European Commission

Development of outlook for the necessary means to build industrial capacity for drop-in advanced biofuels

Annex 3 Report on Task 3

Research and Innovation

Development of outlook for the necessary means to build industrial capacity for drop-in advanced biofuels

European Commission
Directorate-General for Research and Innovation
Directorate C – Clean Planet
Unit *C.2* – Clean Energy Transitions
Contact Dr. Maria Georgiadou
Email Maria.Georgiadou@*ec.europa.eu*
RTD-PUBLICATIONS@ec.europa.eu
European Commission
B-1049 Brussels

Manuscript completed in December 2023
First edition

PDF	ISBN 978-92-68-09666-6	doi: 10.2777/858956	KI-09-23-575-EN-N

Luxembourg: Publications Office of the European Union, 2024

EUROPEAN COMMISSION

Development of outlook for the necessary means to build industrial capacity for drop-in advanced biofuels

Annex 3 Report on Task 3

Edited by:

Maria Georgiadou, European Commission

Theodor Goumas, EXERGIA

David Chiaramonti, POLITO

Author: BEST

The project was executed by a Consortium comprising:

Directorate-General for Research and Innovation
Horizon Europe Programme

2024

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1. Introduction

The objective of Task 3 is the analysis of the capacity potential for the industrial supply of advanced biofuels and biomethane for transport, i.e. fuels that are produced from feedstock listed in Annex IX Part A of the Renewable Energy Directive[1], and to which the specific sub-target of 3.5% by 2030 applies. The analysis was conducted through the analysis of existing infrastructure, technical knowledge and stakeholder capacities for existing and emerging value chains. Real data was collected from industries and industry associations active in technology development, biofuel production and distribution. The analysis covered the following biofuel production technologies, which are at different Technology Readiness Levels (TRLs) and from different regions within the EU:

- Biomethane from anaerobic digestion – TRL 9
- Transesterification – TRL 9
- Hydrotreatment – TRL 9
- Lignin depolymerisation (Annex IX A feedstock) – TRL 8
- Conventional ethanol – TRL 9
- Fermentation of lignocellulosic feedstock – TRL 8
- ATJ/MTJ – TRL 8
- Gasification and methanol synthesis – TRL 9
- Gasification and methanation – TRL 8
- Gasification and FT synthesis – TRL 7
- Pyrolysis – TRL 9
- Hydrothermal liquefaction – TRL 8

Data derived from the analysis is provided in a dataset displaying the possible evolution of biofuels production capacities in Europe. The dataset is accompanied by this report that explains the data and the reasoning for any assumptions.

[1] DIRECTIVE (EU) 2018/2001 OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL of 11 December 2018 on the promotion of the use of energy from renewable sources (recast)

2. Methodology

For the analysis of the capacity building potential data was collected from European industry and associations. This data was complemented with own research and expert analysis. The analysis draws on existing work of ETIP Bioenergy, ART Fuels Forum, IEA Bioenergy Task 39 and projects, such as ADVANCEFUEL. The sources used for creating the dataset are shown in Figure 2-1 and are described in more detail in the following chapters.

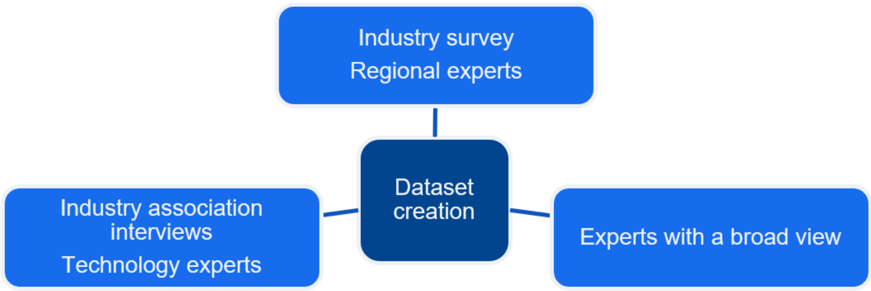

Figure 2-1 Methodology Task 3

Besides capacity building potential, Task 3 also addresses other topics. The following aspects have been considered throughout the data collection:

- Capacity
- Feedstock supply
- Technical skills
- Fuel prices and costs
- Technologies and innovations
- Feedstock evolution
- Financing programmes
- Outlook 2030 and 2050

2.1. Industry survey and regional experts

In a first step, relevant value chains, feedstocks and technologies have been identified within the project. A list of feedstocks was prepared by Task 2 and a list of technologies and pathways was provided by Task 1. Afterwards, the target group for the industry survey has been defined, namely companies, active in biofuels production or technology development in Europe or with plans for European market expansion by 2050. Subsequently, a list of companies has been established. The list was based on the Database on facilities for the production of advanced liquid and gaseous biofuels for transport[2] and complemented by regional experts.

In a next step a questionnaire for the industry survey has been developed with the software LimeSurvey. The survey was distributed online between March 22 and April 16, 2023. The survey included questions to all relevant aspects as mentioned in chapter 0. The questions have been discussed within the project team to ensure that results can be used in subsequent tasks, such as Task 4. After programming the questionnaire, test runs with the project team as well as selected companies were conducted. The questionnaire was adapted according to the feedback provided. The link to the survey was distributed via e-mail by BEST, Exergia and regional experts (in case there were no contact details available). The follow-up to the survey to increase the response rate has been done by Exergia. Additionally, industry associations were asked to forward the link to the questionnaire to their members. In total, the link was sent to about 140 companies within the target group. Total responses amounted to 89, of those 41 responses were evaluable. The evaluation of the survey was summarized in a report and is provided as Annex (Annex I).

In parallel, a group of 4 regional experts were subcontracted. Their expertise was required for two tasks. First, they supported reaching out to the companies with the survey and helped to contact them and they identified and described national funding programs for building advanced biofuels production facilities. A summary of European and national funding schemes is provided as Annex (Annex IV).

2.2. Industry association interviews and technology experts

To complement data from the survey and to gain insights of the advanced biofuels sector, interviews for industry associations have been prepared. A set of guiding questions was developed and potential interview partners have been contacted.

The following industry associations have been interviewed or provided requested information via e-mail:

- Advanced Biofuels Coalition
- Bioenergy Europe
- Copa-Cogeca
- EBA European Biogas Association
- EBB European Biodiesel Board
- ECAC European Civil Aviation Conference
- ePURE European renewable ethanol
- EWABA European Waste-based & Advanced Biofuels Association

[2] https://demoplants.best-research.eu/

- Fuels Europe
- Gmobility
- Maersk (as representative of the maritime sector)

The information provided by the industry associations was analysed and processed according to the aspects mentioned above. The interviews provided information on all eight aspects, but to varying degrees. A summary of the key findings is provided as Annex (Annex II). Further own research included scrutinizing statistical reports and other publication of industry associations and institutions.

The Database on facilities for the production of advanced liquid and gaseous biofuels for transport provided a baseline of current production capacities. Further, a group of technology experts were asked to estimate current and future biofuel production from their respective technology as well as related feedstocks (and some other data), and to document their reasoning in a word document. Information form technology experts have been summarized in a report, which is provided as Annex (Annex III).

2.3. Dataset creation

A dataset template has been created and the layout and content were confirmed by the other Tasks that need to build on this data. Data from the industry survey, association interviews, group of regional and technology experts and literature research has been collected, prepared and provided to a group of 6 experts with a broad view on advanced biofuels. These subcontracted experts were asked to scrutinize the information given. Each of them took a deep dive into a selection of technologies and then presented his or her view to the others during online meetings. All experts then discussed these technologies and jointly arrived to a consolidated view and numbers, as displayed in the dataset and the report. Altogether, the group met online seven times over the course of three weeks. The last two meetings were dedicated to reflecting on the preliminary numbers and key messages. The report as well as the dataset are provided as Annexes (Annex V and Annex VI).

3. Results

The following chapters provide an overview of the results obtained from companies, industry associations, technology experts, regional experts and through the discussion with experts with a broad view. Detailed results are displayed in a number of annexes to this report:

- Annex I Industry survey
- Annex II Association interviews
- Annex III Technology experts (IIIA text, IIIB dataset)
- Annex IV Financing programs
- Annex V Experts with broad view
- Annex VI Final dataset

3.1. Current production and production capacity

This chapter contains information from the technology experts, the discussion with the experts with a broad view, and association interviews. Further details are provided in Annex II, Annex III, Annex V and Annex VI.

As of 2023, four technologies have reached market maturity and are widely deployed in Europe. With respect to EU biofuel production, FAME[3] is leading the pack with some 9.9 million t/y, HVO[4] and ethanol[5] follow with 5.1 million t/y each, and biomethane from anaerobic digestion[6] contributes around 3.8 billion m³ per year. Facilities are sometimes idle when prices for feedstock are high, so actual production could be expanded easily when profitable. Installed production capacities are estimated at 12 million t/y for FAME, and 5.8 million t/y for ethanol[7]. HVO[4] capacities have seen a rapid expansion recently and continue to increase, especially in refineries, and we assume that current production and production capacity are at 5.1 million t/y. Ethanol production takes place in biorefineries that produce a range of products and may also serve the chemical industry. Biomethane is a versatile product that can be used in many different applications; since EU is aiming to replace natural gas imports from Russia, demand for biomethane is huge, and we estimate that only 10% go into the transport sector.

Another set of technologies is currently under small- or large-scale demonstration and needs to prove their technical and economic feasibility. Based on the database of ETIP Bioenergy[8], we estimate around 200,000 t/y of advanced ethanol production, and around 100,000 t/y of pyrolysis oil production[9]. Gasification and subsequent production of biomethane (synthetic natural gas, SNG) is not widely demonstrated yet (2,000 t/y of installed and operational production capacity), gasification and subsequent synthesis to methanol or DME stands at 600 t/y, and hydrothermal liquefaction at 1,400 t/y. We are not aware of demonstrations of gasification and subsequent Fischer Tropsch fuel production at large scale, or alcohol-to-jet fuel facilities in Europe.

Current production capacities for these pathways are summarized in Table 3-1 below. Note that for conventional biofuels, capacities are higher than actual production.

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[3] Combined FAME and HVO production of 15 million t/y according to EBB interview conducted 21.03.2023

[4] HVO production capacity estimated according to EU Biofuels Barometer 2020 and ETIP Bioenergy database on production facilities

[5] ePURE members produced 5.57 billion litres in 2020 and constitute around 85% of EU production capacity, according to ePURE interview conducted 03.03.2023

[6] 37 TWh of biomethane production in EU in 2021, according to EBA interview conducted 14.03.2023

[7] ePURE members have installed production capacity of 6.38 billion litres per year in 2022 and constitute around 85% of EU production capacity, according to ePURE interview conducted 03.03.2023

[8] https://www.etipbioenergy.eu/databases/production-facilities

[9] Note that, because of the addition of hydrogen during the upgrading of fast pyrolysis bio oil (FPBO) to finished transport fuel, the yield from FPBO to finished fuel is around 100%

Fuel/pathway	2023 production capacity
FAME (all feedstock categories)	12 million t/y
HVO/HEFA (all feedstock categories)	5.1 million t/y
Conventional ethanol	5.8 million t/y
Biomethane from anaerobic digestion	3.8 billion m³
Advanced ethanol[10]	200 000 t/y
ATJ	-
Gasification + methanol/DME	600 t/y
Gasification + SNG	2 000 t/y
Gasification + FT – diesel	-
Pyrolysis – bio-oil	100 000 t/y
HTL – biocrude	1 400 t/y

Table 3-1 Capacity of biofuel production in 2023 in Europe

The split between food/feed feedstocks, Annex IX Part A and Annex IX Part B feedstocks is hard to assess since different categories are often reported combined. Based on production values as mentioned above, split between different feedstocks as provided in EU Biofuels Barometer 2020, and converting into Mtoe as to account for different heating values, we estimate 13 Mtoe/y of conventional biofuels (i.e. based on food/feed feedstocks; 4.6 Mtoe/y of FAME, 5.3 Mtoe/y of HVO, 3.2 Mtoe/y of ethanol); 4.6 Mtoe/y of advanced biofuels and biomethane for transport (i.e. based on Annex IX Part A feedstocks; 3.2 Mtoe/y of biomethane, 1.1 Mtoe/y of waste-based FAME, 0.4 Mtoe/y of other liquid fuels); and 3.1 Mtoe/y of biofuels based on Annex IX Part B feedstocks (FAME and HVO). Relative shares are 63% conventional biofuels, 7% advanced biofuels, 15% biomethane, and 15% biofuels based on Annex IX Part B feedstocks.

Fuel/pathway	Estimated current production [Mtoe/y]	Share of total [%]
Conventional biofuels		**63**
FAME	4.60	
HVO	5.25	
Ethanol	3.16	
Annex IX Part A		**22**
FAME	1.06	
HVO	0.14	
Ethanol	0.13	
Pyrolysis – bio-oil	0.04	
Biomethane from anaerobic digestion	3.20	

10 Demonstration and first commercial facilities dedicated to the production of ethanol from lignocellulosic materials

Fuel/pathway	Estimated current production [Mtoe/y]	Share of total [%]
Annex IX Part B		**15**
FAME and HVO	3.09	

Table 3-2 Estimated current production of biofuels and biomethane from different feedstock categories

Interviews with various associations have revealed the following additional data:

In 2021, combined biogas and biomethane production amounted to 196 TWh (biogas 159 TWh, biomethane 37 TWh). In Europe there are about 19,000 biogas and 1,000 biomethane plants. About 58% of biomethane plants are connected to the gas distribution grid and 19% are connected to the transport grid. (European Biogas Association EBA)

Capacities of HVO plants currently in operation are ENI Venice 400 kt/y, ENI Gela 750 kt/y, Neste Porvoo 525 kt/y, Neste Rotterdam 1,400 kt/y and Total Energies La Mede 500 kt/y. Production is mainly according to nameplate capacity. (Fuels Europe)

Combined production of FAME and HVO amounted to about 15 million t/y in 2020. There is idle capacity of some FAME production plants that stopped operation. Smaller FAME producers operate in batch mode. It is estimated that production could increase about 30-40% with current capacity. Typical production size range lies between 150,000 and 200,000 t/y (continuous production). There are also plants of 300,000 t/y size. (European Biodiesel Board, EBB)

Current capacity of EWABA members for the production of waste-based FAME amounts to 3.815 million t/y. Members cover about 75-80% of total European capacity. (EWABA)

Ethanol production capacity was about 6.38 billion l in 2020 (from 50 biorefineries, about 85% of total European capacity). Total ethanol capacity is about 8.78 billion l. Amount of import varies, in 2021 about 1.4 billion l ethanol were imported from the USA and Brazil. Largest importers are ePure members themselves. (ePure)

Biofuels are a small but relevant market for agriculture. About 11-13 million t/y of cereals and 1.3 million t/y of sugar from European agriculture are used for ethanol production. (COPA-COGECA)

The consumption of advanced biofuels in Europe is about 1.2 million t/y. UPM is the biggest producer, with a capacity of 130.000 t/y (nameplate capacity). (Advanced Biofuels Coalition)

Current European potential SAF capacity is based on the Hydro-processed Esters and Fatty Acid (HEFA) technology, and the upper limit of the installed capacity can be considered approximately 2.4 million t/y. (ECAC)

3.2. Feedstock supply

This chapter contains information from the industry survey and association interviews. Further details are provided in Annex I and Annex II.

