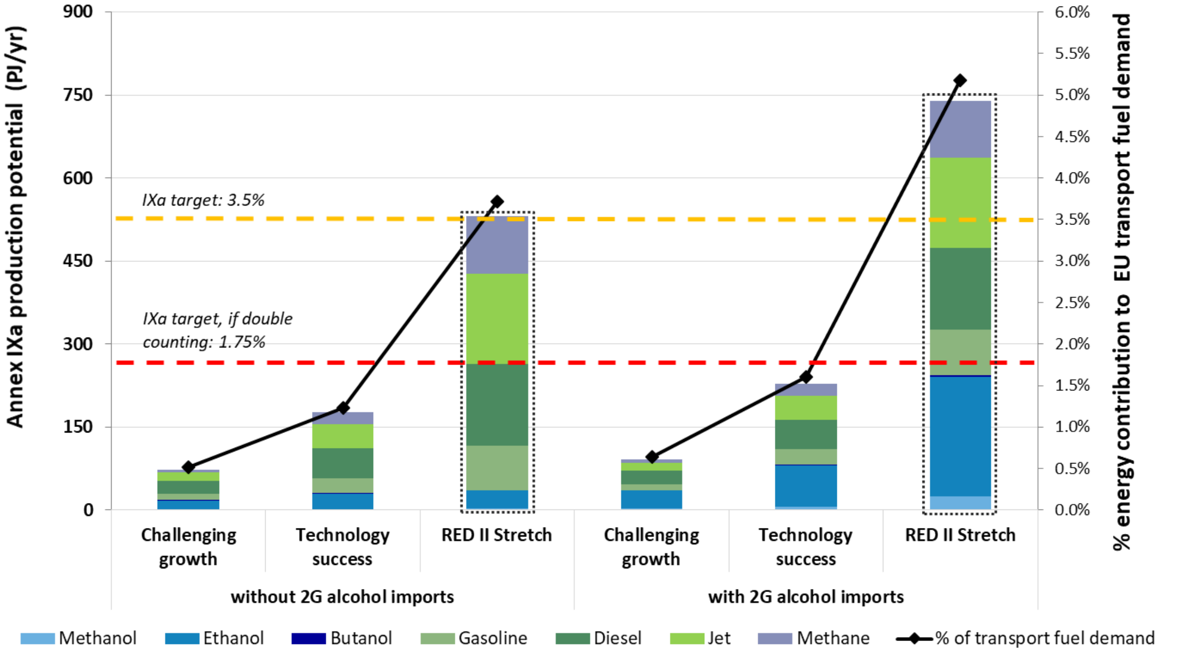

Figure 62 EU Annex IXa biofuel production potential in 2030[178]

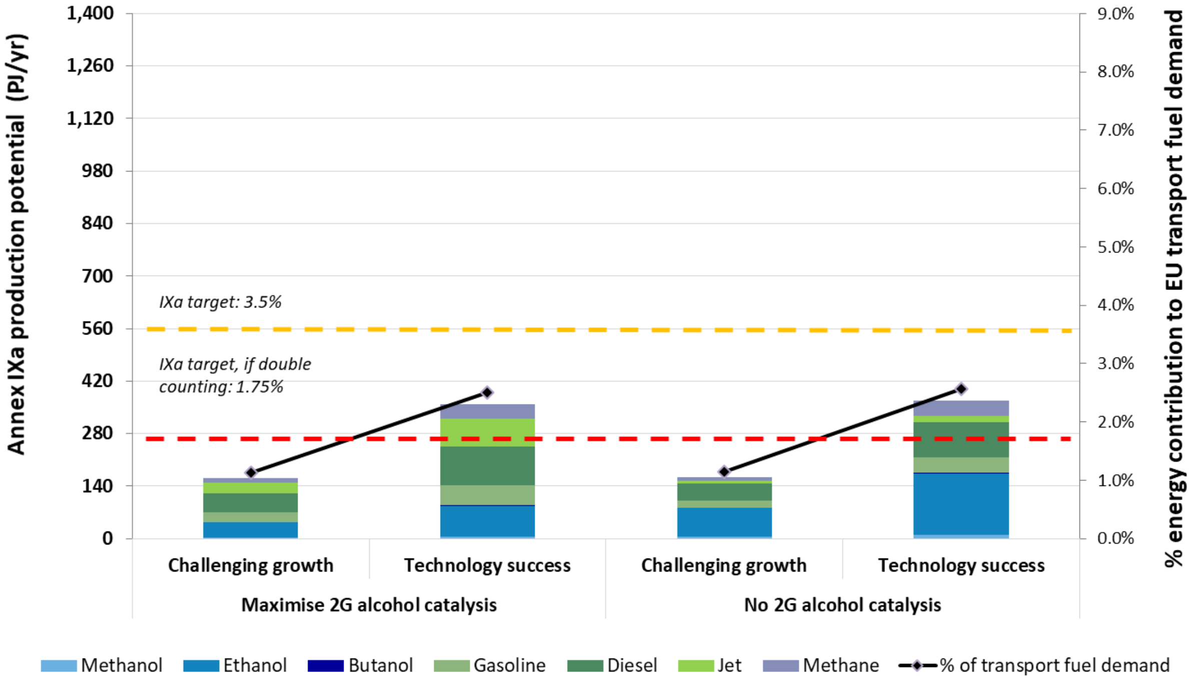

Figure 63 Global ligno-cellulosic biofuel production potential in 2030

Global Annex IXb biofuel capacity is illustrated in Figure 64, considering globally available feedstock. These fuels do not contribute to the 3.5% target for Annex IXa biofuels, and in the REDII the contribution of fuels made from Annex IXb feedstocks towards overall transport fuel targets is capped at 1.7%. Using European feedstock only, the cap is unlikely to be hit, but if substantial use is made of the global waste fats and oils resource then the 1.7% cap will quickly be met. This illustrates

[178] Covering only the ligno-cellulosic, non-food and non-feed biomass as described in section 1.2

that the 1.7% cap will limit the total available global HVO/FAME/co-processing capacity that can be supplied into Europe (Figure 60 and Figure 61).

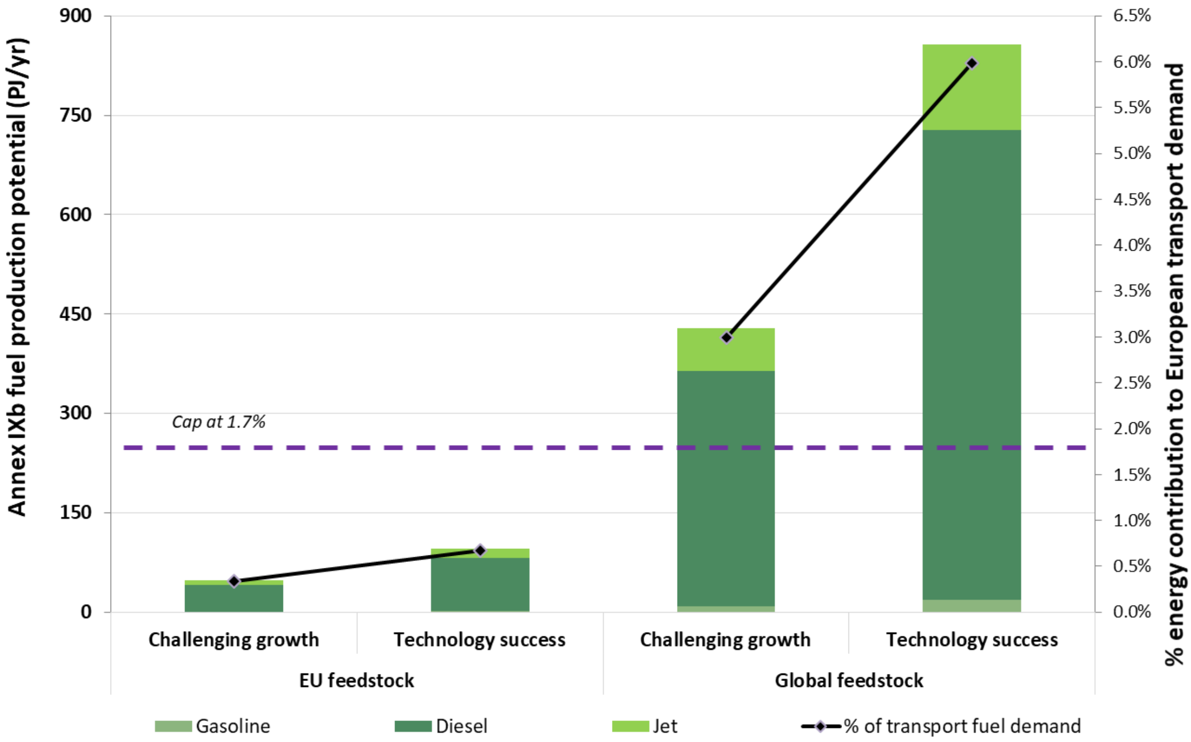

Figure 64 Anticipated EU and Global Annex IXb biofuel production potential in 2030

7.3.4 Comparison with feedstock availability

For the technology-limited routes, which comprise the majority of the advanced biofuel routes considered in this study, the ramp-up is considered to be limited by the number of technology developers and the development and deployment timescale of technology, rather than by the availability of sustainable feedstock. In modelling deployment to 2030, availability of sustainable feedstock was not considered to be a limiting factor. To investigate this further, this section compares the feedstock that would be required under each of the advanced biofuel scenarios presented here with the potential availability.

Based on the conversion efficiency of each of the technology routes from feedstock to fuel, we estimated the amount of feedstock that would be required in 2030 under the two scenarios, in both the EU and the Rest of the World. This was separated out into four broad feedstock categories: agricultural residues, forestry residues, MSW and intermediate alcohols, based on the split of feedstocks currently used by each pathway.

The feedstock potential in the European Union was obtained from Baker et al. (2017)[179], based on the results of the BioBoost project. The figure provided is a 'technical potential' which takes into

[179] Baker, P., Chartier, O., Haffner, R., Heidecke, L., van Hussen, K., Meindert, L., Oberč, B.P., Ryszka, K., Capros, P. de Vita, A., Fragiadakis, K., Fragkos, P., Paroussos, L., Petropoulos, A., Zazias, G. (E3M Lab), Ball, I., Dzene, I., Janssen, R., Michel, J., Rutz, D. (WIP Renewable Energies), Lindner, M., Moiseyev, A., Verkerk, H. (EFI), Witzke, P. (Eurocare), Walker, M. (IUNG), (2017) Research and Innovation perspective of the mid- and long-term Potential for Advanced Biofuels in Europe, D1.4 Forecast of feedstock availability generated from

account the feedstock that is not available to the advanced biofuels industry because it is currently being used for other purposes or which is not available for sustainability reasons. Global feedstock potentials were obtained from IRENA (2014)[180], using their 'low scenario' estimated figures for 2030. These figures also take account of existing uses of the resource, sustainability considerations that limit its extraction, and accessibility of forestry residues. European feedstock availability was subtracted from global figures to provide an estimate for the rest of the World. The availability of 2G alcohols (which are required for the alcohol-to-jet routes) are calculated from the supply model itself.

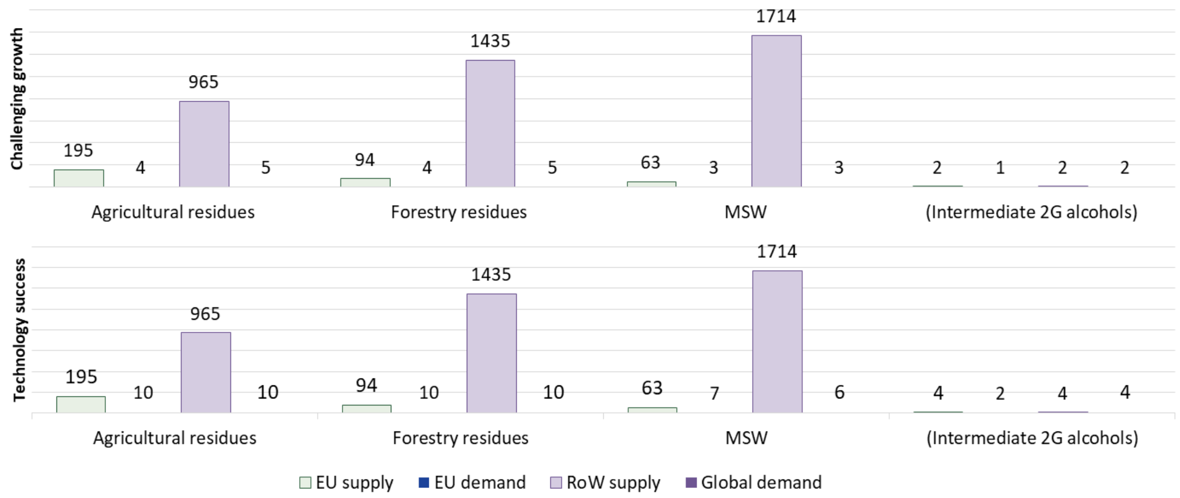

Figure 65 Sustainable feedstock availability and demand from advanced biofuel production, in Modt/year

The EU and Rest of the World biomass potential, and projected demand based on the ramp-up of advanced biofuel technologies is illustrated in Figure 65. Oil-based feedstocks are not included, as the technologies which use these feedstocks are considered to be 'feedstock-constrained' and are assessed in a different way, as discussed in section 7.2.2.

Based on these figures, the sustainable feedstock demands of the advanced biofuel supply scenarios modelled here can be easily supplied at both the EU and global level Under the 'technology success' scenario EU biofuel production would require 8% of available EU agricultural residues, forestry residues and MSW.