For advanced biofuels production, feedstock is limited to feedstocks listed in Annex IX Part A of the Renewable Energy Directive, such as lignocellulosic biomass, straw, forestry residues, waste and residues. Currently, the supply of these feedstocks is not considered constrained, and additional amounts of sustainable forestry residues could still be made available. However, there is uncertainty to future supply, due to potential competition with other sectors, such as the biomaterial and biochemical sector, although these might not be objected to the same restrictions with respect to feedstock eligibility. Also, within the transport sector, there could be competition for certain feedstocks. ReFuelEU Aviation will likely mandate 55% SAF in 2050 and cause a massive ramp-up of SAF demand. According to the Destination 2050 Roadmap, 13 million tons of bio-based SAF could be needed in 2050, requiring about 24 million tons of feedstock, assuming a conversion factor of 55%. This would be about 4-12% of total biomass availability in the EU. Finally, the war in Ukraine and regulatory uncertainties raised feedstock supply issues.

Feedstock can be supplied from own production (e.g. from company owned pulp or saw mills), purchased via a contractor, purchased by the company itself or a mix of the previous mentioned options. About half of the respondents of the industry survey already experienced issues in feedstock supply in the past and about the same amount expect issues in the future. Measures taken to secure feedstock supply include cooperation with feedstock suppliers, long-term supply contracts, increasing flexibility and storage capacity and global sourcing. However, most respondents purchase their feedstock within Europe.

Feedstocks for biogas production include sequential crops, agricultural residues, manure, food waste, industrial waste water and sewage sludge. Most plant operators are farmers and uses their own feedstock. Biogas production requires stable feedstock supply, which requires to plan beforehand.

Smaller FAME plants often operate seasonally, depending on the market. There is no production in case the market is tight and feedstock prices are high. The share of feedstocks used for FAME production is about 70% crops and 30% wastes. Main feedstock is rapeseed, followed by soy, palm, UCO, animal fats and tall oil. There are synergies between food, feed and fuel production, and usually the driving force for cultivation is feed production for livestock rather than oil production. When e.g. rapeseed oil is used for biofuel production, protein is densified and can substitute soy imports as feed. In Europe the demand for feed is much higher than for rapeseed oil for human consumption.

Main feedstocks for advanced FAME are fatty acids, brown grease, distillates, damaged crops, cover crops, POME and food waste. Feedstock supply amounts to about 4 million t/y. There is a high competition for feedstocks and supply contracts are mainly short-term. Some producers have relationships with restaurants or established an own collection. The FAME industry is reliant on imports (mainly from non-EU countries). About three quarters of FAME producers can process Annex IX Part A feedstocks.

Feedstocks used for ethanol production include about 50% maize, 25% common feed-quality wheat, 12% sugars and 12% lignocellulosic materials, the rest are grains (e.g. sorghum).

Most contested feedstocks include saw mill residues (sawdust) and used cooking oil. Due to the low energy density of biogenic residues, transport distances should be kept low and local sourcing becomes even more important. The main problem cited was not the availability of biomass, but its mobilization.

3.3. Technical skills

This chapter contains information from the industry survey and association interviews. Further details are provided in Annex I and Annex II.

According to the report “Towards an Integrated Energy System: Assessing Bioenergy´s Socio-Economic and Environmental Impact”, published by Bioenergy Europe[11], 219,650 people were working in the field of biofuels for transport in 2019, divided in 57,216 direct and 162,434 indirect jobs. In 2020 about 208,000 people were working in the biogas/biomethane sector (based on a multiplier of 1.09 jobs/GWh). However, only a small share of biogas/biomethane is allocated to transport fuels production. The Air Transport Action Group (ATAG) estimates that up to 14 million jobs could be generated with a shift from fossil jet fuel to SAF. The impact assessment of the ReFuelEU Aviation initiative foresees 100,000 net additional jobs by 2040 and 200,000 by 2050.

The number of skilled workers required highly depends on the technology. A fossil refinery is employing about 2,000 workers, plus workers for maintenance at the same order of magnitude. There is potential to keep a similar amount in biorefineries, which also require petrochemically skilled workers. Potential is seen in the shift from skilled workers from the oil industry to the biorefinery sector. Workers can be retained and they are already developing the required skills in internal trainings. However, (bio)refineries are often located on the countryside, which makes them less attractive for workers.

EWABA members employ about 5,500 workers and there are additional 15,000 indirect jobs. In 2030, additional 500 to 1,000 people will work in the plants. FAME production requires a few very skilled workers to run a facility (about 5 skilled workers per plant) and additional workers without specific skill requirements. Skilled workers are hired on European-level, so a lack of skilled workers is not considered as issue. Also, most ethanol producers are not concerned regarding a lack of skilled workers, due to a level of excellence in ethanol production in Europe.

Neither respondents of the industry survey nor the industry associations experienced a lack of skilled workers as a barrier to running their facilities or increasing production capacity. Most companies also expect to get hold of sufficient skilled workers in 2030 or 2050. Only two companies (fermentation, gasification) expressed concerns regarding this issue in the industry survey. Additionally, there could be a lack of people in combustion R&D, and accessibility of seasonal workers in agriculture is a main issue, especially in the last years, due to e.g. travel restrictions. This is not directly affecting biofuels production, but it could affect future feedstock supply. On the other hand, technology innovation and automation are expected to reduce the need for workers in future.

3.4. Fuel prices and costs

This chapter contains information from the industry survey, association interviews, technology experts and discussions with experts with a broad view. Further details are provided in Annex I, Annex II, Annex V and Annex VI.

The price for biofuels is linked to fossil fuel prices and dependent on fossil fuel demand, costs for feedstock and energy and legislation. According to Fuels Europe, current crude oil prices amount to about 40€/bbl (290€/t) and will increase to 110€/bbl (810€/t) by 2050.

[11] https://bioenergyeurope.org/component/attachments/?task=download&id=2034:2022-Deloitte-Report-Towards-an-Integrated-Energy-System_-Assessing-Bioenergy-Socio-Economic-and-Environmental-Impact

Feedstock costs

A main part of biofuels production costs can be allocated to feedstock costs[12,13]. Increasing prices for fertilizers and a subsequent nutrient depletion (if less fertilizers are used) negatively affect yields and can lead to increasing prices for agricultural commodities, feedstock and fuels. Feedstock is mainly purchased via long-term contracts and prices are confidential. However, some respondents of the industry survey provided price ranges for some selected feedstocks:

- Stem and crown biomass: 50-100€/t dry
- Stumps from final felling and thinning: 50-100€/t dry
- Cereals straw: 40-60€/t dry
- Residues from vineyards, fruit trees, olive trees, citrus, nuts: 15-80€/t dry
- Straw from oil seed rape, sunflower, grain maize (stover), rice: 15-60€/t dry
- Bark: 30-50€/t dry
- Other saw mill residues: 45-90€/t dry
- Residues from further wood processing: 50-80€/t dry
- Residues from industries producing semi-finished wood-based panels: 50-80€/t dry
- Sawdust: 50-80€/t dry
- Husks, bran, cobs cleaned: 15-50€/t dry
- Olive pomace and olive stones: 0-15€/t dry
- Pressed grape dregs, grape marc and wine lees: 0-15€/t dry
- UCO: 970€
- Sewage sludge: 10-20€/t dry
- Crude glycerine: 100-200€/t dry
- Non-hazardous post-consumer wood: 30-60 €/t

For biogas/biomethane production, collection costs for waste, cultivation/harvesting of e.g. cover crops and waste treatment are mainly responsible for feedstock costs. There is a cost reduction expected, due to increased plant sizes, better use of digestate, efficiency increase

[12] commodity-price-dashboard_2023-03_en_0.pdf (europa.eu)
[13] https://www.ieabioenergy.com/blog/publications/new-publication-advanced-biofuels-potential-for-cost-reduction/

and a reduction of feedstock costs. Also, improvements in pre-treatment technologies and valorisation of biogenic CO2 could lead to decreased biogas production costs.

With increasing pressure on feedstock supply due to high market demand, increasing prices for feedstocks are expected. This is already being demonstrated by the price of UCO which is around twice the price of virgin vegetable oil.

Biofuel production costs

Biofuel production costs have recently been assessed by two studies, and the cost ranges cited are displayed in Table 3-3 below.

Technology	Production cost ranges [EUR/MWh] [1]	Production cost ranges [EUR/MWh] [2]
Biomethane from anaerobic digestion	40	16 – 19
HVO/HEFA (conventional feedstocks)	78	23 – 56
HVO/HEFA (advanced feedstocks)		15 – 32
FAME (conventional feedstocks)		8 – 23
FAME (advanced feedstocks)		18 – 30
Conventional ethanol		13 – 23
Advanced ethanol	103	43
Gasification+SNG	89 – 112	
Gasification+methanol/DME	89 – 112	97
Gasification+FT	104 - 144	141

1 Advanced Biofuels – Potential for Cost Reduction. Brown A. et al., IEA Bioenergy, 2020
2 DBFZ Report Nr. 44: Monitoring renewable energies in transport, 1. Edition. Leipzig: DBFZ, 2023

Table 3-3 Production cost ranges for various biofuel pathways

In its recent publication on e-fuels, CONCAWE published production costs for biofuels and e-fuels[14]. For the production of ethanol, energy costs play an important role, especially when processing lignocellulosic feedstock. There is a big range in production costs and it is hard to compete with countries that provide financial support to biofuel production (USA, Brazil).

Production costs for e.g. ethanol produced in biorefineries that produce more than one main product are hard to establish, since several products contribute to the value creation.

Fuel prices

Fossil jet fuel prices (no taxes) were about 0.3€/l (375€/t) in 2020 and will increase to 0.8€/l (1,000€/t) by 2050. SAF market prices are 2-6 times higher than traditional fossil jet fuel. The

[14] https://www.concawe.eu/publication/e-fuels-a-techno-economic-assessment-of-european-domestic-production-and-imports-towards-2050/

minimum selling price (rule of thumb) is estimated to lie between 0.7 and 4.0 €/l (930 and 5,330€/t). The current costs for HVO are about 2€/l (2,560 €/t)), e-fuels are expected to cost about 3-4€/l (3,800-5,060€/t). Current FAME costs are about 1,200€/t and production costs for biomethane from anaerobic digestion lie between 50 and 90€/MWh (0.5 to 0.9€/m³) and for thermal gasification between 90 and 100€/MWh (1€/m³). According to Fuels Europe, most technologies have a long-term potential to cost 1.5 to 2€/l (1,930 to 2,580€/t), in case of taxed petroleum and untaxed biofuels.

According to respondents of the industry survey, the following price ranges for advanced biofuels are considered as acceptable:

- Advanced bioethanol: 800 – 1.200 €/t
- Biokerosene: 2,300 – 3,600 €/t
- Biomethanol: 775 – 1,500 €/t

The expected market price evolution for some advanced biofuels by the respondents by 2030 can be seen in Table 3-4. High demand will probably drive price increases.

Fuel	Min €/t	Max €/t
Advanced biodiesel	1,250	2,500
Advanced bioethanol	1,100	1,500
Bioheavy fuel oil	1,500	4,000
Biokerosene (ATJ, FT, HEFA, SIP)	2,300	5,500
Biomethane	1,200	1,800
Biomethanol/bioDME	775	2,000

Table 3-4 Expected market price evolution in 2030 in €/t

3.5. Technologies and innovations

This chapter contains information from technology experts, the industry survey and association interviews. Further details are provided in Annex I, Annex II and Annex III.

Anaerobic digestion

Anaerobic digestion is a mature technology and widely deployed in Europe.

Emerging technologies in the anaerobic digestion sector mainly relate to specific components or specific substrates. Here the recent developments in full scale have been looking into improving the substrate pre-treatment, biogas upgrading and carbon dioxide purification and liquification. In biogas systems that have hydrogen available for methanation, the CO2 in the biogas can be deoxidised to methane, which increases the output of the plant. Here systems with biological methanation (in-situ and ex situ) and thermochemical conversion with catalyst have been applied.

A different approach is used with the reformation of biogas into hydrogen. In this case the gaseous energy carrier is hydrogen and all CO2 can be separated and e.g. used in CCS systems or provided to the production of RFNBOs. Whether this approach will be applied in the future mainly depends on H2 infrastructure and CO2 prices. The technology has been demonstrated and is ready to be implemented in larger numbers, if requested.

These technologies are in the demonstration phase and add to the available options in the sector. Utilization of the carbon dioxide might become a technology used commonly if the prices to be realised for the CO2 are high enough to cover the costs of the purification and liquification.

Lipid-based pathways (HVO, HEFA, FAME, conventional and advanced)

The production of lipid-based biofuels is already established on an industrial scale. Technological development will include waste-based feedstock processing, process optimisation and product improvement (especially by-product quality or alternative application of the same). Further, research is needed in the field of upscaling technologies, efficiency improvements, co-processing (overcome blending limitations), conversion technologies related to SAF and CCS/U to increase GHG savings.

New technologies are associated with a combined or separate use of the biodiesel by-product glycerol/glycerine as e.g. fertilizer or for biogas production. These alternative production pathways will allow an increase in biofuel production without competing with already established production capacities. Another potential new technology is HVO production from solid biomass.

Fermentation pathways (conventional and advanced ethanol, ATJ)

Conventional ethanol production is a mature technology. However, there is continuous research in efficiency improvement and GHG emission reductions.

Further R&D topics include improvement of quality of high-protein food (for human consumption), CO2 capture and utilization, e.g. for RFNBO production, or storage, sustainability hubs (resilient ecosystems) and processing of lignocellulosic feedstocks.

Advanced ethanol production, especially via the enzymatic hydrolysis of lignocellulosic feedstocks, still remains challenging and has just proven feasibility in Europe. More technological learning at large scale is needed to fully develop the technology.

The conversion of ethanol to SAF via ATJ pathways seems to be technically feasible, but requires further development and upscaling.

Gasification pathways (SNG, methanol/DME, FT)

The gasification technology is demonstrated at pre-industrial scale. Further R&D on pathways could include catalytic hydrothermal gasification and upgrading to hydrogen or biomethane and gasification and upgrading to bioethanol. Technology development is required to improve yields, develop further feedstock diversification, integrate tech components and to upscale gasification pathways. Biomass supply chains have to be organized at industrial scale.

Further R&D is required for safe use of ammonia and blending limits for ships.

Note that the FT synthesis is flexible and can be used to process syngas from biomass gasification as well as CO2 and H2, thereby potentially producing RFNBOs.

Pyrolysis pathways

Fast pyrolysis bio-oil (FPBO) production and upgrading to transport fuels has recently proven technical feasibility and is demonstrated at large scale.

The pathway ‘pyrolysis-gasification-FT synthesis’ is treated as emerging technology in this context less to its technical maturity (which is rated at least TRL 6) but rather due to the likelihood that other FPBO uses will prevail midterm (i.e. use as industrial boiler fuel and co-processing in refineries). It is expected that with an increase in FPBO production capacity and also a potential extension to less favorable feedstocks there will be an increased availability of FPBO with lower quality, which is still suitable as gasifier fuel. It is reasonable to assume that there are more large-scale gasifiers available towards 2050 that are or can be equipped to also feed in liquid fuels such as FPBO.

Another emerging technology is ‘intermediate pyrolysis-hydrodeoxygenation’. It is also rated around TRL 6 with a promising application to produce advanced biofuels from sewage sludge.

Hydrothermal pathways

Biomass hydrothermal liquefaction is a multistep process. For commercialization, further innovation and validation of several of the steps is still needed, including feed pre-treatment for size reduction to avoid reactor clogging, lignocellulose biomass pre-processing, heat-exchanger designs, products separation, process waste treatment, removal of nitrogen and oxygen from the bio-crude via upgrading or their reduction in the feedstock before conversion, HTL reaction optimization, catalysts choice, and desalting.

An additional important issue that needs rapid investigation is the study of the HTL supply chains, as in many cases the raw material is distributed and HTL conversion and bio-crude upgrading could take place at different sites. For example, a dedicated HTL conversion facility will produce raw bio-crude and the upgrade will be done in already installed commercial fossil fuel refinery.

One of technically most promising feedstocks for HTL conversion is algal biomass. Currently, algal biomass is used to produce food or biomaterials rather than biofuels, due to the high costs of algae cultivation. However, if technology development proceeds, the aviation sector could potentially purchase algae-based fuels.

3.6. Feedstock evolution

This chapter contains information from the industry survey and association interviews. Further details are provided in Annex I and Annex II. Figure 3-1 shows how many companies have indicated in the industry survey that they are processing a certain feedstock currently, or consider processing in 2030 and 2050. The depicted development indicates that there will be a diversification of feedstocks.

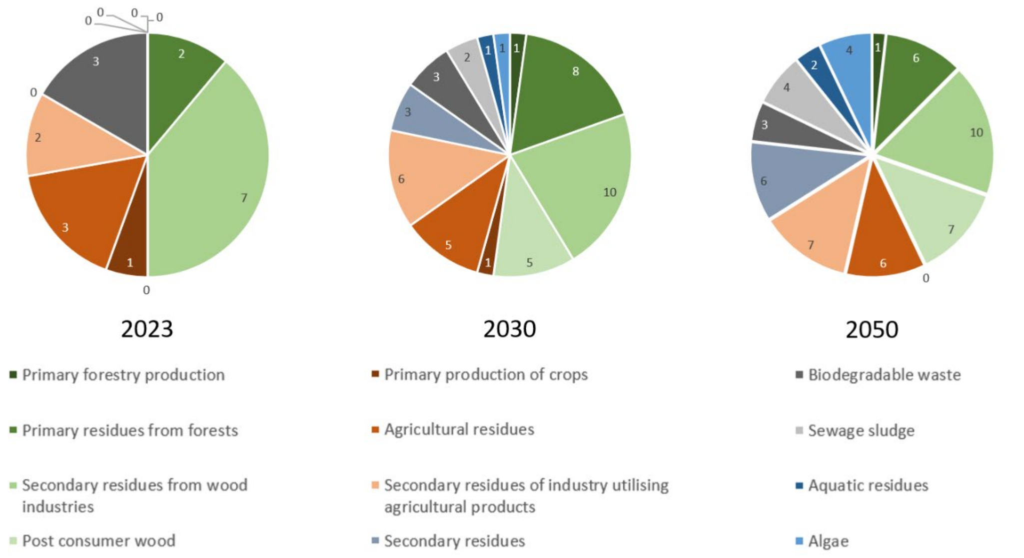


Figure 3-2 Evolution of feedstock portfolio, number of mentions by companies in the industry survey

All companies stated that they expect to obtain sufficient feedstock to run their facilities in 2030 and nearly all companies expect the same for 2050. This indicates that feedstock availability is not seen as an issue, even though increasing competition is expected for Annex IX feedstocks. Potential feedstock availability issues can be addressed with diversification. The feedstock market is adapting and the feedstock base has broadened and will continue to do so, since all kind of feedstocks will be required to produce sufficient amounts of biofuels to achieve decarbonization targets of the various sectors. Noteworthy, algae and aquatic residues have been mentioned by several companies from all types of technology pathways as a possible feedstock in 2030 and 2050, but with no indication of feedstock amounts.

Another issue besides feedstock availability is the mobilization of biogenic residues. Supply chains for biofuels production must be developed. And, due to the low energy density, transport distances need to be kept low. Possible solutions include the introduction of biomass hubs for the decentralized production of intermediate bioenergy carriers, and decentralized biofuel production facilities at scales appropriate for the feedstock available in the area.

One of the most promising potential feedstocks are intermediate crops. These are also favorable for soil maintenance. For the production of biogas/biomethane, key feedstocks in 2030 will be manure (33%), agricultural residues (25%) and sequential cropping (21%). In 2050 sequential cropping will dominate (47%), with a significant contribution of manure (19%) and agricultural residues (17%). Industrial waste water will have a contribution of 10% of the potential in both, 2030 and 2050, according to GMobility.

One feedstock that is already contested is UCO, where Europe has own collection established but needs to top up supply through imports from Asia. UCO prices have doubled recently, and its high profitability increases the risk of fraud. In the future, Asia might reduce UCO exports, thus it will be important for Europe to increase own collection of UCO from households.

According to the proposed ReFuelEU Aviation Directive, the production of sustainable aviation fuels in EU will have to be based on wastes and residues. With most of SAF production today coming from hydrotreating UCO, pressure on UCO will further increase. When surpassing the ability of UCO to support future SAF demand, further SAF production technologies that can process other feedstocks will have to come in. Those two closest to commercialization are the production of FT-SPK and ATJ. The alcohol-to-jet (ATJ) route relies on ethanol as a feedstock, and the availability of ethanol from waste and residues is very low. Europe might have to rely on imports of residues-based ethanol from Brazil for ATJ production. However, such constraints could be avoided if the list of raw materials eligible for advanced biofuels production and for SAF production were revised.

3.7. Financing programs and company investment plans

This chapter contains information from the industry survey, association interviews and regional experts. Further details are provided in Annex I, Annex II and Annex IV.

Financing programs

Support in financing investments and operation of advanced biofuels production facilities is needed, as to share the risks associated with installing first large-scale installations of the respective technologies. The type of support needed can vary largely, since a variety of actors is pursuing the production of advanced biofuels:

- FAME and ethanol production typically are in the hand of companies that trade crops, oils and grains
- Biogas producers are most often farmers or farmer cooperatives
- Refiners most easily integrate HVO and co-processing of vegetable oil and pyrolysis oil
- Utility companies can be expected to invest in gasification for SNG or biomethane from anaerobic digestion
- Waste operators look into anaerobic digestion, gasification and hydrothermal liquefaction technologies

Within the EU there are no programmes which explicitly promote the installation of advanced liquid biofuel production capacities. However, there are numerous instruments that can also provide funding for advanced biofuels. These include grants, loans and equities. For some projects these types of financing might even be combined.

The following financing programs were found for the EU (see Annex IV for details):

- Private Equity Investment
- Marguerite II
- European Circular Bioeconomy Fund
- Breakthrough Energy Ventures Europe
- Breakthrough Energy Fellows

- EIC Pathfinder
- EIC Transition
- EIC Accelerator
- EIC Fund
- InvestEU Fund
- Cohesion Fund
- European Regional Development Fund (ERDF)
- Decarbonising energy supply
- Innovation and new types of energy infrastructure
- Modernisation Fund
- European Green Economy Transition's Programs and themes
- EU Innovation Fund
- Recovery and Resilience Facility (RRF)
- Just Transition Fund
- Clean Energy Transition Partnership (CETP)
- EUREKA
- InnoEnergy
- New Renewable Energy financing mechanism (REFM)
- Horizon Europe
- Interreg Europe
- LIFE

Several countries, but by far not all European countries, also provide national funding for establishing advanced biofuel production facilities. The following programs could be found (see Annex IV for details):

- Austrian financing program Basisprogramm 2023
- Austrian financing program THINK.WOOD.Energie - F&E-Infrastruktur 2022

- Austrian (upcoming) financing program Ausschreibung zur Transformation der Industrie
- Danish financing program The Energy Technology Development and Demonstration Program (Det Energiteknologiske Udviklings- og Demonstrationsprogram, EUDP)
- Danish financing program Green Labs DK
- Finnish financing program Energy aid (Energistöd)
- Finnish financing program Rural recovery fund (Landsbygdsföretags återhämtningsmedel)
- French financing program Première usine
- French financing program SPI – Sociétés de Projets Industriels
- German financing program Development of electricity-based fuels and advanced biofuels for maritime applications
- German (upcoming) financing program Production of electricity-based fuels and advanced biofuels
- Icelandic financing program Technology Development Fun
- Icelandic financing program Icelandic Climate Fund
- Icelandic financing program Icelandic Energy Fund
- Maltesian financing program Renewable Energy Sources Scheme
- Dutch financing program SDE++: Request
- Norwegian financing program Climate Initiative (Klimasats – støtte til klimatiltak)
- Norwegian financing program Biogas (Biogass)
- Norwegian financing program Bionova
- Norwegian financing program Green Growth Loan (Grønt vekstlån)
- Portuguese financing program Hydrogen and Renewable Gases
- Spanish financing program Biogas installations
- Swedish financing program Klimatklivet (Climate step)
- Swedish financing program Industriklivet (Industry step)
- Swedish financing program Almi Invest

- Swedish financing program Swedish Export Credit
- Swedish financing program Governmental loan guarantees
- Swiss financing program Pilot- & Demonstration Program
- Swiss financing program Environmental technology promotion
- Swiss financing program Technology Fund
- Swiss financing program Spezialfinanzierung Luftverkehr (SFLV)

Besides the need for a clear regulatory framework, respondents to the industry survey mentioned economic feasibility and financing as main non-technical barriers for investments in new plants. Large companies are able to fund their own investments, but smaller ones rely on public funding (EU, Innovation Fund, national funding, etc.). Appropriate funding is important to foster investments in Europe. Due to the introduction of IRA, EBB expects that future investments in the FAME sector are more likely to be made in the USA. In the ethanol sector, continuous investments are required to keep up with regulations (GHG savings).

Respondents to the industry survey mentioned the following financing programs:

- Subsidies on investments
- EU/EIB
- National funding programs
- European Innovation Fund
- Government Loan Guarantees
- Privat investor and value chain partner funding

They also expressed their favorized financing options and incentives:

- Capital grants of 25-40% of initial plant costs plus concessional finance for debt 25%-40% for first plants
- Similar program as IRA
- Price guarantee for at least 10 years of operations
- IPCEI dedicated for biofuels
- Loans available to specifically SMEs backed by national government
- EU Loan Guarantees
- Tax or other incentives to large companies when they invest in a SME biofuel plant

- Tax incentives to biomass producers to invest into SMEs biofuels plant and provide long term biomass supply contracts

Company investment plans

Thirteen companies indicated their investment plans for 2030 and 2050. Their joint planned capacity for 2030 amounted to nearly 10 Mtoe/y, representing about 11% of the technically possible capacity estimate. In total, planned investments of these companies for 2030 are 21 billion €. The respondents will mainly invest in capacity increase for lipid-based pathways, co-processing and gasification.

For 2050, the planned joint capacity nearly triples to 28.2 Mtoe/y, again representing about 11% of the technically possible capacity estimate capped by feedstock availability. Investment needed for the additional capacities between 2030 and 2050 was indicated as 115 Billion €. In 2050, respondents mainly invest in increasing capacities of gasification, co-processing and hydrothermal pathways. The higher investment need per capacity is a result of increasing investments in more capital-intense technologies such as gasification and hydrothermal liquefaction.

Capacity and investment indications are summarized in the figure below. Note that the respondents for the pyrolysis pathways did not provide capacity estimates for 2030 and 2050.

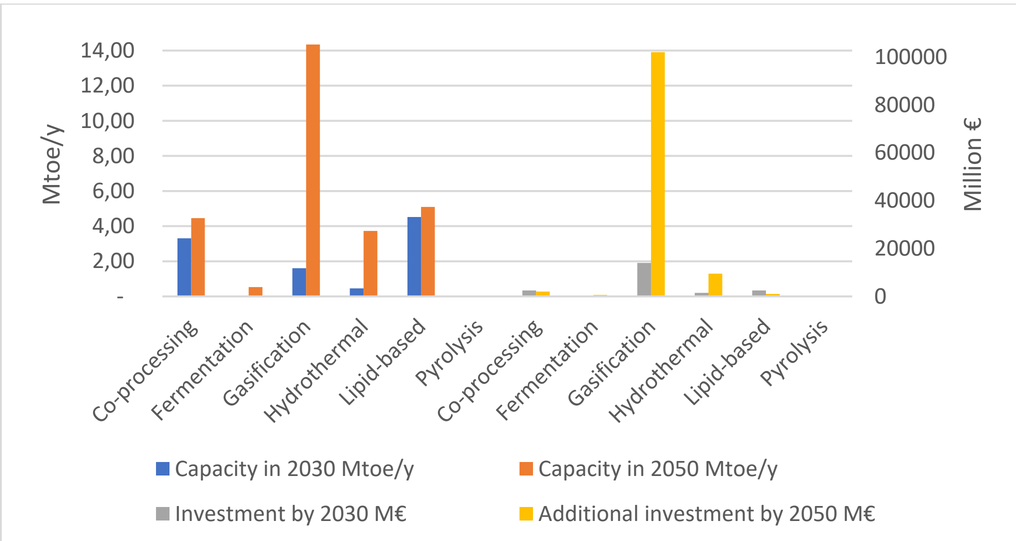


Figure 3-3 Company indications of capacity and investment plans

3.8. Outlook for 2030 and 2050

3.8.1. Expert analysis for current market conditions (cmc)

This chapter is based on extensive discussions with the experts with a broad view, and these discussions were informed by the industry survey, the association interviews and the information provided by technology experts. Further details on the positions of the experts with a broad view are provided in Annex V.

Any estimations of the future development of capacity for the production of advanced biofuels need to consider technological progress, and such progress can only be achieved through learning from the operation of large-scale demonstrations. Also, such large-scale demonstrations support the establishment of additional feedstock supply by mobilizing so far unused resources. Wherever such large-scale demonstrations are not yet available, investments have to be made, and such investments, in particular for those technologies with high CAPEX, will only be made, if investors perceive an interesting business opportunity. Thus, the future capacity estimations in this chapter are based on current technology maturity as well as on considerations on the probability and timing of investments.

Investments in large-scale demonstrations as well as in commercial production facilities will be attractive when there is foreseeable market demand and benefit to make over a few decades. Investments in upcoming technologies will start at lowest perceived risk, essentially where CAPEX is rather low, or retrofitting existing facilities where possible. Values for specific CAPEX of biofuel pathways from a recent study are displayed in Table 3-5 below. As more technologies reach market maturity, they will start adding to the picture. Feedstock availability is not the major concern as long as individual projects can secure their feedstock supply. Demand from other sectors, e.g. the chemical industry or the decarbonization of gas use, can drive the installation of facilities while concurrently competing for feedstocks and fuels.

Technology	Specific CAPEX min [EUR/kW] [1]
Anaerobic digestion	1,500 - 2,000
HVO/HEFA (conventional feedstocks)	200 – 600
HVO/HEFA (advanced feedstocks)	200 – 600
FAME (conventional feedstocks)	
FAME (advanced feedstocks)	
Conventional ethanol	
Advanced ethanol	2,750 – 3,650
Gasification+SNG	2,000 – 3,600
Gasification+methanol/DME	2,000 – 3,600
Gasification+FT	2,600 – 4,500
Pyrolysis	2,340

1. Advanced Biofuels – Potential for Cost Reduction. Brown A. et al., IEA Bioenergy, 2020

Table 3-5 Specific CAPEX ranges for various biofuel pathways

Given the current state of technology development, CAPEX requirements and market demand, we envisage the following merit order of investments:

- Anaerobic digestion, and HVO/HEFA

- 2G ethanol, gasification for the production of biomethane, gasification for the production of biomethanol/DME/ammonia, and pyrolysis

- ATJ, gasification for the production of FT-SPK, and HTL

- RFNBOs

We do not expect much investments into the expansion of FAME production, because of current under-utilization of existing capacities, blending limitations in road transport, the cap on the share that food/feed feedstocks may contribute and the fact that Annex IX Part A and B feedstocks will largely be allocated to HVO/HEFA production.