It should be noted that this comparison of feedstock supply with 2G biofuel demand makes no assumptions about the same feedstocks being demanded by the power, heating, industry or chemical sectors. All these sectors may increase their demand on biomass waste / residue resources in the future, in a bid to decarbonise, which would limit the feedstock supply to the advanced biofuel sector.

residues/waste, Available from: https://publications.europa.eu/en/publication-detail/-/publication/448fdae2-00bc-11e8-b8f5-01aa75ed71a1/language-en

[180] IRENA (2014) Global Bioenergy Supply and Demand Projections, A working paper for Remap 2030, Available from: http://www.irena.org/-/media/Files/IRENA/Agency/Publication/2014/IRENA_REmap_2030_Biomass_paper_2014.pdf

The breakdown of feedstock availability across the EU (Figure 66) illustrates how the biomass resources are distributed across the EU Member states, with a large availability of agricultural residues in France, Spain, Germany and Bulgaria. Forestry residues are also most available in Germany, France, Finland and Sweden, generally reflecting large existing forestry industries. Location of advanced biofuel plants near to sources of waste or residue feedstocks will contribute to the reduction of cost and GHG emissions of feedstock transportation, therefore the distribution of feedstocks illustrated in Figure 66 provides an indication of the countries where it may be most attractive to locate advanced biofuel plants. Even within a given country, access to feedstock can still be limited by poor infrastructure or very low geographic density of resource, although a full consideration of this is outside the scope of this report.

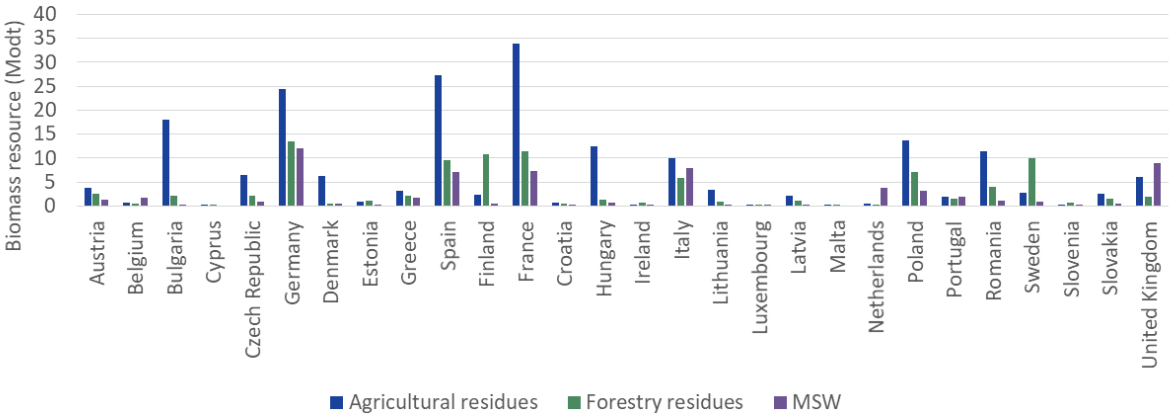

Figure 66 Sustainable feedstock availability across EU Member States (data from Baker et al., 2017)

7.3.5 Costs to 2030

Anticipated production costs of advanced biofuels at commercial scale and at 2030 are given on a mass basis (Figure 67) and on an energy basis (Figure 68). Costs for 2030 are based on reductions from first commercial scale that could be achieved assuming the deployment modelled in the technology success scenario (section 7.3.1.2), with the range for each cost representing the difference caused by alternative plant sizes and configurations.

AD with pre-treatment, BioSNG, and gasification to methanol are the lowest cost advanced biofuel routes, and the only routes of those studied that might be economically viable without subsidy with crude oil prices at $100/bbl. These routes have similar costs to conventional bioethanol and conventional FAME biodiesel in 2030 if deployment reaches the level anticipated in the technology success scenario.

The most expensive routes are currently aerobic fermentation of 2G sugars (due to low yields), and Alcohol to Jet (due to high LC ethanol prices). HTL currently has poor yields, but these could improve significantly, and there are opportunities to upgrade the HTL oil at refineries, which could further reduce costs.

A number of other routes can reach biofuel costs within the €30-40/GJ range, including LC alcohol, gasification + FT, upgraded pyrolysis oil and syngas fermentation. However production costs of €20/GJ must be attained in order to compete with diesel from crude oil at $100/bbl.

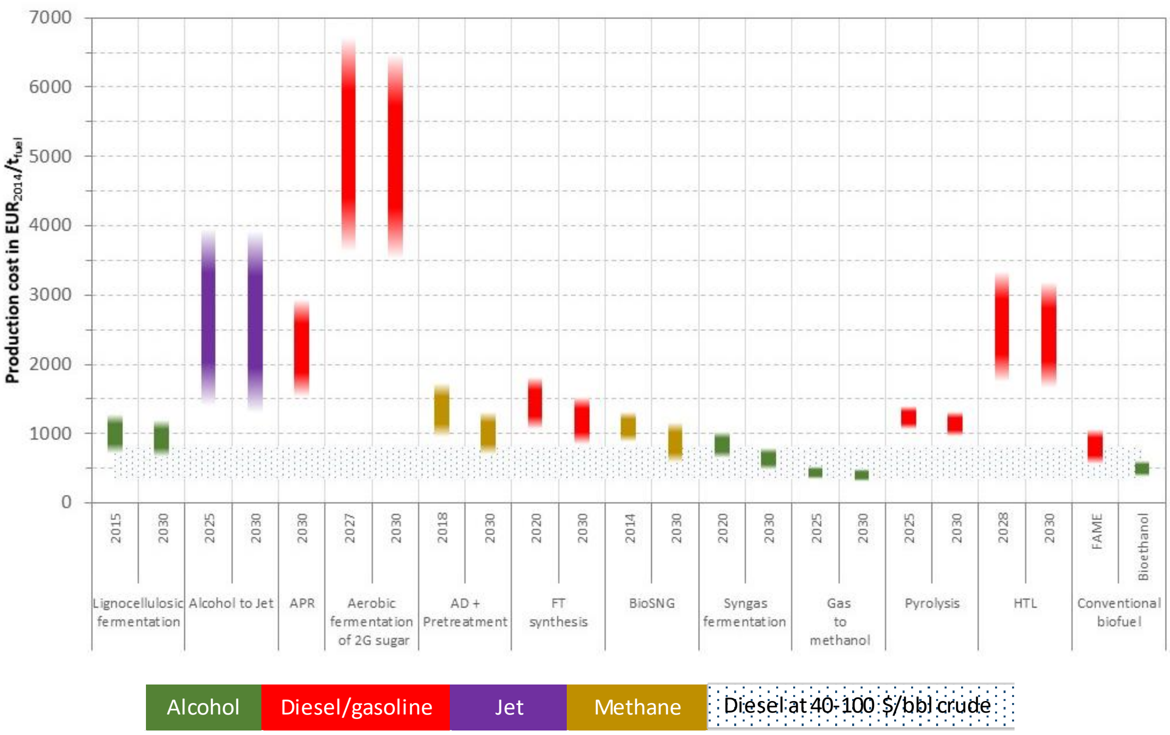

Figure 67 Production costs in EUR_{2014}/t_{fuel}

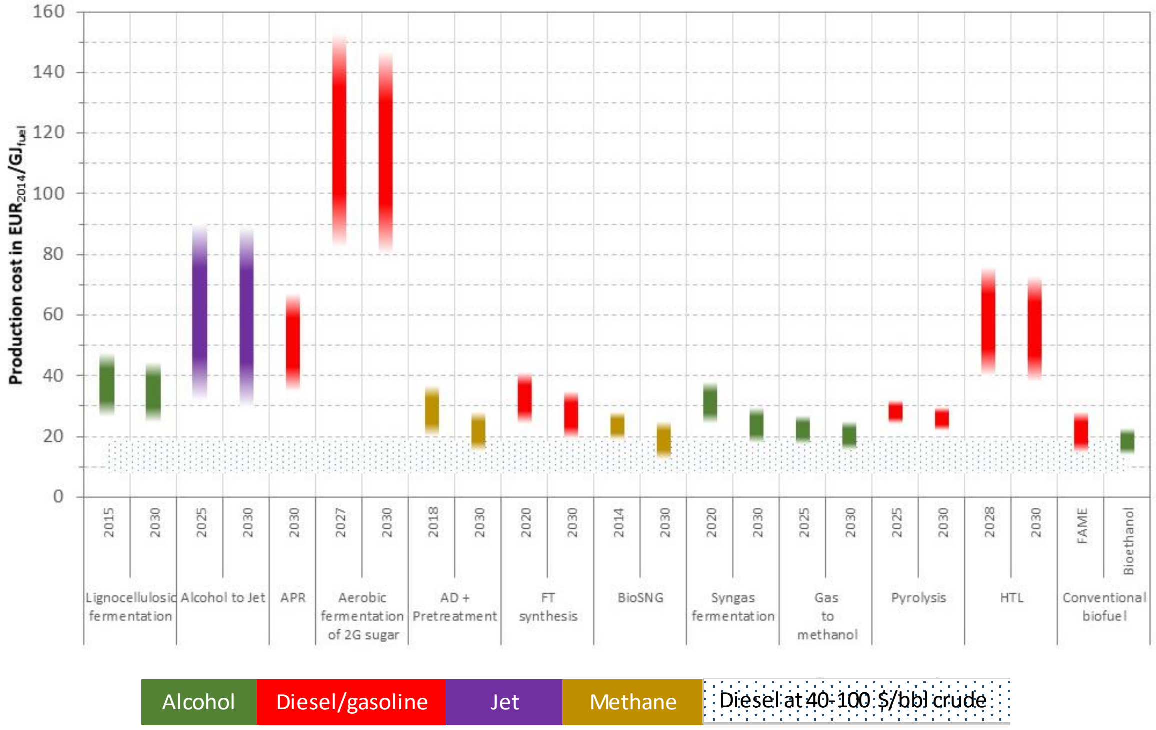

Figure 68 Production costs in EUR_{2014}/GJ_{fuel}

Table 58 Composition of production cost

	Small scale plant			Large scale plant		
	Capital	Feedstock	O&M	Capital	Feedstock	O&M
Ligno-cellulosic fermentation	31%	43%	26%	24%	50%	26%
Alcohol to Jet	42%	38%	21%	6%	89%	5%
Aqueous phase reforming	43%	21%	36%	36%	27%	38%
Aerobic fermentation of 2G sugar	18%	41%	42%	26%	26%	47%
AD + Pretreatment	21%	9%	70%	20%	17%	64%
FT synthesis	49%	34%	17%	35%	48%	16%
BioSNG*	55%	0%	45%	23%	68%	9%
Syngas fermentation	37%	31%	33%	26%	42%	32%
Gasification to methanol	33%	39%	28%	25%	58%	18%
Pyrolysis oil upgrading	34%	37%	29%	13%	48%	39%
Hydrothermal liquefaction	21%	54%	24%	18%	60%	22%

*For BioSNG the range of results represent two different technology types (plasma gasification and allothermal gasification) at same scale, rather than a small-scale and large-scale plant

Table 58 illustrates the breakdown of the overall levelised cost of each technology, with the individual feedstock costs provided in Appendix F, Table 65. In this analysis feedstock cost was assumed to remain constant to 2030, as it is not the scope of this study to look into the wide range of factors which might impact on feedstock cost.

In general, large scale plants have better economies of scale, with capital investment comprising a smaller percentage of the overall levelised cost. At large scale, for most of the technologies, feedstock is the biggest contributor to the overall cost, therefore emphasising the importance of robust supply chains and infrastructure to provide low-cost access to feedstock. In particular for alcohol to jet, the cost of 2G alcohol is a substantial component of the overall fuel production cost. For BioSNG, with two different technology types providing the data range, plasma gasification utilises municipal waste and therefore has zero feedstock cost.

7.4 Recommendations for actions to overcome barriers to advanced biofuel deployment

Based on the market projections to 2030, this section aims to highlight the key actions that would be required to overcome the barriers to the advanced biofuel deployment scenarios modelled. The key barriers, and the actions required to overcome them can broadly be classified into: supply-side challenges, policy barriers, feedstock, infrastructure and consumer perception.

In terms of supply-side barriers, project finance can be a key barrier to the initiation of advanced biofuel plants, and as project initiation rate is one of the key differentiators between the two scenarios modelled, it is clearly an important barrier to overcome. There are many actions available to governments which can overcome barriers in project financing. When the aim is to scale-up technologies, rather than technology development or R&D, the key focus of actions should be that they have a multiplicative effect in terms of bringing in more investment from the private sector. This can be achieved through actions to de-risk the project, including low cost loans or loan guarantees, capital grants, or tax incentives. Technology performance insurance has been used by some developers, and can further help to de-risk the project for investors. Reducing the time and cost for obtaining certification for new fuel types or blends can also support the supply of novel fuels into the market.

The importance of strong policies to overcome demand-side barriers to advanced biofuel deployment is highlighted in Table 56, where the potential impact of many of these policy and regulatory barriers is 'high'. Whilst the USA and EU currently have fairly strong incentives for advanced biofuels through the RFS and the proposed RED II, it is important that these policies are clearly defined, send clear pricing and demand signals, and have a sufficient timeline to provide certainty to investors over several project development cycles. Given that there are many competing uses for a finite biomass resource, it is particularly important that there is a long-term vision from policy-makers on the optimum use of these resources in order to achieve system-wide GHG reductions. Moreover, the aviation and marine sectors, which could provide a significant driver for advanced biofuels, due to the challenges of electrifying boats and planes, are excluded from many existing national low-carbon fuel support schemes. Whilst GHG targets have been agreed at an international level, ICAO or the IMO, policies put in place at EU and national level could stimulate demand for advanced biofuels in these sectors. This could be the inclusion of fuels supplied into the aviation or marine sectors within existing low-carbon fuel support schemes across more MSs, as will occur in January 2019 in the UK. Harmonisation of policies across jurisdictions, for example across EU MSs, reduces complexity and provides a clearer signal to developers.

A key challenge for the industry is securing access to sufficient quantity of sustainable feedstock at a viable price. The biofuels industry needs to engage with biomass suppliers and develop business models that facilitate access to the resource. Collaborative action between government and industry could help to develop supply chain infrastructure and improve the logistics of biomass supply. Advanced biofuel plant owners may have to invest in their feedstock supply chain in order to ensure consistent and reliable access to feedstock, however for small companies developing new technologies such investment increases the challenge of financing projects. Therefore partnership with feedstock suppliers or obtaining secure long-term feedstock supply agreements are also likely to be important. Finally, to ensure sustainability and provide certainty to the industry, there need to be clear rules from governments on what feedstocks will be considered sustainable.