Considerations per technology

Anaerobic digestion and upgrading of biogas to biomethane is already mature today and deployed widely across Europe. Recently, large facilities have been opened e.g. in Denmark, France and Germany, with a view of injecting the biomethane into the gas grid. Any CO2 captured when upgrading the biogas to biomethane can be made available to the production of e-fuels, or combined with hydrogen to increase the biomethane yield, or alternatively be stored away. Once injected into the grid and allocated with a guarantee of origin, the use of biomethane can be manifold, such as process energy for industry, heat for households, precursor for biomethanol production, and for use in natural gas vehicles. Given the ambitious plans of the EU to compensate for former natural gas imports from Russia, there is strong market demand for biomethane. We thus expect investments in significant capacity expansionalready in the near future. However, we expect only a small fraction of the produced biomethane to be used in the transport sector.

The production of HVO and HEFA from vegetable oils as well as from waste feedstocks listed in Annex IX Part A and B of the RED (i.e. primarily UCO, but also animal fats, tall oil and industrial residues) is already mature today and easy to integrate in existing refinery operations or repurposed refineries. HEFA is one of the fractions resulting from processing, and depending on process conditions, can make up some 50% of HVO production. Since demand from the aviation sector is still low (ReFuelEU Aviation regulation not yet published), the HEFA fraction is currently rather sold as HVO with good cold properties. We expect HEFA production (which needs to be based on Annex IX Part A or B feedstocks) to sharply increase until around 2030, and availability of UCO to start limiting production capacity by then. UCO supply in Europe is currently at 3.7 Mt/y and already scrutinized for sustainability guarantee, thus efforts will be needed to collect more from households as to ramp up combined HVO and HEFA production beyond this figure. As HVO and HEFA share a similar processing scheme, HEFA and HVO will both remain available, with HVO volumes expected to gradually move from the road transport to the shipping sector. We also expect significant volumes of HVO produced from virgin vegetable oils, to be used in the road transport and eventually also the shipping sector.

Same as HVO and HEFA, FAME can be produced from vegetable oils as well as from waste feedstocks listed in Annex IX Part A and B of the RED (i.e. UCO and animal fats). The technology is mature and widely deployed in Europe, although – depending on the difference between feedstock costs and biofuel prices – facilities are sometimes idle when profits are low. A moderate expansion of actual production of around 10% – based on better utilization of the already installed capacity - is expected up to 2030 with no significant growth afterwards. FAME is one of the first alternative fuel options for the shipping sector, so FAME volumes are expected to gradually shift from road transport to shipping.

Several pathways exist for the production of ethanol from Annex IX Part A feedstocks. A low-hanging fruit is the fermentation of sugars obtained from wood in the pulping process, however this is coupled to the sulfite pulping process which is applied only in few pulp mills in Europe. The production of ethanol via enzymatic hydrolysis of lignocellulosic materials (e.g. straw) and subsequent fermentation is currently being demonstrated in Romania, with no plans for further projects yet announced; the only large-scale facility operating and having announced plans for further facilities based on the same technology is located in Brazil. Investments in further facilities are hindered by technology risks, the focus on diesel substitutes in Europe, and limited incentives for advanced biofuels in EU Member States. However, once technical and economic feasibility has been proven, we expect further deployment of the technology, as to support the 2030 target of 3.5% advanced biofuels in the transport sector, and with a view of providing a feedstock for ATJ production as well as feedstock for the chemical industry once demand from blending of gasoline is diminishing.

Gasification technologies have high CAPEX requirements but have the advantage of being able to utilize a wide range of lignocellulosic biomass and potentially also waste feedstocks. Also, based on syngas, several different synthesis reactions can be applied, for the production of biomethane (SNG) or hydrogen, methanol or DME or ammonia (fertilizer), or FT fuels; alternatively, syngas can also be fermented to ethanol. CO2 can be separated from the syngas for storage or for the production of e-fuels. All technologies have been demonstrated, yet not at large scale, and the significant investment needed has so far prevented commercial-scale facilities.

Driven by a strong demand to replace natural gas in all sectors, we expect investments in the production of biomethane (SNG) via gasification to start before 2030, although both CAPEX and OPEX are higher than for biomethane production via anaerobic digestion. Yet biomethane is not primarily produced for the transport sector, and we expect only a small fraction of biomethane produced to be used first in road transport and later in shipping. We should bear in mind that only a small fraction of vehicles on the road today is capable of using biomethane, and market signals are rather pushing manufacturers towards electrification than towards gaseous fuels.

We expect demand for methanol for the shipping sector to drive investments in gasification and methanol synthesis facilities. Investments in vessels that can run on methanol have just begun and trigger methanol production both from biomass as well as from CO2 and green hydrogen (e-methanol). Consequently, we expect methanol to be used in the shipping sector, but – once the ATJ pathway has also been approved for the use of methanol feedstock – part of the produced methanol could also support production of sustainable aviation fuels.

CAPEX requirements for gasification and subsequent FT synthesis and fuel upgrading are even higher than for the other gasification-based pathways. Yet, given the strong future demand of the aviation sector, we expect investments, although at lower rate and a bit later than for the other gasification-based pathways.

The production of fast pyrolysis bio-oil (FPBO) and its further processing into biofuels in a refinery has just been successfully demonstrated. Since up to 5% FPBO can relatively easily be co-processed in fossil refineries, deployment of pyrolysis technologies could happen quickly, comparable to the rapid roll-out of vegetable oil co-processing. However, fossil fuel refining will have to significantly decrease towards 2050, thereby reducing the amount of co-processing feedstock needed, thus upgrading of pyrolysis oil in dedicated facilities will also have to be (further) developed. Lower quality fuel could be used in the shipping sector, while highly upgraded fuel could be suitable for the aviation sector.

The production of sustainable aviation fuel through the alcohol-to-jet (ATJ) pathway has been demonstrated, but not at large scale yet. Technological challenges seem to be low, but demand from the aviation sector has not picked up yet, so there are no large investments yet. Prospective regulation within the EU will require any SAF to be produced from wastes or residues, and the availability of such ethanol is currently very low, so it is not likely that any first commercial facilities will be installed in Europe. Yet, given the strong future demand from the aviation sector, we do expect ATJ production in Europe post 2030, which may at least partly be based on imports of ethanol.

Hydrothermal liquefaction (HTL) technology has developed quickly over the past few years and now reached TRL 6-7. HTL can use the same feedstocks as pyrolysis, but can also work very efficiently on wet feedstock. Also, the resulting biocrude is easier to upgrade than pyrolysis oil. Once the technical feasibility has been proven at large scale, we expect investments.

Investments in 1G ethanol facilities are currently not considered attractive due to limited future market demand, at least unless EU regulation would reconsider the production of advanced biofuels and SAF from low-ILUC feedstocks produced in Europe, e.g. intermediate crops. 1G ethanol facilities in Europe deliver 77% GHG emissions on average already today, with some facilities reaching 95%. These facilities are true biorefineries, producing a range of products such as ethanol and animal feed, and offering an attractive opportunity to capture CO2 for either storage or use for e.g. e-fuel production. Ethanol is not only useful as blending component for gasoline, but also as a feedstock for SAF production via the alcohol-to-jet pathway. According to currently proposed regulation, crop-based ethanol will not be eligible as SAF in the EU, but it would be useful to reconsider its eligibility as to allow for domestic production of ATJ fuel rather than relying on SAF imports.

Country-specific conditions make some technologies more attractive in certain regions, e.g. more interest in e-fuels where green electricity can be produced cheaply (North Sea, Portugal, Spain; France if nuclear-based electricity remains qualified), interest in cellulosic ethanol and anaerobic digestion where vast amounts of agricultural residues are available (Poland, Ukraine, Romania, Denmark, Germany, France), and interest in gasification technologies and potentially combined gasification and electrolysis technologies where forest industry is well established (Scandinavia, Austria). Such regional solutions should be promoted, and the use of regionally advantageous feedstocks should be incentivized.

Considerations per transport sector

With the revised Renewable Energy Directive and ReFuelEU Aviation and FuelEU Maritime becoming effective in the near future, the demand for renewable transport fuels in the EU will continue to increase. Future demand in the road transport sector is expected to expand a bit further before shrinking due to the electrification of first light-duty and then also heavy-duty vehicles, at least if current blending is continued. In case biofuel blend limits are expanded to e.g., E20, B20 and B30 in light and heavy-duty vehicles, demand for biofuels in the road transport sector could be kept constant and continue providing essential GHG emission reductions. Depending on the speed of electrification, current FAME, ethanol and HVO production is expected to be able to cover the demand, despite the cap on food and feed feedstock-based biofuels. Reaching the 2030 advanced biofuels sub-target of the Renewable Energy Directive however will be challenging, since there is a lack of investments in cellulosic ethanol, gasification, or pyrolysis facilities. Investment decisions will not be taken until the regulations that are currently under discussion are finalized and published. 3-4 years will be needed from the time of investment decision to the commissioning of a new facility, so facilities will come online only from 2027 onwards. We dare hope that around 20 facilities of each of the technologies in question could be operational by 2030, although this will require very attractive incentives to investors, such as e.g. offering a premium price for the fuel over the first couple of years. This will be particularly true for the ethanol sector where investments in ethanol facilities in general do not appear attractive at the moment, since the gasoline market for road transport is expected to shrink unless higher blending of ethanol is made possible, and 1G ethanol is not eligible in the aviation sector.

The demand for aviation fuels will rise sharply according to the proposed ReFuelEU Aviation Directive. Around 2030 this demand will surpass the possibility of UCO, animal fats and other lipids included in Annex IX of the Renewable Energy Directive to support the required production, so other technologies based on more abundant feedstock will need to fill in. Investments in gasification technologies with subsequent Fischer-Tropsch synthesis and upgrading to FT-SPK are very costly; and further deployment of the alcohol-to-jet technology in Europe is rather unlikely since ReFuelEU Aviation will only accept Annex IX feedstocks, and the availability of ethanol produced from such feedstocks is very limited (unless intermediate crops are considered eligible and become deployed). EU is risking to lose the opportunity of developing its own production technologies and capacities for ATJ and FT-SPK, and will likely have to import increasing shares of aviation fuel demand from outside Europe, should such imports be eligible. RFNBOs can potentially alleviate this situation but depend on the availability of additional production of cheap green electricity. However, it is not a lack of feedstock that constitutes a barrier to SAF production beyond HEFA, but rather very restrictive and prescriptive regulation. Regulators could overcome feedstock limitations by reconsidering the feedstocks eligible for SAF production; some 1G ethanol production facilities today already offer 95% GHG emission reduction, and – following the rationale of decarbonizing transport – feedstocks produced in Europe with low risk of ILUC should be eligible to contribute.

In the shipping sector, the proposed FuelEU Maritime regulation will mandate reductions in the carbon intensity of fuels used. The use of biofuels is attractive, and allows to meet the requirements on sulfur emissions without further measures. Currently, the first choice of ship operators is FAME which can be used in blends of B10, B20 and B30. HVO is also an option but costlier than FAME. Upon further technological development, pyrolysis oils and biocrude from HTL can also be processed into shipping fuels. Another option, and currently favorized by companies such as Maersk, is the use of methanol (either bio- or e-methanol) in adapted engines. Biomethanol can be produced as by-product from pulp and paper plants, from biomethane or via the gasification of biomass and subsequent methanol synthesis. The synthesis step essentially remains the same when applied to captured CO2 and H2 from electrolysis, which makes it hard to predict whether bio- or e-methanol will prevail. Although the use of ammonia as shipping fuel is also being discussed, expectations are that – except for some green corridors - any non-fossil ammonia production would be better used for fertilizer production or stationary energy applications in Asia. Feedstock availability within Europe should be sufficient to provide the required amounts of shipping fuels, since the proposed regulation based on the carbon intensity of fuels is technology neutral and allows operators to choose whatever option seems best.

Evolution of production capacities and allocation to transport sectors

Based on the considerations above and considering all technologies and feedstocks (conventional and advanced), we have estimated the evolution of biofuel production capacities in Europe as depicted in Table 3-6, Table 3-7 and Figure 3-3.

Although we are depicting all biofuel production capacities, not all of the biofuels produced will be available to the transport sector. E.g. the fleet of natural gas vehicles in Europe is small (below 5% of total vehicle fleet[15]), and biomethane has many uses in other sectors to substitute natural gas in power and heat and process energy production. We have thus assumed that only 10% of biomethane produced via anaerobic digestion and only 5% of biomethane produced via gasification (much costlier to produce) will be available for the transport sector for all years. For ethanol we envisage significant future use in the chemical industry and have thus assumed only 60% of ethanol to be available to the transport sector (used to produce ATJ aviation fuel) in 2050. The balance of 40% is assumed to be used in chemical industry.

We have allocated the amounts available to the transport sector to the different sub-sectors road, aviation, and shipping, see Table 3-8, Table 3-9 and Table 3-10 for the allocations in 2023, 2030 and 2050 respectively.

Figure 3-4 shows the resulting estimated distribution of available biofuel production in Europe over different transport sectors.

[15] https://www.acea.auto/figure/share-of-alternatively-powered-vehicles-in-the-eu-fleet-per-segment/

	2023			2030			2050		
Technology	Production capacity [t/y]	Typical size of installations [t/y]	Number of installations	Production capacity [t/y]	Typical size of installations [t/y]	Number of installations	Production capacity [t/y]	Typical size of installations [t/y]	Number of installations
Biomethane from anaerobic digestion*	2 700 000	-	1 000	12 600 000	-	5 000	37 800 000	-	15 000
HVO/HEFA (all feedstocks)	5 100 000	500 000	10	9 000 000	500 000	18	12 000 000	500 000	24
FAME (all feedstocks)	12 000 000	150 000	80	13 200 000	150 000	88	13 200 000	150 000	88
Conventional ethanol	5 800 000	250 000	50	5 800 000	250 000	50	5 800 000	250 000	50
Advanced ethanol	200 000	50 000	4	500 000	50 000	10	3 000 000	75 000	40
ATJ	-	-	-	100 000	50 000	2	7 500 000	150 000	50
Gasification+methanol/DME	600	600	1	450 000	30 000	15	12 000 000	80 000	150
Gasification+SNG*	2 000	2 000	1	500 000	20 000	25	12 500 000	50 000	250
Gasification+FT	-	-	-	50 000	10 000	5	5 000 000	100 000	50
Pyrolysis	100 000	20 000	5	450 000	25 000	18	2 000 000	100 000	80
HTL	1 400	1 000	1	30 000	15 000	2	2 000 000	100 000	20

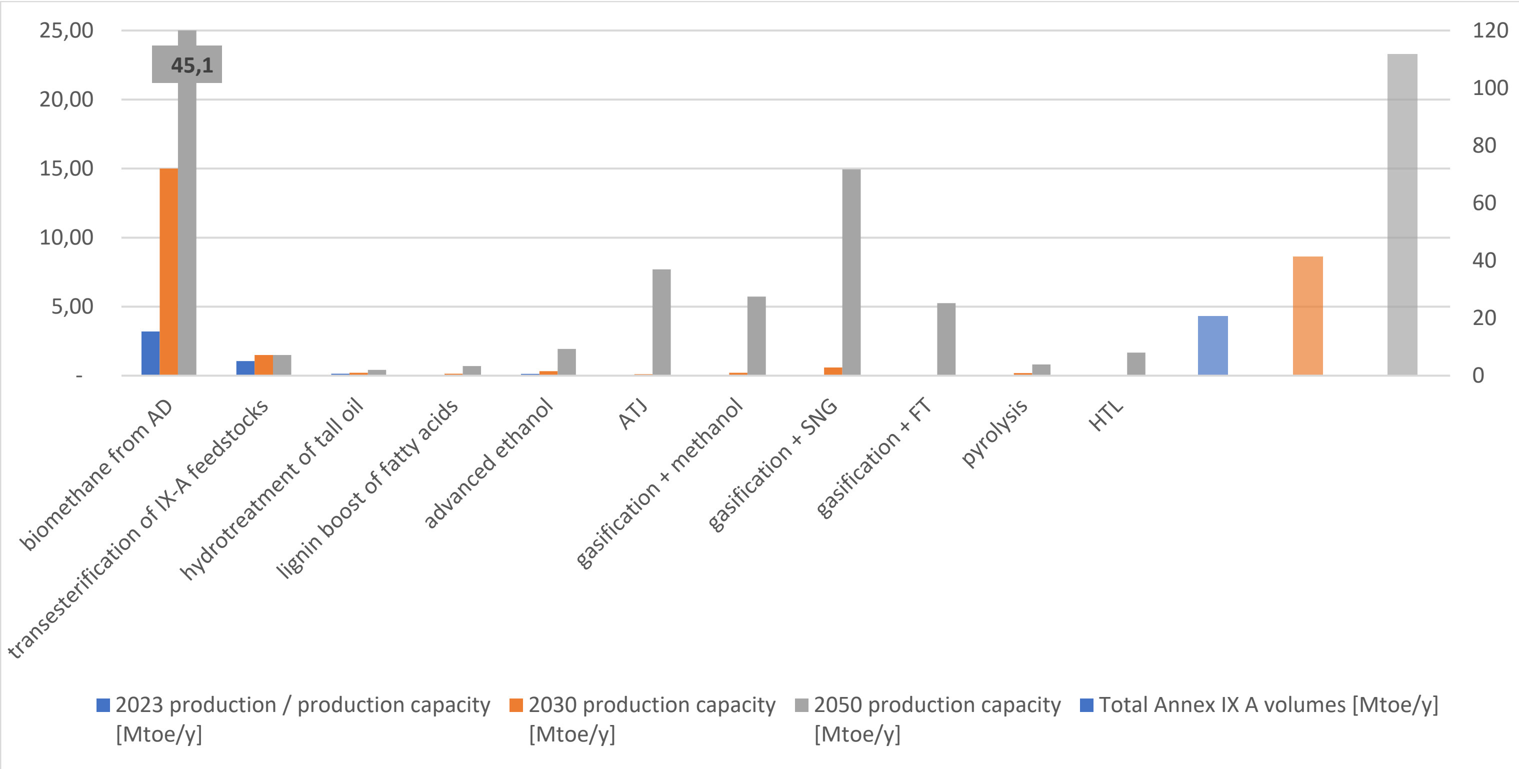
*The table shows overall production capacities, note that current production may be lower; also, the share of production available to the transport sector can be much lower, e.g. 10% or 5% only

Table 3-6 Estimated evolution of biofuel and biomethane production capacities under current market conditions, typical size of installations, and number of installations in Europe (all feedstocks considered)

Technology	2023 Production capacity [Mtoe/y]	2030 Production capacity [Mtoe/y]	2050 Production capacity [Mtoe/y]
Biomethane from anaerobic digestion*	3.2	15.0	45.1
HVO/HEFA (all feedstocks)	5.4	9.5	12.6
FAME (all feedstocks)	10.6	11.7	11.7
Conventional ethanol	3.7	3.7	3.7
Advanced ethanol	0.1	0.3	1.9
ATJ	-	0.1	7.7
Gasification+methanol/DME	0.0	0.2	5.7
Gasification+SNG	0.0	0.6	14.9
Gasification+FT	-	0.1	5.3
Pyrolysis	0.0	0.2	0.8
HTL	0.0	0.0	1.7
Total	23.1	41.5	111.9

*The table shows overall production capacities, note that current production may be lower; also, the share of production available to the transport sector can be much lower, e.g. 10% or 5% only

Table 3-7 Estimated evolution of biofuel and biomethane production capacities in Europe under current market conditions and without allocation of production volumes to other sectors than transport, converted to Mtoe/y (all feedstocks)



*The figure shows overall capacities; the share of production available to the transport sector can be much lower, e.g. 10% or 5% only

Figure 3-4 Estimated evolution of biofuel and biomethane production capacities from Annex IX A feedstocks in Europe under current market conditions, converted to Mtoe/y (Annex IX A feedstocks only)

Technology	% of product in gasoline (road)	% of product in diesel (road)	% of product in aviation	% of product in shipping	% of product to other markets
Transesterification of food/feed crops	0%	98%	0%	2%	
Hydrotreatment of food/feed crops	0%	100%	0%	0%	
Ethanol fermentation of food/feed crops	100%	0%	0%	0%	
Biomethane from anaerobic digestion	10%	1%	0%	0%	90%
Transesterification of Annex IX A feedstocks	0%	98%	0%	2%	
Hydrotreatment of tall oil	0%	98%	2%	0%	
Lignin boost of fatty acids	0%	33%	0%	67%	
Advanced ethanol	100%	0%	0%	0%	
ATJ	0%	0%	100%	0%	
Gasification + Methanol	0%	0%	0%	100%	
Gasification + SNG	5%	1%	0%	0%	95%
Gasification + FT	0%	100%	0%	0%	
Pyrolysis	20%	10%	35%	35%	
HTL	0%	25%	0%	75%	
Transesterification of intermediate crops	0%	98%	0%	2%	
Transesterification of UCO and AF	0%	98%	0%	2%	
Hydrotreatment of intermediate crops	0%	98%	2%	0%	
Hydrotreatment of UCO and AF	0%	98%	2%	0%	

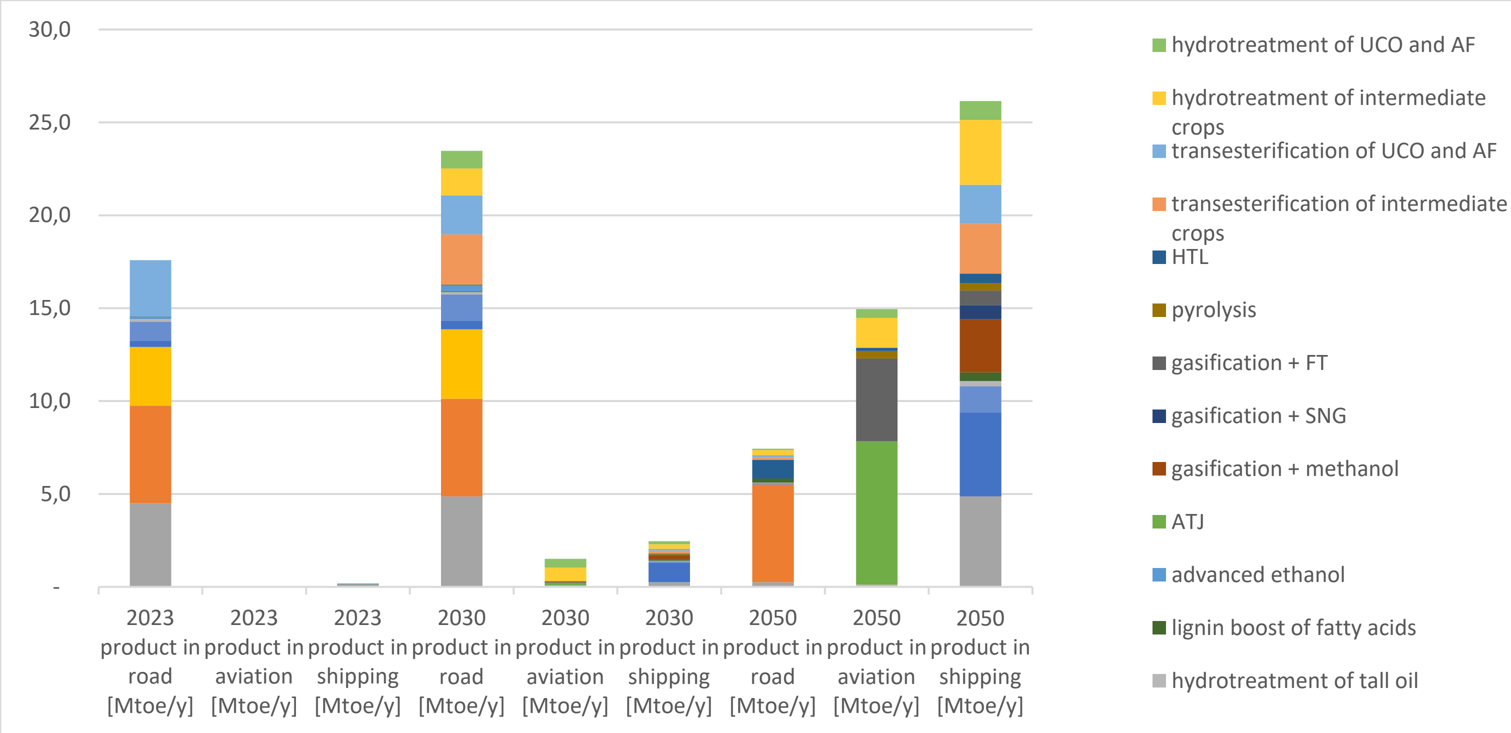
Table 3-8 Allocation of 2023 biofuel and biomethane production capacities in Europe under current market conditions to different transport sectors and other markets (all feedstocks)

Technology	% of product in gasoline (road)	% of product in diesel (road)	% of product in aviation	% of product in shipping	% of product to other markets
Transesterification of food/feed crops	0%	95%	0%	5%	
Hydrotreatment of food/feed crops	0%	100%	0%	0%	
Ethanol fermentation of food/feed crops	100%	0%	0%	0%	
Biomethane from anaerobic digestion	1%	2%	0%	7%	90%
Transesterification of Annex IX A feedstocks	0%	95%	0%	5%	
Hydrotreatment of tall oil	0%	60%	30%	10%	
Lignin boost of fatty acids	0%	33%	0%	67%	
Advanced ethanol	90%	0%	10%	0%	
ATJ	0%	0%	100%	0%	
Gasification + Methanol	0%	0%	0%	100%	
Gasification + SNG	0%	1%	0%	4%	95%
Gasification + FT	0%	0%	100%	0%	
Pyrolysis	20%	10%	35%	35%	
HTL	0%	75%	0%	25%	
Transesterification of intermediate crops	0%	95%	0%	5%	
Transesterification of UCO and AF	0%	95%	0%	5%	
Hydrotreatment of intermediate crops	0%	60%	30%	10%	
Hydrotreatment of UCO and AF	0%	60%	30%	10%	

Table 3-9 Allocation of estimated 2030 biofuel and biomethane production capacities in Europe under current market conditions to different transport sectors and other markets (all feedstocks)

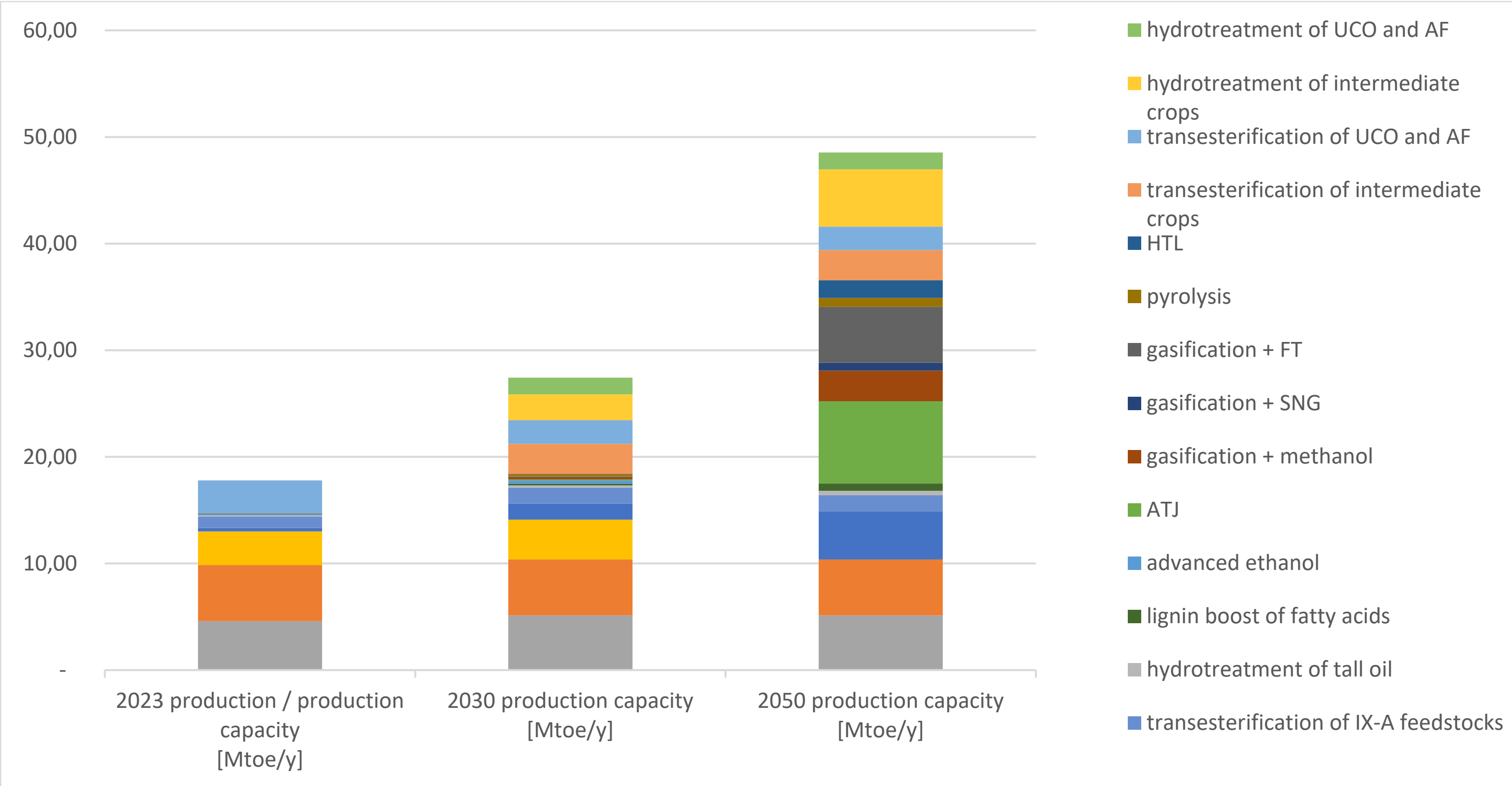
Technology	% of product in gasoline (road)	% of product in diesel (road)	% of product in aviation	% of product in shipping	% of product to other markets
Transesterification of food/feed crops	0%	5%	0%	95%	
Hydrotreatment of food/feed crops	0%	100%	0%	0%	
Ethanol fermentation of food/feed crops	0%	0%	0%	0%	100% chemicals production
Biomethane from anaerobic digestion	0%	0%	0%	10%	90%
Transesterification of Annex IX A feedstocks	0%	5%	0%	95%	
Transesterification of intermediate crops	0%	5%	0%	95%	
Hydrotreatment of tall oil	0%	5%	30%	65%	
Hydrotreatment of intermediate crops	0%	5%	30%	65%	
Lignin boost of fatty acids	0%	33%	0%	67%	
Advanced ethanol	0%	0%	0%	0%	60% ATJ, 40% chemicals
ATJ	0%	0%	100%	0%	
Gasification + Methanol	0%	0%	0%	50%	50% to ATJ
Gasification + SNG	0%	0%	0%	5%	95%
Gasification + FT	0%	0%	85%	15%	
Pyrolysis	0%	0%	50%	50%	
HTL	0%	60%	10%	30%	
Transesterification of UCO and AF	0%	5%	0%	95%	
Hydrotreatment of UCO and AF	0%	5%	30%	65%	