Of the fuels considered in this study, access to refuelling infrastructure is primarily a challenge for natural gas and high-blend alcohols. This is being addressed through the Alternative Fuels Infrastructure Directive (AFID) and the establishment of National Policy Frameworks for the market development of alternative fuels and infrastructure in each Member State. These should support the provision of infrastructure and refuelling stations for alternative fuels, and ensure common specifications across the EU.

Consumer perception of biofuel sustainability and understanding of the different fuel types and blends may become an increasingly important concern as alternative fuel types and higher blends require more engagement with the consumer. Robust sustainability criteria and clear information are therefore important to ensure consumer trust and understanding, and should build on the EU-wide harmonisation of fuel labelling which is being introduced through the AFID

Appendix A – Technology and Commercial Readiness Levels

The Technology Readiness Level (TRL) definitions used within this report are those used by the European Commission[181]:

- TRL 1 – basic principles observed
- TRL 2 – technology concept formulated
- TRL 3 – experimental proof of concept
- TRL 4 – technology validated in lab
- TRL 5 – technology validated in relevant environment (industrially relevant environment in the case of key enabling technologies)
- TRL 6 – technology demonstrated in relevant environment (industrially relevant environment in the case of key enabling technologies)
- TRL 7 – system prototype demonstration in operational environment
- TRL 8 – system complete and qualified
- TRL 9 – actual system proven in operational environment (competitive manufacturing in the case of key enabling technologies; or in space)

The methodology for assessing the commercial / market readiness of a technology is more variable than that for assessing TRL. In this study, Commercial Readiness Levels (CRL) are used, as adapted from ARENA (2014). This scale has also been used by the IEA and provides a useful assessment of progress towards being a mature technology in the energy sector.

- CRL 1 – **Hypothetical commercial proposition**: Technically ready – commercially untested and unproven. Commercial proposition driven by technology advocates with little or no evidence of verifiable technical or financial data to substantiate claims.
- CRL 2 – **Commercial trial: Small scale**, first of a kind project funded by equity and government project support. Commercial proposition backed by evidence of verifiable data typically not in the public domain.
- CRL 3 – **Commercial scale up** occurring driven by specific policy and emerging debt finance. Commercial proposition being driven by technology proponents and market segment participants – publically discoverable data driving emerging interest from finance and regulatory sectors.
- CRL 4 – **Multiple commercial applications** becoming evident locally although still subsidised. Verifiable data on technical and financial performance in the public domain driving interest from variety of debt and equity sources however still requiring government support. Regulatory challenges being addressed in multiple jurisdictions.
- CRL 5 – **Market competition driving widespread deployment** in context of long-term policy settings. Competition emerging across all areas of supply chain with commoditisation of key components and financial products occurring.

[181] https://ec.europa.eu/research/participants/data/ref/h2020/wp/2014_2015/annexes/h2020-wp1415-annex-g-trl_en.pdf

- CRL 6 – "**Bankable" grade asset class** driven by same criteria as other mature energy technologies. Considered as a "Bankable" grade asset class with known standards and performance expectations. Market and technology risks not driving investment decisions. Proponent capability, pricing and other typical market forces driving uptake.

In the following table we note how these two scales overlap:

<table>
<tr><th colspan="2">TRL</th><th colspan="2">CRL</th></tr>
<tr><td>1</td><td>Basic principles observed</td><td colspan="2">N/A</td></tr>
<tr><td>2</td><td>Technology concept formulated</td><td rowspan="6">1</td><td rowspan="6">Hypothetical commercial proposition</td></tr>
<tr><td>3</td><td>Experimental proof of concept</td></tr>
<tr><td>4</td><td>Technology validated in lab</td></tr>
<tr><td>5</td><td>Technology validated in relevant environment</td></tr>
<tr><td>6</td><td>Technology demonstrated in relevant environment</td></tr>
<tr><td>7</td><td>System prototype demonstration in operational environment</td></tr>
<tr><td>8</td><td>System complete and qualified</td><td>2</td><td>Commercial trial, small-scale</td></tr>
<tr><td rowspan="4">9</td><td rowspan="4">Actual system proven in operational environment</td><td>3</td><td>Commercial scale-up</td></tr>
<tr><td>4</td><td>Multiple commercial applications</td></tr>
<tr><td>5</td><td>Market competition driving widespread development</td></tr>
<tr><td>6</td><td>Bankable asset class</td></tr>
</table>

Figure 69 Overlap of TRL and CRL scales

Appendix B – Key assumptions and conversion factors

All data is reported to 2 significant figures.

Appendix C – Methodology for calculating advanced biofuel prices

In order to calculate the EU market share in terms of 'known economic value' for each technology pathway, the known production volume was multiplied by the anticipated wholesale price of the fuel produced.

The wholesale prices used for this analysis are provided in Table 59, and a description of how these were estimated is provided below.

Table 59 Estimated advanced biofuel prices

Biofuel product	Price (€/tonne)
Bioethanol	770
Biomethanol	700
Biobutanol	840
Biogasoline	950
HVO	1000
FAME	970
Biodiesel	1000
Biojet fuel	1200
Biomethane	1500

The underlying value required to calculate a price for advanced biofuels was the wholesale price of crude oil. An average crude oil price over the past 12 months (July 2017 – June 2018) of 61.30 USD/bbl or 400 EUR/tonne[182] was used to estimate the average wholesale price of diesel and gasoline over this period. Similarly, the 12 month average price of EU ethanol T2 Rotterdam and EU FAME were found to be 630 EUR/tonne[183] and 740 EUR/tonne [184]respectively.

To calculate the price of bioethanol from wastes and residues, the price difference between ethanol T2 and gasoline on a volume basis (EUR/gal) was converted to price difference on an energy basis (EUR/GJ). This was multiplied by a factor of two to account for double counting, to give the price premium which biofuels from wastes and residues could expect to receive over fossil gasoline (10EUR/GJ). This price premium was added to the average fossil gasoline price (500EUR/tonne) to give the anticipated sale price of bioethanol, biomethanol, biobutanol and biogasoline produced from wastes and residues. Because of the different energy content and density of these fuels, their price on a mass basis (Table 59) varies slightly.

For HVO and FAME and biodiesel produced from wastes and residues a similar method was employed. For these fuels which are also double-counted in most Member States, the difference in price between single-counted FAME and fossil diesel was multiplied by two, and added to the price

[182] US Energy Information Administration (2018) Crude Oil (petroleum); Dated Brent Daily Price, Available from: https://www.indexmundi.com/commodities/?commodity=crude-oil-brent&months=12
[183] Pennington, C. (2018) EU fuel ethanol prices plummet on market length, EU policy worry. Available from: https://www.icis.com/resources/news/2018/03/29/10207802/eu-fuel-ethanol-prices-plummet-on-market-length-eu-policy-worries/
[184] Neste (2018) Biodiesel Prices (SME & FAME), Available from: https://www.neste.com/corporate-info/investors/market-data/biodiesel-prices-sme-fame-0

of fossil diesel. For biojet, a multiplier of 2.4 was applied, because under the incoming RED II legislation it receives a 1.2 times multiplier, which is then double-counted to get to 2.4. However this policy is not yet in place in member states, so for biojet this is a forward-looking approach. Finally, the price of natural gas and feed-in tariff (FiT) values were used to calculate the price of biomethane. The price of natural gas was averaged over the past 12 months (21EUR/MWh), while the FiT data was taken from the European Biogas Association[185]. The FiT ranged from 8 EUR/MWh in Austria, to 150 EUR/MWh in Italy. Therefore, a minimum, maximum and an average price of biomethane was found by adding the FiT value to the averaged natural gas price.

It should be noted that these values are provided as approximations for the price of biofuels in the EU. The method reflects the treatment of advanced biofuels under the policy of most member states, but not all member states allow double-counting, and moreover eligibility of particular fuels or feedstocks for double-counting can vary.

[185] European Biogas Association (2016). Biomethane in Transport. Available from: http://european-biogas.eu/wp-content/uploads/2016/05/BiomethInTransport.pdf

Appendix D – EU Member State Targets and RED II target, additional information

In 2016, Sweden consumed 1,040 ktoe of biofuels, of which 976 ktoe were advanced, resulting in approximately 25% of total energy in transport being from biofuels. There is currently 230 ktonnes/yr of biofuel capacity in operation Sweden, with an additional 190 ktonnes/yr planned.

For the 2018-2019 period, total fuel use (conventional and renewable) in Germany should achieve a 4% emissions savings compared to a scenario where only fossil energy is used. In 2016, total biofuel consumption was approximately 2,500 ktoe with 600 ktoe from advanced feedstocks. This amounts to approximately 6% of the total energy used in transport coming from biofuels. Comparatively, there is currently 850 ktonnes/yr capacity in operation in Germany, suggesting that Germany is already importing a proportion of their biofuels.

Appendix E – Incentives and support policies for advanced biofuels

The following table provides brief summaries of support policies for advanced biofuels in various countries around the world. Note that the policies listed are policies that either directly support advanced biofuels or would support advanced biofuels over conventional biofuels. The key support policies aimed specifically at advanced biofuels in each region are captured, but it was not the aim of this study to provide an exhaustive list of all possible support mechanisms which could potentially impact advanced biofuels.

Name of the support mechanism	Country	Brief summary (including actors influenced, compliance requirements and total available funding, if applicable)
		North and South America
PAISS Program (Support Program for Industrial Technology Innovation in the Sugarcane and Sucrochemistry Sectors)[i]	Brazil	The aim of this program is to increase the presence of advanced biofuel technologies. Program provides BRL 2 billion in funding for projects developing cellulosic ethanol and chemical products from sugarcane bagasse. The support is offered in the form of a loan. To receive funding, project must fall within three different research areas: (1) second-generation ethanol (2) new products made from sugarcane through biotechnology (3) gasification 57 companies were involved, and 35 business plans were approved. Seven new industrial and demonstration plants are being implemented as a result of this program
PAISS Program (Agriculture)[ii]	Brazil	The aim of this program is to increase the presence of advanced biofuel technologies. Program provides BRL 1.48 billion in funding for the 2014-2018 period to be used for loans (including traditional credit lines) and variable income instruments. There is a further BRL 80million in funding for non-reimbursable resources (of which BRL 40 million will be released through the Technological Fund and the other BRL 40 million through a Finep subsidy). To receive funding, project must fall within three different research areas: (1) second-generation ethanol (2) new products made from sugarcane through biotechnology (3) gasification This program played a role in the development of one pilot and two commercial second generation ethanol plants. These plants have a combined production capacity of 140 million litres.

Name of the support mechanism	Country	Brief summary (including actors influenced, compliance requirements and total available funding, if applicable)
RenovaBio[iii]	Brazil	Created by Law no. 13,576/17, the Renovabio programme sets an emission reduction target of 10% by 2028 for the transport energy sector, which should result in cumulative emission savings of 600 million tonnes of carbon. Modelled after the California Low Carbon Fuel Standard, this programme is fuel agnostic, and rather focuses on the carbon intensity of the fuel. It includes a credit trading mechanism, whereby biofuel producers receive credits (CBios) based on the lifecycle emissions savings of their fuel compared to petrol. CBios are then traded on the financial markets where fuel suppliers purchase them to comply with mandated yearly targets. This programme is seen as a measure required to help Brazil achieve its COP 21 Nationally Defined Contributions. The programme is expected to come into effect in 2019.
Advanced Biofuel Production Payments in Bioenergy Program for Advanced Biofuels (Agricultural Act of 2014 Section 9005)[iv]	United States of America	Producers of advanced biofuels (or fuels derived from renewable biomass excluding corn kernel starch and forestry biomass) are eligible for payments to support expanded production of advanced biofuels. This is support by the Office of Rural Development, Business and Cooperative Programs. This support mechanism is currently funded until 2018, after which it will require congressional support to extend the funding. Eligible advanced biofuels must fulfil the following criteria: - Be considered an advanced biofuel as per the definition in 7 CFR Part 4288.102 - Be liquid, gas or solid - Be a final product - Be produced in the United States - Be a fuel where the buyers and sellers act independently and have no relationship Producers must have also produced advanced biofuels in the year prior to the fiscal year in which the payment is being sought for. Further, the plant cannot be offline for more than 20 days (excl, weekends) in the year prior to the fiscal year in which the payment is being sought for.
Renewable Fuel Standard[v]	United States of America	This national standard mandates the mixing of renewable fuels in petroleum-based fuels by refiners, blenders and importers. The standard sets an overarching target for 2018 of 19.29 billion gallons of renewable fuel. Advanced biofuels have a separate target of 4.29 billion gallons, of which 280 million gallons from cellulosic ethanol and 2.1 billion gallons from biomass-based diesel. The standard also sets a cap of biofuels from conventional feedstocks at 15 billion gallons. Biofuels are classified as advanced not based on their feedstock, but rather on if their lifecycle GHG emissions are at least 50% lower than the lifecycle emissions of fossil fuels. Cellulosic biofuels should reduce emissions by at least 60% and biomass-based diesel by at least 50%. When renewable biofuels are produced, each gallon is given their own RIN number. Compliance can be met by either generating a RIN number (through the direct production of a renewable biofuel) or by

Name of the support mechanism	Country	Brief summary (including actors influenced, compliance requirements and total available funding, if applicable)
		purchasing a RIN number on the market. A supplier with excess RINs can either sell them or keep them for use in the following year.
Biomass Crop Assistance Program[vi]	United States of America	The US Department of Agriculture provides financial assistance to landowners who grow feedstocks to be used in advanced biofuel production facilities. Producers can be eligible for reimbursement of 50% of the cost of establishing the feedstock. They are also eligible for annual payments of up to 5 years for herbaceous feedstocks and 15 years for woody feedstocks. The program also provides matching financial support for the collection, harvest, storage and transportation of the feedstock to the advanced biofuel production facilities. The program is funded through fiscal year 2018, and is subject to congressional appropriations thereafter.
Biorefinery, Renewable Chemical, and Biobased Product Manufacturing Assistance Program[vii]	United States of America	The program subsidizes the development, construction and retrofitting of new and emerging technologies for advanced biofuels, renewable chemicals and biobased products. The support is in the form of loan guarantees with a maximum value of $250 million. Via a lender with legal authority, the following are eligible for this support: - Individuals - Public and private entities - State and local governments - Corporations - Indian tribes - Farm Cooperatives and Farm Cooperative Organizations - Associations of Agricultural Producers - National Laboratories - Institution of Higher Education - Public Power entities The plant must be located in a State. Federal participation in the project through this loan must not exceed 80% of the total eligible project costs. The borrower and other principles in the project must also make a significant cash equity contribution to the project.
Second Generation Biofuel Producer Tax Credit (PTC)[viii]	United States of America	The Internal Revenue Service (IRS) provide a tax incentive of $1.01 per gallon of second-generation biofuel produced and sold and/or used. If the biofuel qualifies for an alcohol fuel tax credit, the tax incentive decreases to $0.46 per gallon of ethanol-based biofuel and $0.41 per gallon of non-ethanol-based biofuel. To be classified as second generation, the

Name of the support mechanism	Country	Brief summary (including actors influenced, compliance requirements and total available funding, if applicable)
		biofuel should be produced from ligno-cellulosic or hemicellulosic matter that is available on a renewable basis (e.g. algae, cyanobacteria or lemma). Further, fuels with an alcohol proof of less than 150, with a water or sediment content above 4% and an ash content above 1% are not considered second generation biofuels. Under current legislation, fuel producers are only eligible for this incentive if they produced second generation biofuel in the United States between 1 January 2009 and 31 December 2017 for use in the United States.
Special Allowance for Second Generation Biofuel Plant Property[ix]	United States of America	The Internal Revenue Service (IRS), through this support mechanism, allows for a 50% special depreciation allowance to recover the cost of the plant property. Under the current law, the property needs to have been purchased between 21 December 2006 and 31 December 2017. The allowance only applies for the first year of the property. Properties placed in 2017 may be eligible to take an additional 50% or 100% special depreciation allowance.
The Biorefinery Assistance Program (Section 9003) Advanced Biofuel Production Grants and Loan Guarantees[x]	United States of America	The Office of Rural Development, Business and Cooperative Programs provide support via loan guarantees for the development, construction and retrofitting commercial-scale biorefineries producing advanced biofuels. The maximum loan guarantee is $250 million, and the maximum grant funding is 50% of project costs. Individuals, state or local governments, farm cooperatives, national laboratories, institutions or higher education and rural electric cooperatives can apply for funding
Defense Production Act (DPA) Title III Advanced Drop-in Biofuels Production Project (ADBPP) Biofuels 2[xi]	United States of America	This programme aims to develop advanced drop-in biofuels for military aviation and marine diesel applications. It is anticipated that one project will receive up to $55 million of match-funding. The funding is open to production sources in the United States and Canada. The feedstock for these fuels must be produced domestically (United States or Canada) and must not be otherwise consumable feedstocks. Further, the production facility must deliver at least 10 million gallons of neat biofuel per year.
Low Carbon Fuel Standard (LCFS)[xii]	California, USA	Administered by the California Air Resources Board, the LCFS is a market-based cap and trade approach to lower GHG emissions from petrol-based transport fuels. The LCFS requires fuel producers to reduce their carbon intensity by 10% by 2020. Based on lifecycle assessments, each fuel is given a carbon intensity. For fuels that have a lower carbon intensity than the target established in that year generate LCFS credits, while fuels with a higher carbon intensity generate LCFS deficits. Producers with credits can sell their excess to producers in deficit. Used Cooking Oil, Technical Corn Oil and Tallow have the greatest emission savings, and therefore generate the most credits that can be sold.
Oregon Clean Fuels Program[xiii]	Oregon, USA	Based on the California Low Carbon Fuel Standard, the Clean Fuels Program sets yearly carbon intensity targets that producers must comply with. There is an overarching target to reduce the carbon intensity of fuels by 10% by 2025 as compared to 2015.

Name of the support mechanism	Country	Brief summary (including actors influenced, compliance requirements and total available funding, if applicable)
Washington State House Bill 2338[xiv]	Washington State	The Bill has just cleared the House Transportation Committee in February 2018. If the bill passes, it would implement a program similar to the California's LCFS at a national scale. It would be administered by the Department of Ecology. It would require producers cut emissions by 10% by 2028, as compared to 2017. The program, if past, would begin in 2020.
Alternative and Renewable Fuel and Vehicle Technology Program (ARFVT) – Community-Scale and Commercial-Scale Advanced Biofuels Production Facilities[xv]	California, USA	The ARFVT are providing USD $37million of grant funding, with maximum reward per project of USD $6million). Eligible biofuels must be either diesel substitutes, gasoline substitutes and biomethane. These fuels must also produce emission savings as compared to corn ethanol or soybean biodiesel. The following types of applicants are eligible: - Businesses - Public agencies - Non-profit organizations - Vehicle and technology entities - Public-private partnerships - Academic institutions Funding is based on proposed production capacity. Need to produce at least 100,000 diesel gallon equivalent per year to receive the minimum funding.
Support for Advanced Biofuel Deployment[xvi]	California to the United States Federal government	The California legislature has formally urged the US Congress and US EPA to amend the US Renewable Fuel Standard to favour non-food crop biofuel feedstocks and promote advanced biofuels.
The North Dakota Industrial Commission's Renewable Energy Program – Advanced Biofuel Incentives[xvii]	North Dakota, USA	Provides grants and other support measures to promote R&D in advanced biofuels.
Biofuel Production Grant Program[xviii]	Minnesota, USA	The Minnesota Department of Agriculture provides grants to advanced biofuel producers. The grants are equivalent to USD $2.1053 per mmBtu for advanced biofuels produced from cellulosic biomass and USD $1.053 for advanced biofuels produced from sugar or starch-based crops. Payments will not be made for biofuels produced after 30 June 2035.

Name of the support mechanism	Country	Brief summary (including actors influenced, compliance requirements and total available funding, if applicable)
		Facilities must obtain 80% of their feedstock in Minnesota, begin production by 30th June 2020 and not have produced more than 23,750 mmBtu of biofuel quarterly before 1 July 2015.
Biomass Research and Development Initiative – Research Projects to Advance Biofuels, Bioenergy, and Biobased Products[xix]	United States	Two selected projects – one at the University of Tennessee and the other at Northwestern University – will receive between $1 million to $2 million each to develop biofuels from cellulosic ethanol and ligno-cellulosic biomass, respectively. If successful, these projects are anticipated to help the Bioenergy Technologies Office achieve their target of $3/gallon for advanced biofuels.
Bioenergy Technology Office's Advanced Algal Systems Program – Algal Biomass Yield, Phase 2[xx]	United States	Over $18 million of funding has been awarded by the Department of Energy to four projects to develop algae-based biofuels. The program's overall aim is to reduce the production costs by improving algae biomass yields. The four projects selected are Global Algae Innovations, Algenol Biotech LLC, MicroBio Engineering Inc., and National Renewable Energy Laboratory – Rewiring Algal Carbon Energetics for Renewables (RACER). The RACER projected was the latest project selected.
BioEnergy Engineering for Products Synthesis[xxi]	United States	This program, with a total funding of up to $28 million, supports projects that are aiming to create efficient conversion processes for biomass and waste derived fuels. In September, 16 projects were selected for this program.
Efficient Carbon Utilization in Algal Systems[xxii]	United States	Seven projects were selected to be part of this $15 million program to improve the carbon utilization and productivity of algae systems.
Process Development for Advanced Biofuels and Biopower[xxiii]	United States	This program supports 10 projects with $22 million. Some of the projects within this program are researching renewable drop-in fuels derived from domestic biomass feedstocks and wastes.
Affordable and Sustainable Energy Crops[xxiv]	United States	This program supports the R&D into non-food dedicated energy crops, which can be used to produce biofuels, bioproducts and biopower. Three projects are being supported with a total funding of up to $15 million.
Department of Energy – Project Definition for Pilot- and Demonstration-Scale Manufacturing of	United States	In December 2016, 6 projects were selected to receive $12.9 million in funding to manufacture advanced or cellulosic biofuels, bioproducts, refinery-compatible intermediates, and/or biopower. The projects selected that will produce advanced biofuels are as follows (one project received funding for a biopower based project): - AVAPCO, LLC – given $3.7 million of funding to develop jet and biodiesel from woody biomass.

Name of the support mechanism	Country	Brief summary (including actors influenced, compliance requirements and total available funding, if applicable)
Biofuels, Bioproducts, and Biopower[xxv]		- LanzaTech, Inc. – given $4 million of funding to produce jet and diesel from industrial waste gases. - Global Algae Innovations – given $1.2 million of funding to improve the productivity of open pond cultivation and energy-efficiency of the algae harvest. - ThermoChem Recovery International, Inc. – given $800,000 of funding to produce biofuels from waste wood and agricultural feedstocks. - Water Environment & Reuse Foundation – given $1.2 million of funding to produce biocrude oil, biogas and fertilizer from sludge arising at a wastewater treatment plant. The biocrude oil can be upgraded to produce transport fuels. The funding from the program cannot exceed 50% of the total cost of the project, requiring projects to at least match funding from other investors.
Advanced Research Projects Agency - MARINERS[xxvi]	United States	The "Macroalgae Research Inspiring Novel Energy Resources" (MARINER) program aims to increase the production of marine biomass in the United States. The project teams are developing technologies to improve the economics to use renewable biomass for energy applications, without needing land, fresh water or synthetic fertilizers. The Advanced Research Projects Agency requested $500 million in funding (in 2016, they received, $291 million). Information detailing how much of this spending went to the MARINERS program was not found.
Advanced Research Projects Agency - TERRA[xxvii]	United States	The "Transportation Energy Resources from Renewable Agriculture" aims to facilitate the production of advanced biofuels crops (e.g. energy sorghum), through the development of remote sensing platforms, data analytics tools, and plant breeding technologies. The program also aims to develop the largest database on the characteristics of the sorghum plant, to allow for further research into agricultural crops by public and private investors. The Advanced Research Projects Agency requested $500 million in funding (in 2016, they received, $291 million). Information detailing how much of this spending went to the MARINERS program was not found.
Clean Fuel Standard[xxviii]	Canada	The Clean Fuel Standard, if passed, will use a carbon intensity target to reduce GHG emissions in transportation, industry and buildings. The overall objective of the regulation is to achieve 30 Mt of emissions reduction by 2030. It would place separate targets for liquid, gaseous and solid fuels. It is expected to incentivise the development of a broad range of low carbon fuels, including advanced biofuels. However, as this is still a developing policy and it does not only apply to transportation fuels, the extent to which it will promote advanced biofuels is unknown. Note that biofuel mandates in Canada exists but have comparatively low blend rates (2% diesel, 5% gasoline), and they do not apply to the Northern provinces of the country (likely related to the colder temperatures).

Name of the support mechanism	Country	Brief summary (including actors influenced, compliance requirements and total available funding, if applicable)
Renewable and Low Carbon Fuel Requirements Regulation (RLCFFR)	British Columbia, Canada	The RLCFFR requires a 10% reduction in carbon intensity of fuel sold in British Columbia (BC). BC became the first Canadian province to regulate the carbon intensity of biofuels. It further mandates volumetric blending mandates – 5% renewable fuels in gasoline and 4% in diesel. However, if the volumetric blending mandates are met, the carbon intensity mandate can be met from fuels such as natural gas, electricity and hydrogen. Therefore, while the carbon intensity target could promote the use of advanced biofuels, it may also compete with other sources.
Greener Diesel Regulation[xxix]	Ontario, Canada	Prescribes the minimum renewable fuel blending requirement in diesel. In 2017, there is a mandated 4% biofuel mixed into diesel and there needs to be an average carbon intensity reduction of 70% relative to conventional, diesel fuel. The volumetric mandate can be decreased based on the carbon intensity of the fuel mixed in, where fuels with lower carbon intensities decrease the volume needed.
Renewable Fuel Standard	Alberta, Canada	This Renewable Fuel Standard mandates biofuel blending in diesel (2%) and petrol (5%). It also mandates an carbon intensity reduction, where supplied fuel must have 25% carbon savings compared to petrol and fuel. Most biofuels meet this target, suggesting that while in theory this could promote advanced biofuel production, it likely will promote the production of conventional biofuels.
		Asia
Subsidies[xxx]	China	*Cellulosic ethanol*: Introduced in 2014, there is a subsidy of RMB 600 per ton ($0.07/litre). It is unclear if this subsidy remained in 2017/2018. Ethanol production subsidies using non-food grain feedstocks will become phased out by 2018.
Tax exemption[xxxi]	China	*Biodiesel tax exemption:* Biodiesel produced from used cooking oil can receive a tax exemption of RMB 0.8/L. *1.5 G and 2G Ethanol (non-grain):* 100% VAT exemption and has no excise tax placed on it. However, this only applies to ethanol produced in China (not imported ethanol).
Implementation plan for expanding biofuel ethanol production and promoting vehicle ethanol use[xxxii]	China	According to a plan released by the National Development and Reform Commission, the National Energy Administration and the Ministry of Finance, by 2020, China will have implemented a nationwide use of ethanol in gasoline. It further plans to target large-scale production of cellulose ethanol and advanced biofuel technologies by 2025. There is an unofficial target to produce 3,801 million litres of cellulosic and non-grain based ethanol by 2020.
National Policy on Biofuels[xxxiii]	India	As part of their strategy, the government aims to promote the commercialisation of second generation ethanol technologies, while also promoting drop-in fuels produced from MSW, industrial wastes, biomass and other feedstocks. The Policy further stipulates that incentives will be put in a place to drive infrastructural growth. Offtake assurances will also be implemented for second generation biofuel producers for periods of 15 years. Generally, the policy offers

Name of the support mechanism	Country	Brief summary (including actors influenced, compliance requirements and total available funding, if applicable)
		potential pathways for support mechanisms. However, these have yet to be implemented as the policy was approved in June 2018.
Programme on Energy from Urban, Industrial and Agricultural Wastes/Residues[xxxiv]	India	This is a $15 billion program, in which non-conventional biofuels produced from crop residue, industrial waste, municipal solid waste or waste gases are being considered.
Advanced biofuel production target[xxxv]	Thailand	Thailand has set mandates for advanced biofuel production at 25 million litres per day by 2022. This compares to daily consumption targets of 9 million litres of ethanol and 6 million litres of biodiesel by 2022.
	European Union	
Renewable Energy Directive – Directive 2009/EC/28 of 23 April 2009 on the promotion of the use of energy from renewable sources and amending subsequently repealing Directives 2001/77/EC and 2003/30/EC[xxxvi]	EU-28	Promotes the use of biofuels from wastes, residues, non-food cellulosic material, and ligno-cellulosic material by allowing their energy content to be double-counted to achieve the transport target. Member States must transpose the directive.
Double counting of advanced biofuels	Austria[xxxvii]	Allowed for biofuels produced from waste or residues from agricultural and forestry production incl. fisheries and aquaculture, residues from processing, cellulosic non-food materials or ligno-cellulosic materials. Feedstock eligibility are decided on a case-by-case basis
Double counting of advanced biofuels	Belgium[xxxviii]	Legislation permits double counting of advanced biofuels. However, feedstocks are approved on a case by case basis. A 2018 law limits double counting to 0.6% and to the feedstocks listed in Annex IX of the iLUC Directive by 2020.
Double counting of advanced biofuels	Croatia[xxxix]	The law allows second generation and waste biofuels to be double counted.