Table 3-10 Allocation of estimated 2050 biofuel and biomethane production capacities in Europe under current market conditions to different transport sectors and other markets (all feedstocks)



*as indicated in tables 3-8, 3-9 and 3-10, some of the biofuel and biomethane production has been allocated to other sectors than transport

Figure 3-5 Estimated distribution (under current market conditions) of biofuel and biomethane production in Europe available to different transport sectors (Mtoe/y, all feedstocks)



*as indicated in tables 3-8, 3-9 and 3-10, some of the biofuel and biomethane production has been allocated to other sectors than transport

Figure 3-6 Estimated distribution of available biofuel and biomethane production in Europe under current market conditions available to the entire transport sector (in Mtoe/y, all feedstocks)

Technology	2023				2030				2050			
	Road	Aviation	Shipping	Total	Road	Aviation	Shipping	Total	Road	Aviation	Shipping	Total
transesterification of f/f crops	4.5	-	0.1	4.60	4.9	-	0.3	5.13	0.3	-	4.9	5.13
hydrotreatment of f/f crops	5.3	-	-	5.25	5.3	-	-	5.25	5.3	-	-	5.25
ethanol ferm. of f/f crops	3.2	-	-	3.16	3.7	-	-	3.74	-	-	-	-
biomethane from AD	0.3	-	-	0.32	0.5	-	1.1	1.50	-	-	4.5	4.51
transester. of IX-A feedstocks	1.0	-	0.0	1.06	1.4	-	0.1	1.50	0.1	-	1.4	1.50
hydrotreatment of tall oil	0.1	0.0	-	0.14	0.1	0.1	0.0	0.21	0.0	0.1	0.3	0.42
lignin boost of fatty acids	-	-	-	-	0.0	-	0.1	0.14	0.2	-	0.5	0.70
advanced ethanol	0.1	-	-	0.13	0.3	0.0	-	0.32	-	-	-	-
ATJ	-	-	-	-	-	0.1	-	0.10	-	7.7	-	7.70
gasification + methanol	-	-	0.0	0.00	-	-	0.2	0.21	-	-	2.9	2.87
gasification + SNG	0.0	-	-	0.00	0.0	-	0.0	0.03	-	-	0.7	0.75
gasification + FT	-	-	-	-	-	0.1	-	0.05	-	4.5	0.8	5.25
pyrolysis	0.0	0.0	0.0	0.04	0.1	0.1	0.1	0.18	-	0.4	0.4	0.81
HTL	0.0	-	0.0	0.00	0.0	-	0.0	0.03	1.0	0.2	0.5	1.67
trans. of intermediate crops	-	-	-	-	2.7	-	0.1	2.83	0.1	-	2.7	2.83
transester. of UCO and AF	3.0	-	0.1	3.09	2.1	-	0.1	2.21	0.1	-	2.1	2.21
hydrotr. of intermediate crops	-	-	-	-	1.5	0.7	0.2	2.42	0.3	1.6	3.5	5.36
hydrotr. of UCO and AF	-	-	-	-	0.9	0.5	0.2	1.58	0.1	0.5	1.0	1.58
Total	**17.6**	**0.0**	**0.2**	**17.79**	**23.5**	**1.5**	**2.5**	**27.43**	**7.4**	**14.9**	**26.2**	**48.54**

Table 3-11 Estimated distribution of biofuel and biomethane production in Europe under current market conditions available to different transport sectors (in Mtoe/y, all feedstocks; note that some production has been allocated to other sectors than transport)

This view is complemented by the following statements on the outlook for 2030 and 2050 that were provided by associations during the interviews:

- ADVANCED BIOFUELS COALITION: A significant growth of the sector is expected, with SAF being the main market by 2040. The biggest drivers for advanced biofuels are the Effort Sharing Targets.

- BIOENERGY EUROPE: The solid biomass sector will continue to grow, but maybe transformed to deal with more market segments. Decline is only seen, if policies would hinder the sector.

- COPA-COGECA: The future development of the EU agricultural sector strongly depends on the political frame conditions, which brings huge risks. An opportunity is to transform the sector to produce advanced biofuels (e.g. for aviation) and intermediate crops.

- EBA: There will be a big need for biomethane, since different sectors can use it. Long-term offtake agreements and contracts will be required since gas prices are fluctuating.

- EBB: HVO capacity should double by 2030, but investments could be taken in the USA. It could become even four times the current production if the road transport sector will be included in EU-ETS.

- ECAC: Due to ambitious decarbonization goals, a significant market ramp-up is expected. A total of 104 to 106 additional SAF production plants in Europe are required to satisfy the SAF supply obligation, corresponding to an increase in production capacity of around 25.5 to 25.6 million t/y of SAF. The amount of bio-based SAF needed to achieve net zero carbon emission will be 13 million ton in 2050 (considering that e-fuels will be a relevant part of the SAF mix).

- EPure: There is still room to grow, but regulatory uncertainties make it difficult to estimate market development. Lignocellulosic feedstock is hard to process and the production of 2nd generation ethanol requires a lot of energy and can emit more GHG emissions than 1st generation ethanol production. A ban on 1st generation ethanol for SAF production would mean to lose a big opportunity and a lot of know-how would get lost. In that case it is expected that ethanol production will move to USA and Brazil.

- EWABA: Due to legislation and subsequent increasing demand a significant growth of capacity is expected. There is great trust that there will be higher blends used in future. For 2030 a capacity increase to 4.5 to 5 million t/y is assumed, even up to 6 million t/y in case of strong investments. The capacity increase is estimated to be about 30 to 50% by 2050, compared to 2030 (about 8 million t/y).

- Fuels Europe: A clear transformation of the industry can be seen. Fossil fuels production will shrink and biofuels production will grow. With a supportive framework a capacity of 150 Mtoe of low carbon fuels could be achieved. Announced HVO production plants include Neste Rotterdam (2023) 1,300 kt/y, Repsol Cartagena (2024) 300 kt/y, St1 Gothenburg (2023) 200 kt/y, Shell Rotterdam (2024) 820 kt/y, Total Energies Grandpuits (2024) 400 kt/y, summing up to 3 million t/y.

- GMobility: There is robust growth of the sector expected. By 2030 the capacity could increase to >900 TWh (90 billion Sm^3/a or 63 billion t/y) Capacity forecast of EBA foresees a potential of >1,500 TWh (150 billion Sm^3/a or 105 billion t/y) of biogas/biomethane by

2050, representing 30% of total NG market. In its 2022 Statistical Report, EBA shows that the potential in 2050 could be even higher (~1,670 TWh or 117 billion t/y).

- Maersk: The goal of Maersk is a 100% GHG emission reduction by 2040. Growth for methanol and ammonia is expected. But ammonia is maybe used as fertilizer or in land-based power plans. There is also growth expected for pyrolysis. The main issue when using ammonia is its toxicity and subsequent safety concerns. Maersk run safety studies to find a way to safely store and use ammonia as shipping fuel.

The overall finding of this assessment is that EU regulations are very restrictive and prescriptive. Prescribing a list of eligible feedstocks for advanced biofuels production rather than performance criteria such as GHG emission reductions or severity of risk of ILUC poses a barrier to innovation and moreover misses out on driving technologies to optimize on GHG emission reductions. Modern conventional ethanol facilities can deliver 95% GHG emission reductions, more than probably can be achieved when producing ethanol from agricultural residues. Europe could produce biomass feedstocks at very low risk of ILUC if e.g. cover crops were eligible. Finally, if SAF can only be based on wastes and residues, there is a risk that ATJ facilities will not be deployed in Europe, since availability of appropriate ethanol is low. If Europe does not develop and deploy advanced biofuels technologies, we will have to rely on imports.

As has been noted by several associations and companies, the policy environment provided by the USA seems to be much more attractive to investors than the European regulations. There is a risk that investments will be made there instead of Europe. The long political discussions on upcoming legislation (which still is not published) will leave only very little time for the erection of advanced biofuel production facilities to achieve the 2030 targets for renewable energy sources and advanced biofuels in particular. EU will have to step up efforts and offer strong incentives such as e.g. premium selling price for the first years of production if we are to meet these targets from domestic biofuel production.

3.8.2. Estimations of technically possible capacity expansion

In order to be able to show the technical potential of biofuels capacity expansion, another assessment was carried out. Technologies that are already commercial today, i.e. anaerobic digestion, transesterification, hydrotreatment and fermentation of sugar and starch crops to ethanol, were assessed based on market data, industry association interviews, the technology expert report for lipid-based technologies, and an interview with LanzaTech. Technologies at the edge of commercialization were assessed based on interviews conducted with 9 leading technology developers, one for each of the pathways considered. Estimates for 2030 and 2050 capacities were made by the author under the assumption that the regulatory framework is absolutely favorable and money for investments is available. Technologies at lower technology readiness level, or from competitors of the interviewed companies, were considered through a factor applied to estimates of 2030 production capacities. Where feedstock availability (taken from the high mobilization scenario of Task 2 of this project) became a constraint, the capacity estimate was revised downwards to match potential supply. All estimates reflect the author´s view and may exceed calculations or publications of the interviewed companies or associations.

The results of these estimations are provided in Annex VI.

Commercial technologies

Anaerobic digestion and upgrading of biogas to biomethane

According to the EBA statistical report 2022, Europe´s biomethane production in 2021 amounted to 3.5 billion m³ (i.e. 2.9 Mtoe, produced in 1,067 plants), which is an increase of 20% compared to 2020. RePowerEU aims for 35 billion m³ by 2030, but we doubt that sufficient feedstock can be mobilized for biogas production, thus our estimation is a production capacity of 18 billion m^3 by 2030 (15 Mtoe). Capacity expansion by 2050 is estimated at 3 times the 2030 capacity, and will strongly depend on mobilization of feedstock.

Transesterification and hydrotreatment

FAME and renewable diesel (HVO) production and consumption capacities are often reported jointly and are thus difficult to pull apart. Also, most installations can use conventional feedstocks as well as Annex IX Part A and Part B feedstocks, so that shares of fuels produced from any of these feedstock categories will vary over time. An attempt to estimate current production capacities for different pathways and different feedstocks has been made based on EU Biofuels Barometer 2020 data and interviews with EBB, EWABA and Fuels Europe.

According to EBB, combined EU production of FAME and HVO/HEFA is at 15 million t/y. 30-40% higher FAME production would be possible if all facilities would utilize their full capacity year-round. 70% of production (i.e. 10.5 million t/y) are based on food/feed crops and 30% (i.e. 4.5 million t/y) on Annex IX Part A and Part B feedstocks.

EWABA claims that their members have produced 3.8 million t of FAME from waste feedstocks, and this represents 80% of total waste-based FAME production. Total waste-based FAME production was thus estimated at 4.75 million t/y. This does not entirely match with EBB figures but was considered close enough for the purpose of this assessment.

Fuels Europe sums up individual HVO/HEFA production capacities of Eni, Neste and TotalEnergies to 3.6 million t/y. Considering also other producers the figure could be as high as 5 million t/y, matching well with values presented in the EU Biofuels Barometer 2020. Given that all waste-based production was already attributed to FAME, this leaves HVO production entirely based on conventional feedstocks, i.e. vegetable oils, disregarding that 130 kt/y of tall-oil based renewable diesel is produced by UPM and Preem. So, while the above assumption is not entirely correct, it was considered close enough for the purpose of this assessment. Production capacity from the processing of tall oil is indicated separately in the dataset on production capacities (Annex VI).

Based on the above figures, total FAME production was estimated at 10 million t/y in 2023, with actual production capacity being around 30% higher, i.e. 13 million t/y. The EU Biofuels Barometer 2020 reported 1.3 million t/y of Annex IX Part A based FAME and 3.5 million t/y of Annex IX Part B based FAME; since this matches well with the overall number of 4.75 million t/y of waste-based FAME, these values were used for assumed production in 2023. Subtracting the reported 4.8 million t/y of waste-based FAME production result in 5.2 million t/y of conventional FAME production.

2030 capacities were estimated as follows:

Industry announcements of HVO/HEFA capacity additions and expansions sum up to a project pipeline of 3 to 5 million t/y, potentially leading to 10 million t/y production capacity in

2030. Again, UPMs capacity addition of 0.5 million t/y is indicated separately in the dataset.

FAME production in 2030 was estimated at 40% higher than production in 2023, partly due to the addition of new facilities and partly due to better utilization of existing capacities. The split between crop- and waste-based feedstocks was assumed to remain constant.

Conventional ethanol production

Production capacities for ethanol are based on value provided by ePURE. ePURE members represent around 85% of total European ethanol production capacity. Their combined ethanol production was 5.57 billion l, i.e. 4.3 million t in 2020, of which 80% (3.5 Mt) were produced for fuel use. 7.8% of the total production were based on Annex IX Part A feedstock, which amounts to 340 kt of advanced ethanol production. This advanced ethanol production likely is generated by the “conventional” ethanol biorefineries when using feedstock such as e.g. wine lees. It is worth noting that according to ePURE the average carbon saving of ethanol biorefineries for conventional ethanol production in Europe is 77%, with single facilities even reaching 95%.

Based on the above figures, conventional ethanol production capacity was estimated at 5.1 million t/y, and capacity expansion by 13% to 5.8 million t/y by 2030 was assumed, based on information from ePURE. No further expansion by 2050 was assumed, since gasoline demand is expected to decrease through increasing electrification of in particular passenger cars, and current discussions of the upcoming ReFuelEU Aviation regulation indicate that only waste and residue-based sustainable aviation fuels will be eligible. Any ATJ production in Europe will thus have to be based on advanced ethanol rather than conventional ethanol.

Ethanol could also be produced via the LanzaTech technology through the fermentation of waste gases. If these waste gases are fossil-based, this will produce a recycled carbon fuel (RCF). Member states can choose whether or not to allow RCF to count towards the 2030 target share for renewables in the transport sector, so the regulatory situation is not yet entirely clear. In Europe, a first facility with a capacity of 60 kt/y is already operating, and three further facilities with a capacity of 46 kt/y each are currently operating in China, converting industrial emissions to ethanol. Based on the interview with LanzaTech and assuming that money was available – a capacity expansion to 0.6 million t/y of such RCF ethanol seemed feasible by 2030. In the dataset this RCF ethanol is included in the line on conventional ethanol, adding to the 5.8 million t/y cited above and summing up to 6.4 million t/y.

Technologies at the edge of commercialization and based on Annex IX Part A feedstocks

In order to estimate future possible production capacities of technologies at TRL 7 and 8, interviews were conducted with selected technology developers. These interviews served to learn about current production capacity, the pipeline of projects, the lead time of projects until being fully operational, standard capacity of future commercial facilities, and the number of projects that the company is capable of supporting per year. It is worth noting that all companies interviewed were well prepared for the deployment of their technologies, with e.g. internal studies conducted, partnerships with key manufacturing and engineering companies set up, a long list of clients and projects under development, licensing concepts elaborated, and ideas in place how to deal with manpower and engineering capability in case of steep ramp-up of projects. Several companies have developed or are currently developing standard modules for production facilities, and some are targeting lower value product markets to establish a first set of facilities before targeting transport fuel markets.

The following pathways were assessed through interviews.

Represented biofuel pathway	Main product assumed	Main feedstock assumed
Hydrotreatment of tall oil	renewable diesel	tall oil
Lignin boost of fatty acids	renewable diesel	lignin from black liquor and fatty acids
Advanced ethanol	ethanol	agricultural residues
ATJ	kerosene	advanced ethanol
Gasification + methanol	methanol	wood and agricultural residues
Gasification + SNG	biomethane	wood and agricultural residues
Gasification + FT	renewable diesel	wood and agricultural residues
Pyrolysis	FPBO upgraded to renewable diesel	wood and agricultural residues
HTL	biocrude upgraded to renewable diesel	wood and agricultural residues

Table 3-12 Pathways assessed through company interviews

Information from these interviews was complemented with data from the advanced biofuels demonstration database, which is a joint effort of IEA Bioenergy Task 39, 33 and 34 and ETIP Bioenergy[16].