Name of the support mechanism	Country	Brief summary (including actors influenced, compliance requirements and total available funding, if applicable)
Double counting of advanced biofuels	Cyprus[xl]	Biofuels made produced from wastes, residues, non-cellulosic material and ligno-cellulosic material can be double-counted.
Double counting of advanced biofuels	Czech Republic[xli]	There is currently no mechanism allowed for double counting. Once the iLUC Directive is fully transposed, in the Act on Air Protection, double counting will be allowed.
Double counting of advanced biofuels	Denmark[xlii]	Biofuels from the following waste and residue feedstocks are eligible for double-counting: straw, bagasse, husks, bellows, the non-edible part of cornhobs, nutshells, animal manure, raw glycerine, sulphate pitch, animal fat categories 1 and 2. Used cooking oils are not eligible for double counting.
Double counting of advanced biofuels	Estonia[xliii]	Waste and residues from non-food cellulose material and ligno-cellulose can be double-counted. The Minister is responsible for establishing a list of eligible waste and residues.
Double counting of advanced biofuels	Finland[xliv]	Biofuels made from waste or remains or inedible cellulose or lignocellulose are eligible for double-counting.
Double counting of advanced biofuels	France[xlv]	Biofuels produced from the following feedstocks can be double counted: UCOME, animal fats category 1 and 2, marcs and lees, non-food cellulosic material, ligno-cellulosic material. Further, there is a cap on the amount of biofuels that can be double counted – 0.35% of biodiesel and 0.25% of ethanol in energy content.
Double counting of advanced biofuels	Greece[xlvi]	Biofuels made from the following feedstocks are eligible for double counting: used cooking oils, animal fats, animal manure, non-food cellulosic and ligno-cellulosic materials (straw, nutshells etc.), wastes and residues of agriculture, forestry, agriculture.
Double counting of advanced biofuels	Hungary[xlvii]	Biofuels produced from Part A and B Annex IX feedstocks are eligible for double-counting.
Double counting of advanced biofuels	Ireland[xlviii]	Biofuels produced from the following feedstocks are eligible for double counting: wastes, residues, non-food cellulosic material, and ligno-cellulosic material.
Double counting of advanced biofuels	Italy[xlix]	Biofuels produced from wastes, residues, non-food cellulosic material, and ligno-cellulosic material are eligible for double counting. Destinazione Italia Law No. 145 outlines a list of eligible feedstocks. This list was further updated by the Decree of 10 October 2014.
Double counting of advanced biofuels	Luxembourg[l]	Biofuels made from Annex IX (Part A and B feedstocks) can be double counted.
Double counting of	Malta[li]	Biofuels produced from waste, residue, non-food cellulosic and ligno-cellulosic feedstocks are eligible for double counting.

Name of the support mechanism	Country	Brief summary (including actors influenced, compliance requirements and total available funding, if applicable)
advanced biofuels		Waste is defined in line with the Waste Framework Directive 2008/98/EC.
Double counting of advanced biofuels	Netherlands[lii]	Double-counting is allowed. The double counting mechanism will be continue for Annex IX feedstocks until 2021. From January 2019, advanced biofuel producers will need to prove that the feedstock was not produced intentionally for advanced biofuel production in order to be eligible for double counting.
Double counting of advanced biofuels	Poland[liii]	Biofuels produced from feedstocks listed in Annex IX (Part A and B) are eligible for double counting. Double counting is capped at 0.3% for 2018 (before double counting). This cap increases to 0.5% in 2019 and 1.5% in 2020.
Double counting of advanced biofuels	Portugal[liv]	Biofuels produced from waste, residue, non-food cellulosic and ligno-cellulosic feedstocks are eligible for double counting. Waste is defined in line with the European Waste Directive. Ordinance no. 8/2012 of 4 January 2012 defines residues and which feedstocks can be double counted.
Double counting of advanced biofuels	Romania[lv]	Biofuels produced from waste, residue, non-food cellulosic and ligno-cellulosic feedstocks are eligible for double-counting.
Double counting of advanced biofuels	Slovakia[lvi]	UCOME, biofuels from animal fats and cellulosic ethanol are eligible for double counting.
Double counting of advanced biofuels	Spain[lvii]	Double counting has been approved by the Royal Decree 235/2018, which includes a list of eligible feedstocks. However, double counting is not currently operating as the Spanish Competition Authority has not determined the procedures for the double counting mechanism.
Double counting of advanced biofuels	United Kingdom[lviii]	Biofuels produced from eligible wastes and residues can be double counted. The RTFO determine the eligible feedstock and the list can be found in Tables 2-4 of the RTFO Guidance Note (2018).
iLUC Directive (EU) 2015/1513[lix]	EU-28	The overall goal of the directive is to limit the global land conversion of biofuels. It sets an indicative target, of 0.5% of total transport energy, for advanced biofuels, which countries can opt to implement. The directive also caps conventional biofuels at 7%, which indirectly creates an incentive for greater advanced biofuel uptake. Annex IX introduces a list of feedstocks that are eligible for double-counting. Member States must transpose the directive
Advanced biofuel target	Austria[lx]	Target of 0.5% of total transport energy beginning in 2020
Advanced biofuel target	Belgium[lxi]	Target of 0.1% of total transport energy beginning in 2020
Advanced biofuel target	Bulgaria[lxii]	Starting in September 2018, there is a target of 1% (by volume) of transport fuel must come from advanced biodiesels.
Advanced biofuel target	Croatia[lxiii]	Blending mandate of 0.1% for second generation biofuels, which may increase in 2019 depending on available supplies.

Name of the support mechanism	Country	Brief summary (including actors influenced, compliance requirements and total available funding, if applicable)
Advanced biofuel target	Czech Republic[lxiv]	Target of 0.5% of transport energy from advanced biofuels in 2020.
Advanced biofuel target	Denmark[lxv]	Target of 0.9% of transport energy from advanced biofuels beginning in 2020.
Advanced biofuel target	Estonia[lxvi]	Diesel fuel must have at least 0.5% advanced biofuel beginning in 2019.
Advanced biofuel target	Finland[lxvii]	Target of 0.5% of transport energy must be met by 2020 from advanced biofuels made from Part A of Annex IX feedstocks or other eligible feedstocks as determined by the Energy Agency.
Advanced biofuel target	France[lxviii]	Target of 1.6% for gasoline fuel and 1% for diesel fuel must come from advanced biofuels. By 2023, these targets increase to 3.4% for gasoline fuel and 2.3% for diesel fuel.
Advanced biofuel target	Greece[lxix]	Proposed target of 0.2%.
Advanced biofuel target	Ireland[lxx]	In April 2017, Ireland set an advanced biofuel target of 0.25% of transport energy in 2020.
Advanced biofuel target	Italy[lxxi]	Target of 0.6% of transport energy. This target is further sub-divided in that 75% of the advanced obligation should come from biomethane and 25% from other advanced biofuels. These splits can change based on availability and economic activities. Subsequent targets have been set for 2020 (0.9%) and 2022 (1.85%). A fuel supplier that does not fulfil the obligation will be liable to pay EUR 750 for every 10 gigacalories missing.
Advanced biofuel target	Lithuania[lxxii]	Target is set at 0.5% in 2020.
Advanced biofuel target	Luxembourg[lxxiii]	Advanced biofuels should account for at least 5.5% of fuel based on calorific value, and at least 15% once they have been double counted.
Advanced biofuel target	Malta[lxxiv]	Target is set at 0.5% in 2020.
Advanced biofuel target	Netherlands[lxxv]	Target is set at 0.6% for 2018 for biofuels produced from Annex IX Part A. Subsequent targets are set for 2019 (0.8%) and 2020 (1%). These targets include the effect of double counting.
Advanced biofuel target	Poland[lxxvi]	Target is set at 0.1% for biofuels produced from Annex IX Part A feedstocks beginning in 2020.
Advanced biofuel target	Slovakia[lxxvii]	Target is set at 0.1% beginning in 2019. Subsequent targets are set for 2020-2024 (0.5%) and 2025-2030 (0.75%).
Advanced biofuel target	Slovenia[lxxviii]	Target is set at 0.5% in 2020.
Advanced biofuel target	Spain[lxxix]	Target is set at 0.1% beginning in 2020.
Crop Caps as defined by the iLUC Directive[lxxx]	(see list in Brief Summary)	The following countries have implemented a 7% cap on biofuels from conventional feedstocks[lxxxi]: - Austria - Belgium

Name of the support mechanism	Country	Brief summary (including actors influenced, compliance requirements and total available funding, if applicable)
		- Bulgaria - Croatia[lxxxii] - Denmark - Estonia - Finland - France - Greece - Hungary[lxxxiii] - Ireland - Italy[lxxxiv] - Latvia (included in a draft law that has yet to be approved) - Lithuania[lxxxv] - Malta - Poland - Slovakia - Slovenia[lxxxvi] - Spain - Sweden
Crop cap	Germany	Crop-based biofuels are capped at 6.5% energy content.
Crop Cap	Netherlands [lxxxvii]	Crop-based biofuels are capped at 3% in 2018, 4$ in 2019 and 5% in 2020.
Crop Cap	United Kingdom[lxxxviii]	Crop-based biofuels are capped at 4% in 2018. From 2021, the cap will be reduced progressively to achieve 3% by 2026 and 2% in 2032.
Directive of the European Parliament and of the Council on the promotion of the use of energy from	EU-28	The directive promotes the use of advanced biofuels in transport by setting mandatory targets. Biofuels and biogases produced from feedstocks listed in Part A Annex IX must contribute at least 0.2% by 2022, 1% by 2025 and 3.5% by 2030 of the total share of energy in transport. The double counting mechanism is maintained for Part A and B Annex IX feedstocks. Only feedstocks from Part A of Annex IX can contribute towards the advanced biofuel target. However, all

Name of the support mechanism	Country	Brief summary (including actors influenced, compliance requirements and total available funding, if applicable)
renewable resources (recast)[lxxxix]		feedstocks in Annex IX can be double counted. Member States will transpose the directive
New Entrants' Reserve 300 (NER300)[xc]	EU-28	The money raised from the sale of 300 million emission allowances from the NER is used to fund projects. There have been several advanced biofuel projects funded in this manner. Funds are being distributed through the InnovFin Energy Demo Projects instrument. In 2014, EUR 1 billion was awarded to 19 projects. A project in Denmark was awarded EUR 39.3 million for a commercial-scale production of second-generation ethanol from plant dry matter. In Spain, the W2B project received EUR 29.2 million to convert municipal solid waste to bio-ethanol.
Horizon 2020 – Societal Challenge 2: Food security, sustainable agriculture and forestry, marine, maritime and inland water research and the bioeconomy[xci]	EU-28	With a budget of EUR 3.85 billion for the 2014-2020 period, this support mechanism funds bio-based industries public-private partnership. It focuses more specifically on developing bio-refining technologies to convert waste and residues into bio-based products, materials and fuels. Currently there are 19 funded advanced biofuel projects under the Horizon 2020 program.
Horizon 2020 – Societal Challenge 3: Secure, clean and efficient energy[xcii]	EU-28	With a budget of EUR 5.93 billion for the 2014-2020 period, this support mechanism funds several calls related to advanced biofuels. Currently there are 19 funded advanced biofuel projects under the Horizon 2020 program.
Act 1994/1472 on liquid fuels excise duty[xciii]	Finland	Advanced biofuels do not have to pay the carbon aspect of the excise tax.
Thirty-eighth Ordinance on the Implementation of the Federal Pollution Control Act[xciv]	Germany	This is the ordinance that lays down provisions on the reduction of GHGs in the case of fuels. Within the ordinance, there is a provision requiring a minimum proportion of advanced fuels should be placed on the market by an obligated party. The minimum share is 0.05% from 2020 onwards for companies that supplied more than 20 PJ of fuel in the previous year. This increases to 0.1% from 2021 onwards for suppliers who supplied more than 10 PJ in the previous year. It increases further in 2023 to 0.2% for suppliers who supplied more than 2 PJ in the previous year. And finally it increases to 0.5% by 2025.
State Aid: Support scheme for the production and distribution of advanced	Italy	The scheme, approved by the EU, aims to support the production of advanced biofuels and advanced biomethane. It has an indicative budget of EUR 4.7million. It will run between 2018 and 2022. Producers of advanced biofuels and biomethane receive a premium to compensate for the higher costs, allowing them to be more competitive with fossil

Name of the support mechanism	Country	Brief summary (including actors influenced, compliance requirements and total available funding, if applicable)
biofuels, incl. advanced biomethane[xcv]		fuels in the transport sector. The premium amount will be updated yearly to reflect production costs, ensuring producers are not overcompensated. The scheme is financed by transport fuel retailers, who by law must blend advanced biofuels into their transport fuels.
The Law of 3 February 2004 on the excise of mineral oil, as amended[xcvi]	Slovakia	A tax incentive has been introduced, which would allow for EUR 40/1000L to be claimed by producers who in 2020 mix in their petrol a minimum of 0.5% of advanced biofuels. The requirement for the tax incentive increases to 1% in 2021 and 1.5% in 2022. For diesel producers, the tax incentive is set at EUR 26/1000L when at least 0.5% advanced biofuels are mixed in by 2020. This increases to 1% in 2021.
Renewable Transport Fuel Obligation - Development fuels[xcvii]	United Kingdom	Rather than setting an advanced biofuel target based off Annex IX Part A feedstocks, the RTFO have decided to incentivize development fuels, which are renewable fuels produced from sustainable wastes and residues of non-biological origin. To quality for double rewards (i.e. two renewable transport fuel credits), the feedstock must comply with the waste hierarchy requirements. A target is set for 2019 at 0.1% of development fuels mixed into transport fuels and rises to 3.1% by 2032. Suppliers that do not meet this target are liable to pay a penalty.
Advanced Biofuels Demonstration Competition[xcviii]	United Kingdom	Launched by the DfT, this £25 million competition aims to support the development of an advanced biofuel industry. Three projects won the competition in 2015, and the funding is being used to build three demonstration-scale advanced biofuel plants in Swindon, Tees Valley and Grangemouth. Projects must match fund the grants provided by the competition.
Fuels for Flight and Freight Competition[xcix]	United Kingdom	Launched by the Department for Transport, this £22 million match-funding grant competition aims to promote the development of low carbon, advanced fuels for flight and freight. This competition is currently ongoing and matches amendments made to the RTFO to include development fuels. The competition will provide up to £20million in capital grant funding to (various) developer(s) of advanced biofuels and up to £2million in project development funding.

Appendix F - Methodology for assessment of market outlook to 2030

More detail is provided in this Appendix on the methodology that was used to model the likely supply of advanced biofuel to 2030, as summarised in section 7.2.

Technology-limited routes

Project timelines

The development timeline defines how long it would take from project inception to a fully operational plant. This includes Project development & financing (PD), Construction (CO), Commissioning & ramp up (CM) phases. For each technology type (biological, thermochemical and chemical) and for each stage of plant scale-up (pilot, demonstration, 1st commercial, 2nd commercial and Nth commercial) an average development timeline is applied, as illustrated in Figure 70.

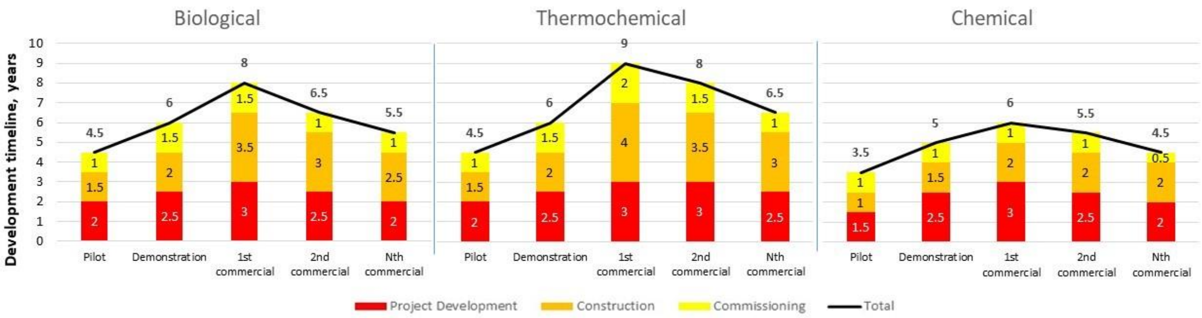

Figure 70 Illustrative development timeline assumptions

Small pilot and demo plants are relatively quick to design, built and commission, whereas 1st commercial plants typically take the longest number of years. 2nd and subsequent (Nth) commercial plants were assumed to be quicker, due to developer learning and replication of technical plans, contracts etc.

Thermochemical routes (those using gasification, pyrolysis, APR, HTL) are the most capital intensive, and will typically have longer timelines. Chemical routes (2G alcohol catalysis) are the least capital intensive with shorter timelines. Biological routes (LC fermentation, aerobic fermentation) generally lie somewhere in between.

Lifetime of plants

The following assumptions were made concerning plant lifetimes:

- Pilot plant = 3 years
- Demonstration plant = 5 years
- Commercial plant = 25 years

By taking this approach, any pilot and demo plants built early in the time period do not contribute to the total production capacities at the end of the period. The short lifetime of pilot and demonstration plants reflects the fact that they are often loss-making facilities, and generally developers choose to operate these plants for only long enough to gain valuable test data and experience, in order to finance future plants. Given the pilot and demo capacities are very small compared to the commercial facilities, then choosing longer or shorter lifetimes has limited impact on the ramp-up results.

Generic plant output

The 1st commercial and 2nd commercial plant sizes were based on the size of plants already constructed or planned by companies. For Nth commercial plants, it was assumed that each technology route converged to using an average output fuel capacity per year figure for all the Nth commercial plants within that route.

The assumptions around the capacity of Nth commercial plants are provided in Table 60. These are not assumed to vary by scenario, given the economically viable plant scales are not particularly dependent on the wider industry development – rather they depend on capital costs, operating costs and efficiencies, trading off against feedstock prices and local availability near plants (or imports). Within the 12 year time period, there will not be multiple rounds of Nth commercial plants built, so these assumptions will apply to all modelled Nth commercial plants.

Table 60: Nameplate capacities of commercial plants

Conversion pathway	kt/yr	PJ/yr
Enzymatic hydrolysis and fermentation	67	1.8
2G alcohol catalysis (ETD, ATJ, MTG)	143	6.3
APR of 2G sugars with catalytic upgrading	103	4.5
Aerobic fermentation of 2G sugars	43	1.9
AD with pre-treatment	10	0.5
Gasification with Fischer-Tropsch	88	3.9
Gasification with methanation	60	2.8
Gasification with syngas fermentation	110	2.9
Gasification with catalytic synthesis	237	4.7
Fast pyrolysis with catalytic upgrading	65	2.9
HTL with catalytic upgrading	56	2.5

Availability of plants

All plants across all pathways were assumed to run at 90% utilisation once successfully constructed and commissioned, so actual annual fuel production is slightly below the nameplate capacities.

Number of developers

The number of developers is a key determinant of future deployment of that technology, as each developer is expected to take their technology to commercial scale (subject to any failure rates), and start initiating new commercial projects (either under an owner operator or licensing model).

Table 61 outlines the number of technology developers in each conversion pathway, based on the data collected during Tasks 1-3. These were not assumed to vary by scenario or over time, as this number is an actual, current number of developers within each pathway. This continues the database working principle that only includes developers which have at least a pilot plant. Lab-scale facilities – often in research institute - are excluded.

Table 61: Number of technology developers

Conversion pathway	
Enzymatic hydrolysis and fermentation	24
Alcohol catalysis (ETD, ATJ, MTG)	5
APR + catalytic upgrading	1
Aerobic fermentation	2
AD + pre-treatment	10
Gasification + Fischer-Tropsch	4
Gasification + methanation	4
Gasification + syngas fermentation	3
Gasification + catalytic synthesis	5
Fast pyrolysis + catalytic upgrading	10
HTL + catalytic upgrading	7

Three scenarios

Given the large degree of uncertainty in many of these factors, it is appropriate to use different assumptions, grouped under three different scenarios. These scenarios were designed to reflect a pessimistic and optimistic view for advanced biofuels, with an additional scenario to simulate how RED II target can be met. Not all factors will vary on scenario, as they are in reality quite fixed and won't change based on developer inputs. However, factors such as initiation rate, launch points, failure rate, and location of deployment could varies depending on scenarios, reflecting the pessimistic to optimistic views that conjugate wider political and economic environment that cannot be predicted.

Initiation rate

The initiation rate is the number of N^{th} commercial projects that start construction per year (globally), per developer. The main drivers underpinning the initiation rate are the attractiveness of licensing the technology, which depends on economics, constraints (such as feedstocks), and the capacity of each N^{th} commercial plant (investment quanta).

In general if plant capacities (and hence investment required) are high for a particular technology then initiation rate is low, whereas for plants at smaller scale such as AD + pre-treatment initiation rates can be much higher. The initiation rates assumed are summarised in Table 62.

Table 62: Number of Nth commercial projects started each year, by each developer

Conversion pathway	Challenging Growth	Technology Success	RED II Stretch
Enzymatic hydrolysis and fermentation	1	2	3
2G alcohol catalysis (ETD, ATJ, MTG)	1	2	**5**
APR of 2G sugars with catalytic upgrading	1	2	3
Aerobic fermentation of 2G sugars	1	2	3
AD with pre-treatment	5	10	25
Gasification with Fischer-Tropsch	1	2	3
Gasification with methanation	1	2	3
Gasification with syngas fermentation	1	2	**5**

Conversion pathway	Challenging Growth	Technology Success	RED II Stretch
Gasification with catalytic synthesis	1	2	3
Fast pyrolysis with catalytic upgrading	1	2	3
HTL with catalytic upgrading	1	2	3

Launch-points

The launch points define when the next technology stage (project) is most likely to start. These were assumed to vary according to the technology stage, and between scenarios, but not vary significantly between technologies, reflecting the fact that investors are likely to require a similar number of years of operational evidence before taking larger investment decisions, independent of the specific technology.

Table 63: Launch point assumptions for each technology stage

Stage	Rules	Challenging Growth	Technology Success	RED II Stretch
Pilot	Only actual or announced pilot plants will be featured			
Demo	Any actual or announced demo projects will be featured If no plans, demo project development assumed to begin **# (see right)** years after the start of pilot operations	1	0.5	0
1st commercial	Any actual or announced projects will be featured If no plans, 1st commercial plant construction assumed to begin **# (see right)** years after the start of demonstration operations. Investors often require ~10,000hrs of operational data before investing in a 1st commercial plant	3	2	1
2nd commercial	Any actual or announced projects will be featured If no plans, 2nd commercial plant construction assumed to begin **# (see right)** years after the start of 1st commercial plant operations	3	2	1
Nth commercial	Nth commercial construction begins **# (see right)** years after the start of 2nd commercial plant construction. Several plants can be initiated simultaneously (see initiation rate slide), with the same number of new plants initiated the next year, and the next year, etc.	2	1.5	1

Success rate

Projects and developers may not be successful, so a % success rate was used to define the expectation of any particular project being successful from inception to operation. In the 'RED II stretch' scenario all plants were assumed to be successful with a 100% success rate, with lower rates in the medium and the challenging growth scenarios (Figure 71 and Figure 72).

		Compounded success rate if a developer already has an operating plant at X technology stage today				
Future technology stage	Individual plant success rate	Pilot	Demo	1st com	2nd com	Nth com
Pilot	50%	100%	100%	100%	100%	100%
Demonstration	60%	60%	100%	100%	100%	100%
1st commercial	70%	42%	70%	100%	100%	100%
2nd commercial	80%	34%	56%	80%	100%	100%
Nth commercial	90%	30%	50%	72%	90%	100%

Figure 71 Success rate assumptions by technology state, in a challenging growth scenario

		Compounded success rate if a developer already has an operating plant at X technology stage today				
Future technology stage	Individual plant success rate	Pilot	Demo	1st com	2nd com	Nth com
Pilot	75%	100%	100%	100%	100%	100%
Demonstration	80%	80%	100%	100%	100%	100%
1st commercial	85%	68%	85%	100%	100%	100%
2nd commercial	90%	61%	77%	90%	100%	100%
Nth commercial	95%	58%	73%	86%	95%	100%

Figure 72 Success rate assumptions by technology state, in a Technology success scenario

The compounded success rates on the right-hand side of the tables reflect that if a developer currently has e.g. an operating demo plant, then the likelihood of success of a future 2nd commercial plant also depends on the success of an intermediate 1st commercial plant. These compounded success rate %s were used to calculate the likely average fuel production by multiplication by the individual plant production outputs.

Location of deployment

For this study the deployment of advanced biofuels in the EU and the rest of the world was modelled. For plant which are already under construction or planned, their existing known location was used. It was assumed that pilot, demonstration and first commercial plants would be located in the same country as existing plants developed by that particular company. For future plants, technology deployment is not likely to be limited to the country of origin of the company, therefore from the second commercial plant onwards the plants were assumed to have a 50:50 split between Europe and RoW.

Validation of input assumptions and results

The key input assumptions and preliminary modelling results were shared and discussed with a sub-set of the technology development companies included in the Task 2 database. This ensured the assumptions were considered reasonable by the industry players.

Feedstock-limited routes

The ability to increase production of FAME, HVO or co-processed fuel to 2030 is likely to be limited by the availability of sustainable waste feedstock, and not by technology development. Current waste feedstock availability of 28,100 ktonnes/annum (EU and RoW) and 42,333ktonnes/annum in 2030[186] was assumed to increase linearly, therefore limiting the amount of transport fuel that could be produced via these routes. Global production volume is estimated assuming a 92% conversion factor regardless of conversion pathway. Using this feedstock method, production in specific location (Europe or RoW) will not be meaningful as feedstock import could significantly alter actual production volume – as is the case currently. Hence, biofuel supply projection and impact are only discussed in global context without considering regional specificity.

The challenging growth scenario assumes 25% of potential waste grease supply is being used for biofuels and technology success scenario assumes 50%.

Future production cost

The cost of advanced biofuel technologies is assessed based on their anticipated first commercial plant costs, collected from literature review. If the first commercial plant is anticipated before 2030 then a 2030 cost is also estimated, based on a learning rate approach. All of the technologies' production cost is referenced from IRENA[187], with the exception of 2G alcohol catalysis[188], aerobic fermentation of 2G sugar[189], AD + Pretreatment[190], BioSNG[191], Gasification to Methanol[192], and HTL[193].