Table 3-13 provides an example of the methodology used for estimating the possible 2030 production capacity of the interviewed companies, based on the assumption that the regulatory framework would be favorable and financing would not be an issue. Reasoning for choice of capacity ramp up is provided in the following subsections for each technology separately.

Table 3-14 provides overall production capacities in 2030 and 2050 for each of the selected pathways. Based on the resulting estimate of 2030 production capacity for each of the companies, the overall production capacity of the represented pathway was calculated by means of multiplication with a factor that accounts for an estimated number of competitors deploying the same pathway simultaneously. Reasoning for choice of competitors' factor is provided in the following subsections for each technology separately. Note that values in that table are given in Mtoe/y, as to account for the different heating values of the biofuels

[16] European facilities are displayed under https://www.etipbioenergy.eu/databases/production-facilities, while the global picture is presented at https://demoplants.best-research.eu/

produced, and make data easier to compare.

The 2050 production capacity of each pathway was finally calculated by means of multiplication with a factor that varied from 3 to 10. The standard value of that factor was 7, based on 7fold further capacity expansion of a technology with 4 years of lead time. The factor was lowered if capacity expansion was assumed to be restricted by the availability of lipid feedstocks (as to be in line with the methodology used for conventional FAME and HVO/HEFA calculations), and increased if the commercial capacity was not reached in the calculations for 2030 capacity. Resulting production capacities were capped according to expected feedstock availability (high mobilization scenario).

<u>Hydrotreatment of tall oil</u>

Current EU production capacity is 130 kt/y, and plans have been announced to build a facility with a capacity of 500 kt/y. Further capacity additions are aimed at the chemical industry, not the transport sector. No further capacity increases were assumed for this technology.

The competitors' factor was set to 1. The 2050 capacity will be limited by tall oil availability, and the 2050 factor was set accordingly.

<u>Lignin depolymerization</u>

This technology is based on combining two feedstocks, lignin (separated from black liquor from pulp mills) and fatty acids and catalytically converting them to a bio-oil. This bio-oil can then be added to the hydrotreater of a refinery to produce biofuels.

Essentially, this technology allows to double the amount of biofuels produced from fatty acids.

In deploying this technology, it is necessary to find a pulp mill willing to separate the lignin and a refinery willing to invest in such bio-oil production and to process it in the hydrotreater, so initiating projects can be difficult. But on the other hand, the conversion technology does not require high investments since temperature and pressure are low, and there is no need for careful siting of the facility in a region with good access to biomass. Lead times thus are low (around 2 years), and deployment could take place quickly, with average production capacity ramping up over a couple of years since current average capacity is well below future commercial capacity.

The competitors' factor was set to 3, as to account for possible competing technologies. The 2050 factor was chosen to reflect the likely restriction in fatty acid availability.

<u>Fermentation of lignocellulosic feedstock</u>

Cellulosic ethanol technologies are usually based on pre-treatment, enzymatic hydrolysis, and subsequent fermentation of sugars to ethanol. In Europe currently there is one operational commercial facility at 50 kt/y production capacity. Another facility is currently under construction, and several more are in the engineering phase. Multiple further projects are under development. Likely average size of a facility in Europe is 100 kt/y, based on feedstock availability.

	Technology example
Installed capacity in Europe in 2030	0 t/y
Largest operational facility globally	30 000 t/y
Size of a future commercial facility	180 000 t/y
Lead time (incl. feasibility study) until fully operational	4 years
Number of facilities that the company can support by year	3
Average capacity of one facility installed in 2024	30 000 t/y → 90 000 t/y
Average capacity of one facility installed in 2025	90 000 t/y → 270 000 t/y
Average capacity of one facility installed in 2026	180 000 t/y → 540 000 t/y
Average capacity of one facility installed in 2027 - 2030	Facilities built in these years cannot contribute to 2030 operational capacity because of 4 years lead time
Resulting 2030 capacity of this company	**900 000 t/y**

Assessment together with company

Own calculation

Table 3-13 Example of the methodology used for estimating the possible 2030 production capacity of the interviewed companies

Company (main fuel product)	LHV of main fuel product [MJ/kg]	resulting 2030 capacity of company [Mtoe/y]	factor for competitors doing the same	total 2030 capacity of pathway [Mtoe/y]	factor for 2050	total 2050 capacity of pathway [Mtoe/y]
Hydrotreatment of tall oil	44	0.7	1	0.7	2.5	1.7
Lignin boost of fatty acids	44	2.3	1	2.3	5	11.7
Advanced ethanol	27	1.0	5	5.0	7	34.7
ATJ	43	0.9	3	2.8	7	19.8
Gasification + methanol	20	0.3	5	1.4	7	9.7
Gasification + SNG	50	3.0	5	14.9	7	104.6
Gasification + FT	44	1.6	5	8.2	10	81.8
Pyrolysis	17	1.0	5	5.1	7	35.5
HTL	35	0.3	3	0.8	10	7.6

Table 3-14 Technically possible 2030 and 2050 production capacities of selected pathways in Mtoe/y

There is quite a number of competitors globally, so the competitors' factor was set to 5. Despite the shrinking market for gasoline substitutes post 2030, continued roll-out is assumed, since advanced ethanol will be needed for ATJ production.

Alcohol-to-Jet pathway

In the alcohol-to-jet pathway ethanol is converted into kerosene, with some renewable diesel occurring as by-product. With the likely restriction of sustainable aviation fuels to waste-based fuels in Europe, ATJ production will have to rely on advanced ethanol as a feedstock. Availability of such ethanol is currently very limited. This, and the fact that the world´s first ATJ production facility is expected to come online only next year, is reflected in the assumed ramping-up of capacities over the next years. The number of competitors is lower than for ethanol production, so the competitors' factor was set to 3. Continued roll-out towards 2050 is expected due to the expected high demand from the aviation sector.

Gasification and methanol synthesis

This technology combines gasification with methanol synthesis. The first facility of the interviewed company with 30 kt/y of production capacity is operational, and another project with around 200 kt/y is pending final investment decision. Average capacity of facilities in 2024 is assumed at 90 kt/y since another project in the pipeline is significantly smaller than the commercial capacity of 200 kt/y.

The number of competitors could be significantly higher than for ethanol production, but gasification can support several different main products, so the level of deployment of the specific combination with methanol synthesis could be comparable to advanced ethanol deployment and the competitors' factor was set to 5. Continued roll-out towards 2050 is expected since there will be high demand from shipping sector, and also – once a methanol-to-jet pathway has been certified, methanol could be further processed into sustainable aviation fuel.

Gasification and methanation

In this specific example for the gasification and methanation pathway a slow pyrolysis process is used to produce biochar which is then ground and gasified, followed by a methanation to produce biomethane. Already without the methanation step the hydrogen-rich syngas can be used as heating gas. A first facility of 3 kt/y production capacity is operating continuously and generating income by providing heating gas while gathering experience with the facility and demonstrating its reliability. Basic engineering for a first module with 11 kt/y capacity is under development, thus capacity roll-out was assumed to start in 2025 only, and also at much lower than future expected commercial capacity.

As mentioned also above, quite some competitors are around developing gasification processes, so the competitors' factor was set at 5.

Gasification and FT synthesis

AThe technology of the interviewed company for biomass gasification was demonstrated and tested at low FT synthesis capacity (lab scale), since FT production has already been demonstrated in an earlier project. Gasifier and FT synthesis can potentially build very large, making this technology first choice at sites with high biomass availability. Fossil-based gasification and Fischer-Tropsch technologies are commercial at much larger scale than biomass-based projects aim for, so the technology risk in scaling up is limited. However, the gap between demonstrated production capacity and potential commercial capacity is huge, and we have assumed limited ramp-up of capacities in the few years that – due to the long lead time of 5 years – can still contribute to 2030 capacity.

Again, there are quite some competitors around, so the competitors' factor was set to 5. A 2050 factor of 10 was applied to account for the further ramp-up of average facility production capacity.

Pyrolysis

This technology produces a fast pyrolysis bio-oil that can be used directly as heating oil, or co-processed within a refinery, or upgraded within the refinery or in a stand-alone facility. The capacity of a standard module is relatively small, but partnerships have been arranged so that 2 such modules can be built per month, giving the company the capability to support up to 24 projects per year.

The number of competitors is comparable to advanced ethanol or gasification, thus again the competitors' factor was set at 5. Roll-out towards 2050 is expected to continue along the lines to 2030.

Hydrothermal liquefaction

This technology processes biomass or waste plastic in supercritical water, creating a biocrude. The interviewed company operates a demonstration facility, and a first 25 kt/y commercial module is currently under construction hah. HTL technology has developed quickly over the past years, but since it has not yet been demonstrated at larger scale, it was assumed that the first facility in Europe would be built in 2025 only. A ramp-up of average capacity is assumed over the first years.

The number of competitors seems a bit lower than for advanced ethanol, so the competitors' factor was set to 3. The 2050 factor was set to 10 to account for the fact that 2030 production capacity is low due to later ramp-up to full commercial capacity.

Summary of estimated capacity evolution for pathways based on Annex IX Part A feedstocks

The capacity evolution of technology pathways based on Annex IX Part A feedstocks that is technically possible under the assumption that the regulatory framework would be favorable and financing would not be an issue, is presented in Figure 3-6 and Figure 3-7. Since feedstock availability can be a limiting factor (although importing feedstock would also be an option), the technically possible capacities were capped by EU feedstock availability and are presented in Figure 3-8. For correct interpretation, three facts are worth noting:

- Biomethane (both from anaerobic digestion as well as from gasification) will likely not be available to the transport sector alone, but will also be sought after by industry as well as private consumers for heat provision.
- In 2050, any ethanol produced from Annex IX Part A feedstocks is likely to be used as feedstock for ATJ production and should therefore not be included when summing up capacities to an overall figure.
- Extrapolation to 2050 capacities is highly uncertain and for the technically possible capacity evolution has been made without consideration of feedstock limitations, with exception of lipid-based pathways.