Future specific capital investment is projected on the basis of a learning rate model, with average learning rates from literature specific to each pathway. The learning rate represents the cost reduction while doubling installed capacity (e.g. a learning rate of 0.92 is equivalent to 8 % cost reduction when installed capacity is doubled). The equation used is shown below

$$i_n = i_0 \left(\frac{P_n}{P_0}\right)^{\frac{\log(LR)}{\log(2)}}$$

- i_n: specific capital investment for plant at 2030

[186] LMC International (2017), Global Waste Grease Supply. Available from: http://biodiesel.org/docs/default-source/policy--federal/nbb-rfs-2018-19-comments-attachment-1.pdf?sfvrsn=2
[187] IRENA (2016), Innovation outlook advanced liquid biofuels
[188] NREL (2016), Review of Biojet Fuel Conversion Technologies
[189] de Jong et. al. (2015), The feasibility of short-term production strategies for renewable jet fuels – a comprehensive techno-economic comparison
[190] E4tech analysis
[191] E4tech analysis
[192] Sub Group on Advanced Biofuels – Sustainable Transport Forum (2017), Final Report Building Up the Future
[193] de Jong et. al. (2015)

- i_0: current specific capital investment from literature review
- P_n: expected total production volume at 2030 for middle scenario
- P_0: expected total production volume when 1st commercial plant is online
- LR: learning rate (Table 64)

For the other components of production cost: operational and maintenance costs are calculated as a percentage of capital costs, which will decrease alongside capital investment; no conversion efficiency improvement is modelled here, hence levelised feedstock costs will remain the same from 1st to Nth commercial plant for the same size of plant.

Table 64 Learning rate for different technology pathways

	Learning rate	Year of first commercial plant	Conversion efficiency, $MJ_{feedstock}/MJ_{fuel}$
Ligno-cellulosic fermentation	0.97	2013	0.45
Alcohol to Jet	0.93	2025	0.91
Aqueous phase reforming	0.92	2030	0.42
Aerobic fermentation of 2G sugar	0.92	2027	0.34
AD + Pretreatment	0.92	2018	0.56
FT synthesis	0.92	2019	0.44
BioSNG	0.92	2014	0.63
Syngas fermentation	0.92	2020	0.47
Gasification to methanol	0.92	2025	0.47
Pyrolysis oil upgrading	0.92	2025	0.59
Hydrothermal liquefaction	0.92	2028	0.64

The feedstock cost assumed for each technology is given in Table 65.

Table 65 Levelised feedstock cost, EUR_{2014}/GJ

Ligno-cellulosic fermentation	13 – 20
Alcohol to Jet	28 – 34
Aqueous phase reforming	9 – 14
Aerobic fermentation of 2G sugar	22 – 62
AD + Pretreatment	3.3 - 3.5
FT synthesis	12 – 14
BioSNG	19 – 0
Syngas fermentation	10 – 12
Gasification to methanol	10 – 11
Pyrolysis oil upgrading	12 – 12
Hydrothermal liquefaction	46 – 22

Appendix G – Advanced biofuel deployment to 2030 on an energy basis

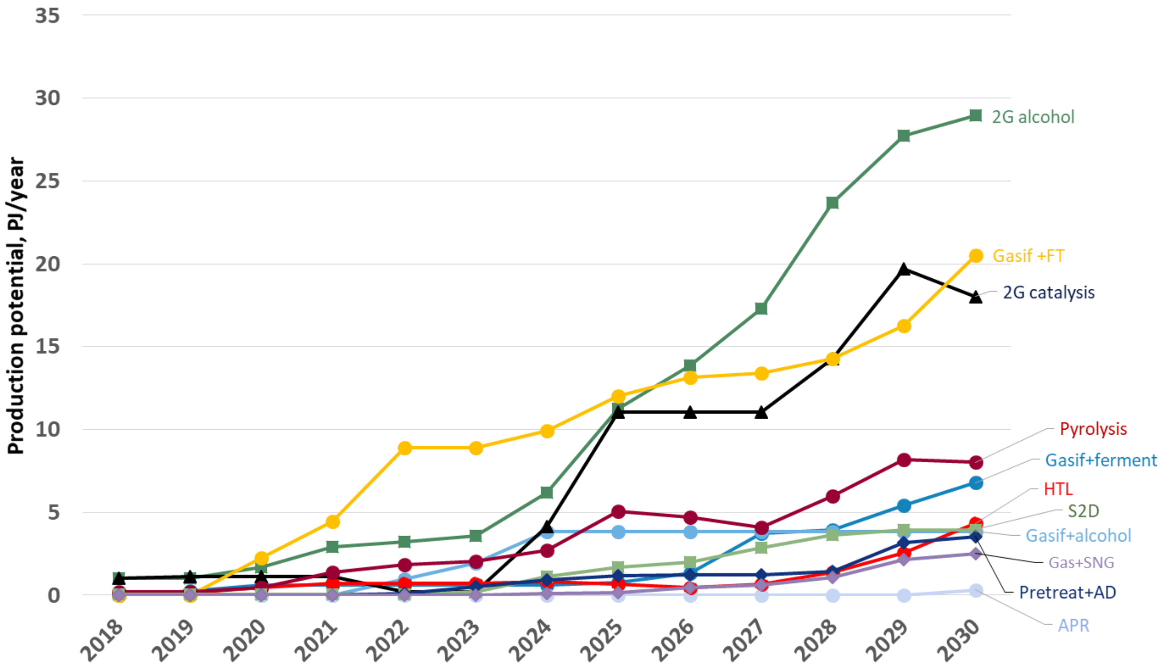

Figure 73 Anticipated EU production potential to 2030 under the challenging growth scenario, in PJ/year

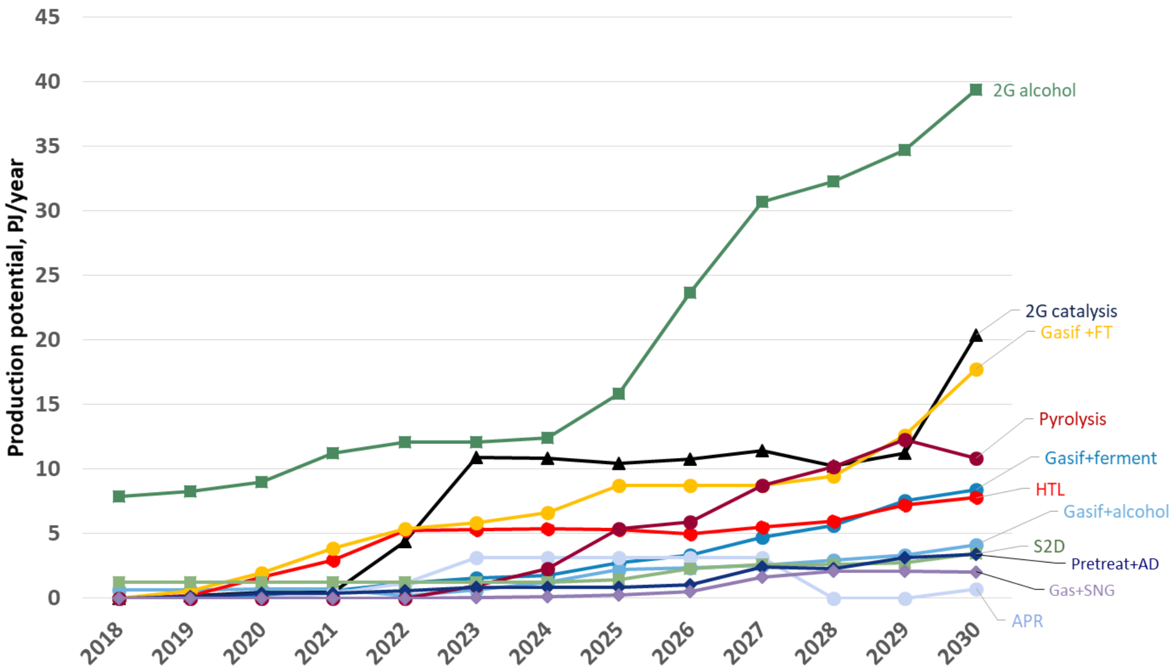

Figure 74 Anticipated RoW production potential to 2030 under the challenging growth scenario, in PJ/year

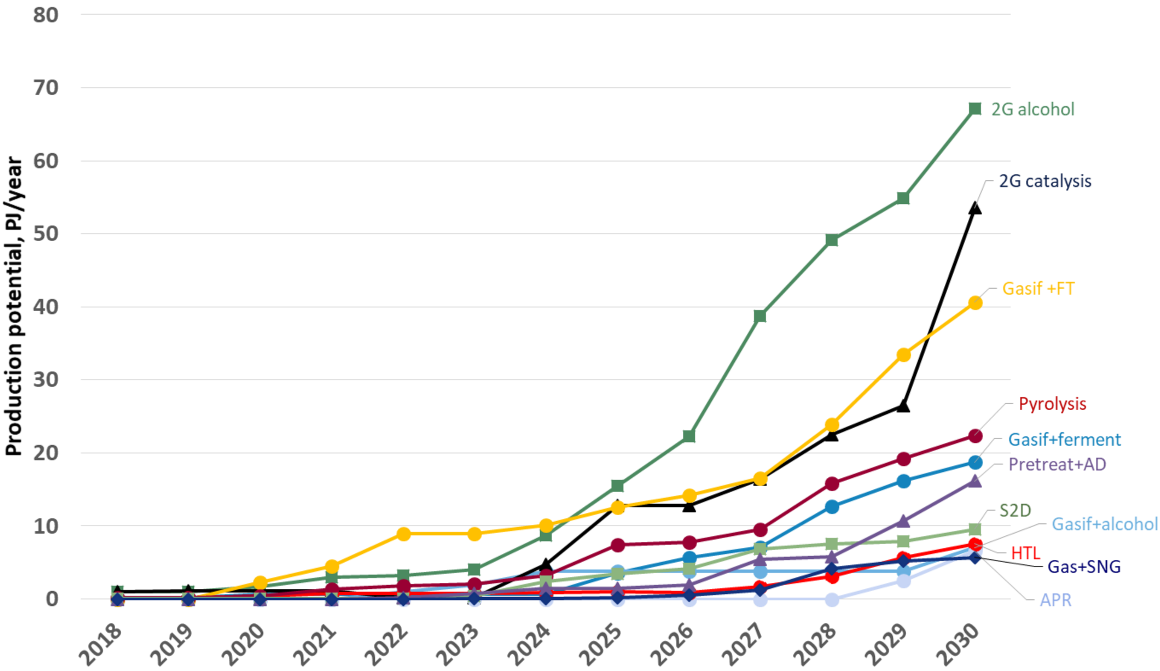

Figure 75 Anticipated EU production potential to 2030 under technology success scenario, in PJ/year

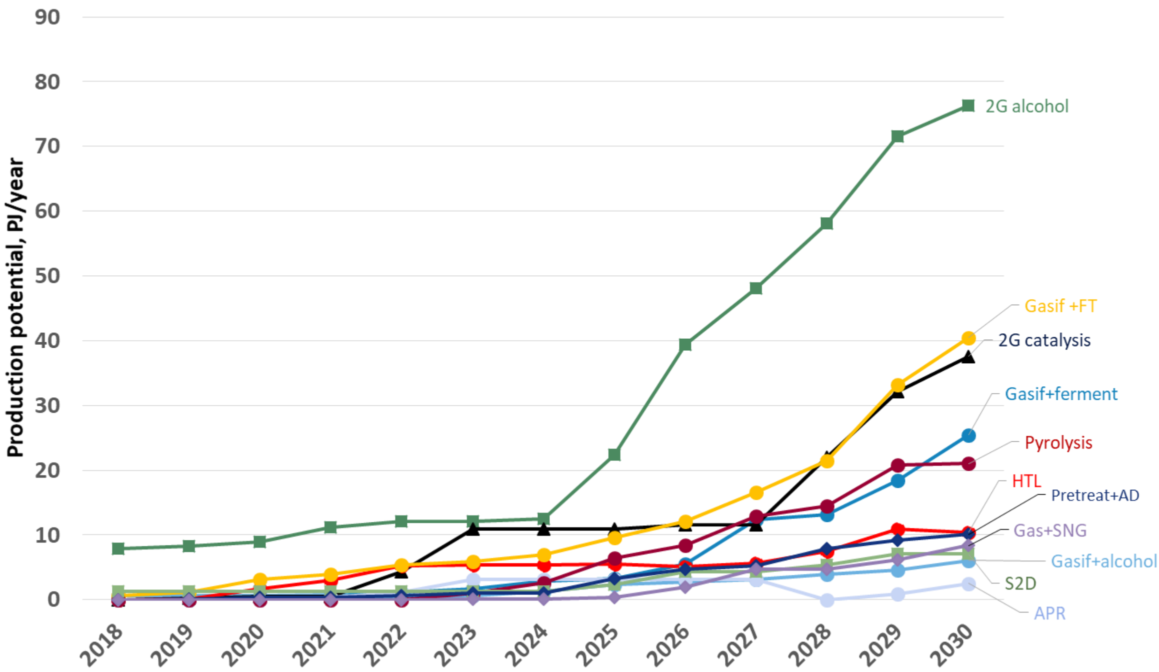

Figure 76 Anticipated RoW production potential to 2030 under technology success scenario, in PJ/year

[i] Ethanol Producer Magazine (2013) "Financing complete on Brazil's first commercial 2G ethanol plant". Available at: http://www.ethanolproducer.com/articles/9876/financing-complete-on-brazils-first-commercial-2g-ethanol-plant
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[ii] The Brazilian development bank (2014) "BNDES and Finep launch a R$1.48 bn program to encourage innovation in the sugar-based ethanol sector". Available at: https://www.bndes.gov.br/SiteBNDES/bndes/bndes_en/Institucional/Press/Noticias/2014/20140217_PAISS.html
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IRENA (2016) "Innovation Outlook: Advanced Liquid Biofuels". Available at: http://www.irena.org/DocumentDownloads/Publications/IRENA_Innovation_Outlook_Advanced_Liquid_Biofuels_2016.pdf
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[viii] Renewable Fuels Association (n.d.) "Current Tax Incentives". Available at: https://ethanolrfa.org/tax-2/
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[x] U.S. Department of Energy (n.d.) "Alternative Fuels Data Center". Available at: https://www.afdc.energy.gov/laws/search?utf8=%E2%9C%93&keyword=advanced&search_by=keyword
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Annex 2. List of Annex IX feedstocks from Directive 1513/2015

(a) Algae if cultivated on land in ponds or photobioreactors.

(b) Biomass fraction of mixed municipal waste, but not separated household waste subject to recycling targets under point (a) of Article 11(2) of Directive 2008/98/EC.

(c) Bio-waste as defined in Article 3(4) of Directive 2008/98/EC from private households subject to separate collection as defined in Article 3(11) of that Directive.

(d) Biomass fraction of industrial waste not fit for use in the food or feed chain, including material from retail and wholesale and the agro-food and fish and aquaculture industry, and excluding feedstocks listed in part B of this Annex.

(e) Straw.

(f) Animal manure and sewage sludge.

(g) Palm oil mill effluent and empty palm fruit bunches.

(h) Tall oil pitch.

(i) Crude glycerine.

(j) Bagasse.

(k) Grape marcs and wine lees.

(l) Nut shells.

(m) Husks.

(n) Cobs cleaned of kernels of corn.

(o) Biomass fraction of wastes and residues from forestry and forest-based industries, i.e. bark, branches, pre-commercial thinnings, leaves, needles, tree tops, saw dust, cutter shavings, black liquor, brown liquor, fibre sludge, lignin and tall oil.

(p) Other non-food cellulosic material as defined in point (s) of the second paragraph of Article 2.

(q) Other ligno-cellulosic material as defined in point (r) of the second paragraph of Article 2 except saw logs and veneer logs.

(r) Renewable liquid and gaseous transport fuels of non-biological origin.

(s) Carbon capture and utilisation for transport purposes, if the energy source is renewable in accordance with point (a) of the second paragraph of Article 2.

(t) Bacteria, if the energy source is renewable in accordance with point (a) of the second paragraph of Article 2.

Part B. Feedstocks, the contribution of which towards the target referred to in the first subparagraph of Article 3(4) shall be considered to be twice their energy content:

(a) Used cooking oil.

(b) Animal fats classified as categories 1 and 2 in accordance with Regulation (EC) No 1069/2009 of the European Parliament and of the Council (*)

Annex 3. JRC-EU-TIMES Model results

The JRC-EU-TIMES model offers a tool for assessing the possible impact of technology and cost developments. It represents the energy system of the EU28 plus Switzerland, Iceland and Norway, with each country constituting one region of the model. It simulates a series of 9 consecutive time periods from 2005 to 2060, with results reported for 2020, 2030, 2040 and 2050.

The model was run with three global storylines:

- **Baseline**: continuation of current trends; it represents a 'business as usual' world in which no additional efforts are taken on stabilising the atmospheric concentration of GHGs; only 48 % CO_2 emissions reduction by 2050.
- **Diversified**: usage of all known supply, efficiency and mitigation options (including CCS and new nuclear plants); CO_2 emissions reduction target of 80 % is achieved by 2050.
- **ProRES**: same as diversified scenario in terms of CO_2 emissions reduction target by 2050 but there are no new nuclear plants and no underground storage of CO_2 (no CCS).

For the decarbonised scenarios (Diversified and ProRES), sensitivities have been designed with different assumptions on the technology learning, the use of resources and policies (see Figure 10). Detailed information on the features of the model and all scenarios can be found in deliverable report D4.7 prepared by the JRC-EU-TIMES modelling team (Nijs et al., 2018).

In summary, sensitivities on technology learning assume lower or higher learning rates in LowLR and HighLR scenarios respectively and the achievement of SET Plan targets in the Res4_SET scenario. Two more sensitivities include more optimistic assumptions for the CAPEX of Direct Air Capturing (Div4_DAC and Res5_DAC scenarios).

In terms of resources, sensitivities have been run assuming cheaper fossil fuels (CheapFossil scenario) or a higher forestry biomass potential (HighForest scenario).

At the policies level, two specific sensitivities restrict CCUS: in the Div6_NoCC_InPower scenario, carbon capture is not deployed in the power sector, while in the Res8_NoCCU scenario, the utilisation of CO_2 is restricted on top of the geological storage restriction that was already in place in the ProRES scenarios. There is also a near zero carbon energy variant of the ProRES scenario that assumes a long-term decarbonisation target of 95% below 1990 levels in 2050.

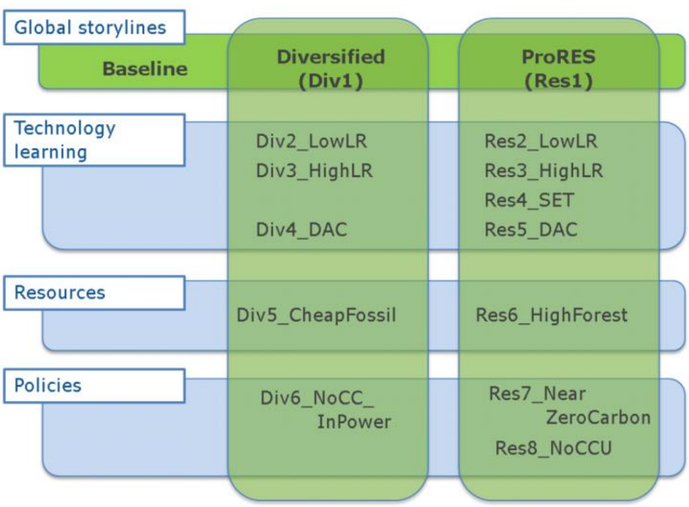

Figure 10 Overview of all scenarios and sensitivities (Source: Nijs et al., 2018)

Modelling results in terms of capacity installed and investments for the production of sustainable advanced biofuels used in transport from 2020 to 2050 are shown in Figure 11 and Figure 12 for the global storylines scenarios and sensitivities scenarios.

Figure 11 shows the installed capacity (in PJ) for the production of second generation biofuels per year (on the left axis) and the cumulative capacities (on the right axis).

According to the model results, the installed cumulative capacity increases from 2020 to 2030 and drops significantly from 2040 to 2050, both in the baseline and the diversified scenarios (around 170 PJ in 2050 in both scenarios). All sensitivities scenarios show the same trend (see upper part of Figure 11).

In contrast, in almost all ProRES scenarios, the cumulative capacities for the production of advanced biofuels increase substantially from 2020 to 2050, reaching more than 1,500 PJ in 2050. In particular, in the SET Plan scenario and in the HighForest scenario, the growth is more evident with a total installed capacity of around 2,000 PJ in 2050 in both scenarios.

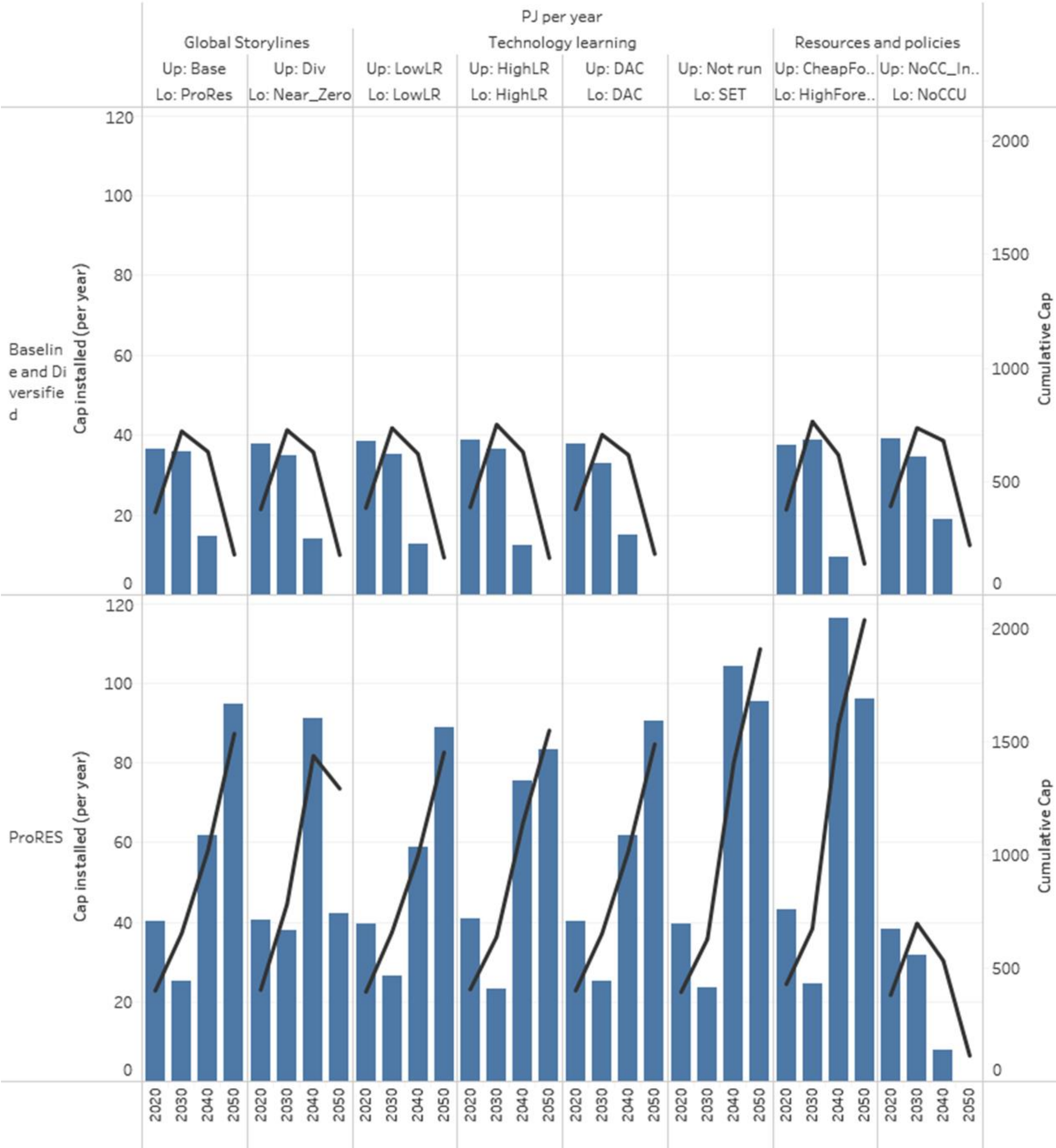

Figure 11 Installed capacities per year and cumulative capacities (in PJ) of second generation biofuels technologies in EU for different scenarios (Source: JRC-EU-TIMES modelling results)

Figure 12 shows the model results in terms of investments from 2020 to 2050 (in billion Euro) for the global storylines scenarios and sensitivities scenarios. The amount of investment shows the same trend as the installed capacities commented above with the exception of the SET Plan scenario.

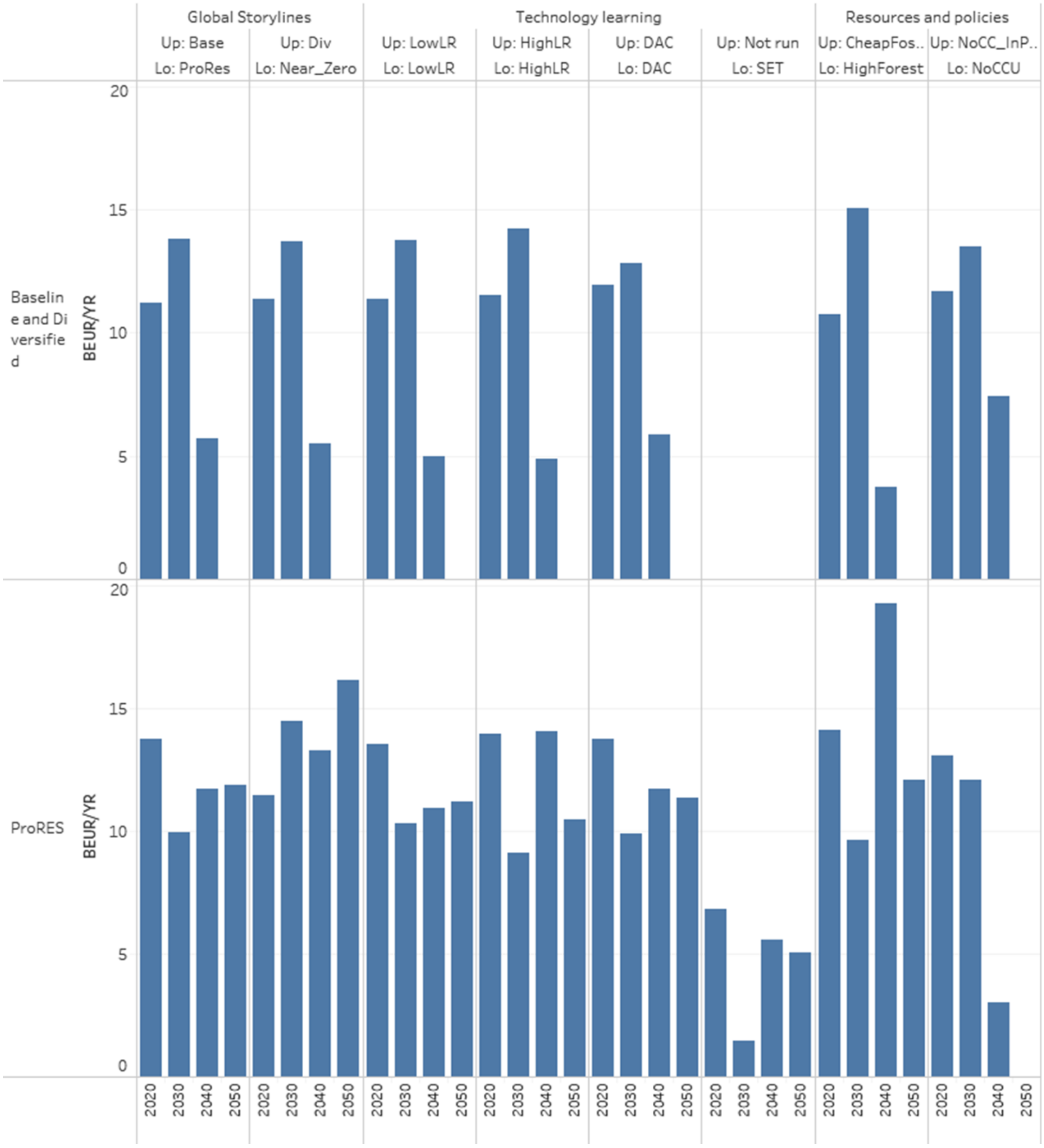

Figure 12 Total investment (billion Euro/year) in second generation biofuels technologies in EU for different scenarios (Source: JRC-EU-TIMES modelling results)

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