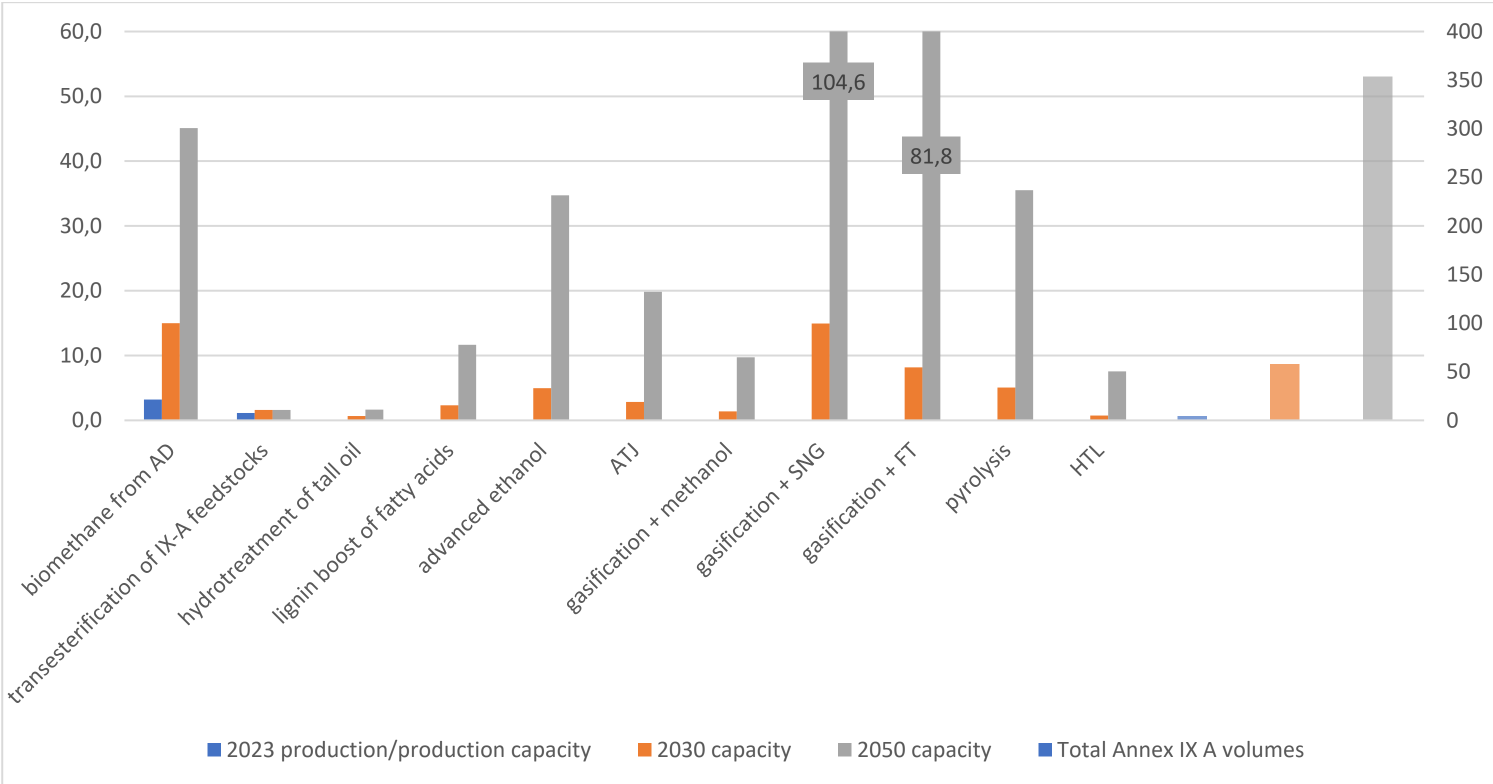
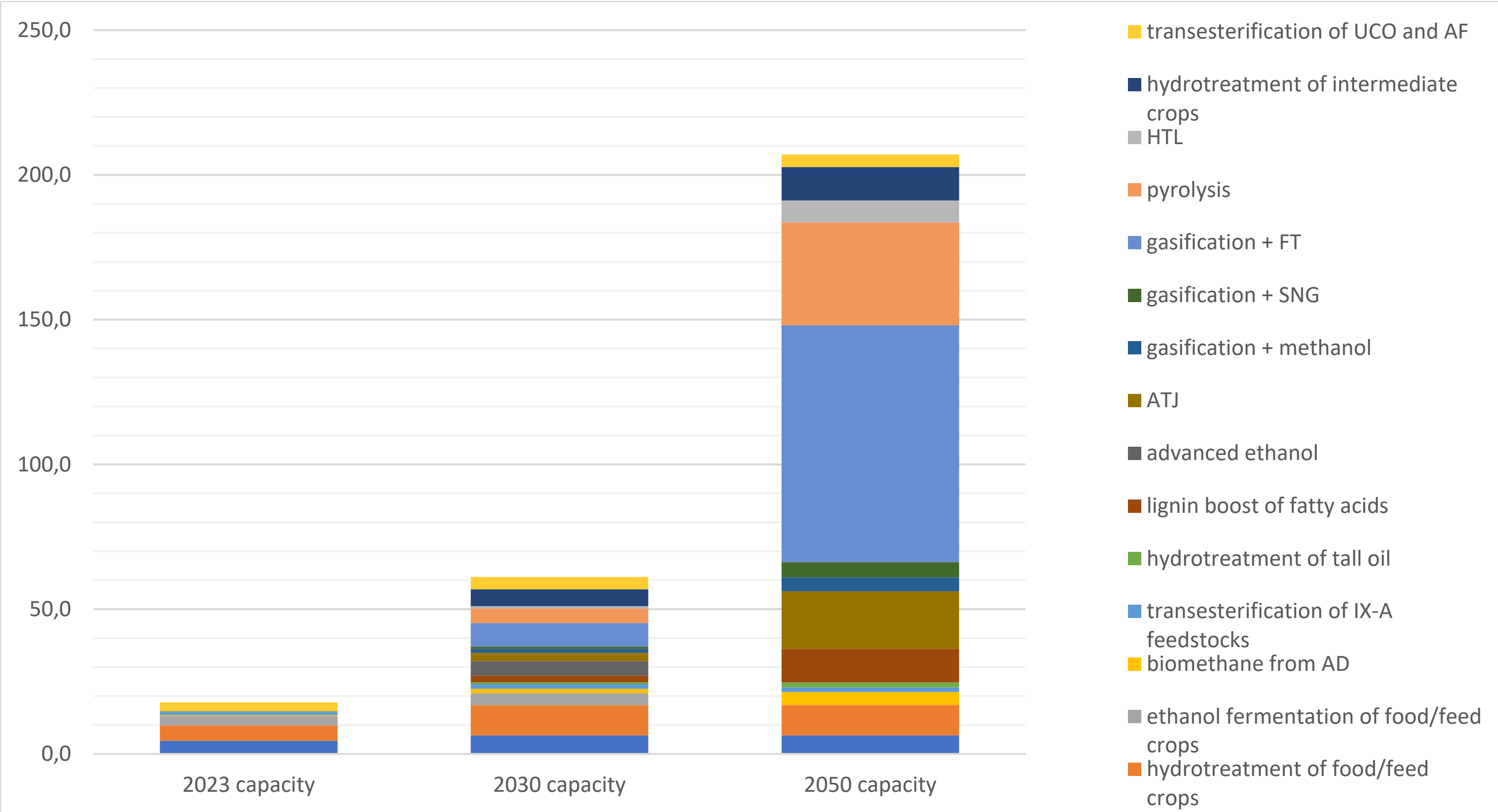
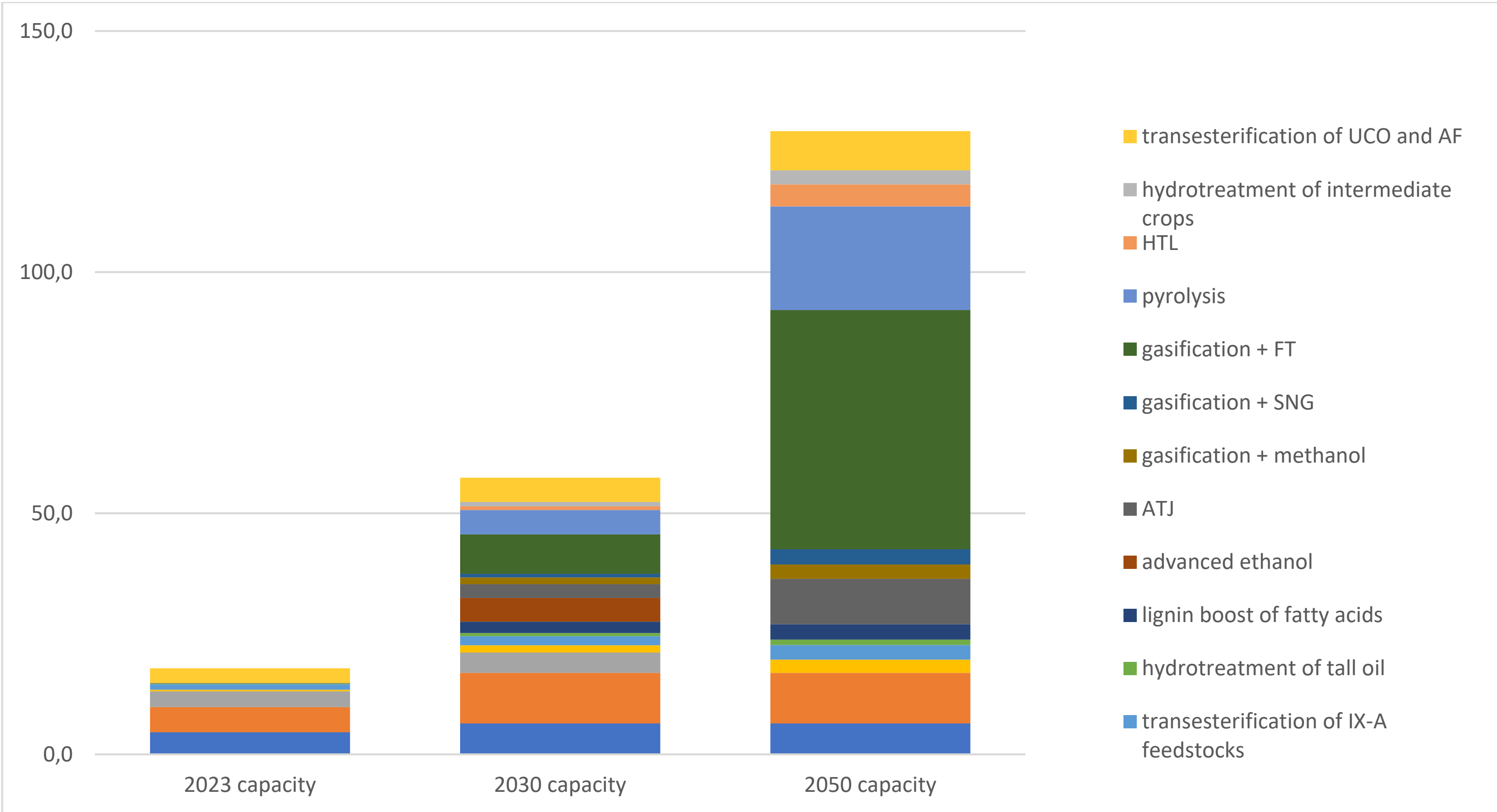


Figure 3-7 Technically possible capacity evolution from Annex IX Part A feedstocks in Mtoe/y by technology



*the same allocation of volumes to different sectors (some of them not for transport) has been made as indicated in tables 3-8, 3-9 and 3-10 for the current market conditions scenario

Figure 3-8 Estimated technically possible capacity evolution of biofuels and biomethane production available to the transport sector in Mtoe/y



*the same allocation of volumes to different sectors (some of them not for transport) has been made as indicated in tables 3-8, 3-9 and 3-10 for the current market conditions scenario

Figure 3-9 Capacity evolution capped by feedstock availability of biofuels and biomethane production available to the transport sector in Mtoe/y

3.8.3. Comparison of capacity expansion estimates for advanced biofuels and biomethane for transport

The possible capacity evolution has been estimated in three different ways. Values for 2023 combine production estimates for conventional biofuels and capacity estimates for advanced biofuels. The figure below shows the evolution of capacities for the production of advanced biofuels and biomethane from Annex IX A feedstocks.

- The "current market conditions (cmc)" estimate is based on current market conditions and considers investor´s appetite as the main barrier to advanced biofuels deployment. The resulting capacity estimates are at the low end of the spectrum.

- The "technically possible capacities (tpc)" estimate considers an entirely favourable regulatory environment and no restrictions to capacity evolution other than the ability of current technology leaders to support multiplication of their technologies. As a result the estimates are at the high end of the spectrum.

- The "capped by feedstock capacities (cbf)" estimate is based on the tpc scenario but considers limitations by feedstock (based on the high availability scenario elaborated in Task 2, and not considering feedstock imports).

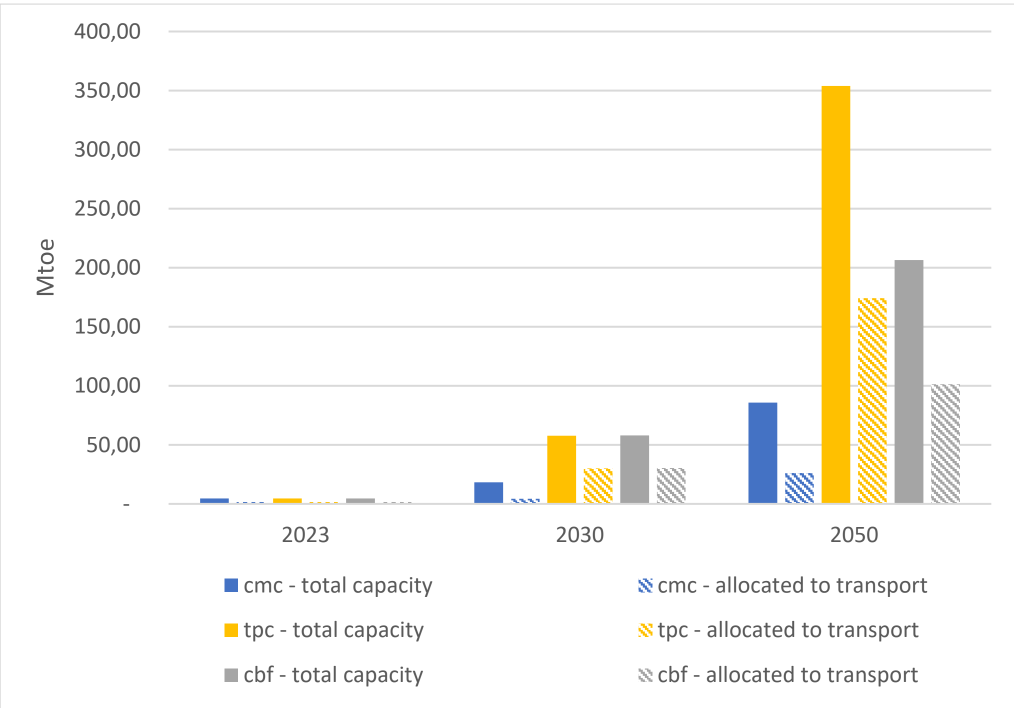


Figure 3-10 Evolution of advanced biofuels and biomethane production and capacities from Annex IX A feedstocks in all three scenarios (in Mtoe)

	Capacity 2023	Capacity 2030	Capacity 2050
Current market conditions (cmc)			
Total volume	**20.7**	**41.5**	**111.9**
Conventional	13.0	14.1	14.1
Annex IX Part A	4.6	18.4	85.8
Advanced biofuels	*1.4*	*3.4*	*40.7*
Biomethane	*3.2*	*15.0*	*45.1*
Annex IX Part B	3.1	9.0	12.0
Technically possible capacities (tpc)			
Total volume	20.7	88.8	390.7
Conventional	13.1	21.0	21.0
Annex IX Part A	4.6	57.7	353.8
Advanced biofuels	*1.4*	*42.7*	*308.7*
Biomethane	*3.2*	*15.0*	*45.1*
Annex IX Part B	3.1	10.1	15.9
Capped by feedstock (cbf)			
Total volume	20.7	85.1	238.5
Conventional	13.1	21.1	21.0
Annex IX Part A	4.6	58.0	206.5
Advanced biofuels	*1.4*	*43.0*	*179.0*
Biomethane	*3.2*	*15.0*	*27.5*
Annex IX Part B	3.1	5.9	11.0

Table 3-15 Evolution of total biofuels and biomethane production and capacities in all three scenarios (in Mtoe, all feedstocks, entire production)

	Capacity 2023	Capacity 2030	Capacity 2050
Current market conditions (cmc)			
Total volume	**17.8**	**27.4**	**48.5**
Conventional	13.0	14.1	10.4
Annex IX Part A	1.7	4.3	26.2
Advanced biofuels	*1.4*	*2.8*	*21.7*
Biomethane	*0.3*	*1.5*	*4.5*
Annex IX Part B	3.1	9.0	12.0
Technically possible capacities (tpc)			
Total volume	**17.8**	**61.1**	**207.0**
Conventional	13.1	21.0	16.9
Annex IX Part A	1.7	30.0	174.3
Advanced biofuels	*1.4*	*28.5*	*169.7*
Biomethane	*0.3*	*1.5*	*4.5*
Annex IX Part B	3.1	10.1	15.9
Capped by feedstock (cbf)			
Total volume	**17.8**	**57.4**	**129.2**
Conventional	13.1	21.1	16.9
Annex IX Part A	1.7	30.3	101.3
Advanced biofuels	*1.4*	*28.8*	*98.5*
Biomethane	*0.3*	*1.5*	*2.7*
Annex IX Part B	3.1	5.9	11.0

Table 3-16 Evolution of total biofuels and biomethane production and capacities available to the transport sector in all three scenarios (in Mtoe, all feedstocks)

4. Summary and conclusions

Current production of biofuels in Europe is around 20.7 Mtoe/y, with FAME providing the main share of this (9.9 Mtoe/y), followed by HVO and conventional ethanol at 5.4 Mtoe/y and 3.2 Mtoe/y respectively. Production capacity for biomethane from anaerobic digestion is at 3.8 billion m^3/y (3.2 Mtoe/y), but given the high demand for natural gas substitutes from many other sectors, we estimate that only 10% of this amount is available to the transport sector. Advanced biofuel production capacities are still very small in Europe, with advanced ethanol and pyrolysis oil production together amounting to only 170,000 toe/y.

Most of the feedstocks used in current biofuels production are crops or grains. Only 30% of feedstocks used in FAME production are wastes, most of which is UCO. UCO is a highly contested feedstock and UCO prices are twice the price of virgin vegetable oil. HVO production relies on the same feedstocks as FAME. Ethanol production is also largely based on food/feed crops, while biomethane production from anaerobic digestion is based on sequential crops as well as on various wastes and residues. Except for the competition on UCO supply and some competition for saw mill residues, current producers do not consider feedstock supply to be constrained, and additional amounts of sustainable forestry residues could still be made available. Also, intermediate crops could be able to provide significant amounts of feedstocks, if they become eligible as feedstock for advanced biofuels and can be mobilized accordingly.

Feedstock supply is expected to be an issue with respect to scaling up the production of SAF. Since these will have to be based on wastes and residues, the availability of UCO will largely determine initial SAF production capacity through the HEFA pathway. Measures should be taken to increase UCO collection from households in Europe, as to be independent from UCO supply from Asia. However, further SAF volumes will need to come from other production pathways, such as ATJ and Fischer-Tropsch. The ATJ pathway relies on ethanol, and given the very low availability of waste and residue-based ethanol in Europe, imports will be needed to fulfil SAF demand. This could be avoided if the list of raw materials eligible for SAF production was revised.

The availability of skilled workers to support biofuels production is not seen problematic by biofuel producers. Neither the companies who responded to the survey nor the associations interviewed voiced any major concerns. The number of skilled workers needed to operate biofuel facilities is generally low. Only the refinery sector mentioned the need for many skilled operators, but expects that workers laid off due to the expected decrease in fossil refining capacities will be able to support the growing biorefining sector.

Production costs of biofuels are largely dominated by feedstocks costs. Due to higher CAPEX requirements of advanced ethanol, pyrolysis and gasification technologies (ranging from 2,000 to 4,500 EUR/kW product), capital costs can make up a larger share in biofuel production costs than for the well-established current production technologies. HVO/HEFA production can often be integrated into refineries and leverage on existing equipment and utilities and show lowest specific CAPEX in the range of 200 to 600 EUR/kW. This provides HVO/HEFA with a big advantage versus advanced biofuel production technologies and explains the massive ramping up of production capacities.

Biofuel prices are often much higher than their fossil equivalents. According to Fuels Europe, most technologies have a long-term potential to cost 1.5 to 2€/l. Respondents to the industry survey considered prices of 800 – 1.200 €/t for advanced ethanol, 2,300 – 3,600 €/t for biokerosene, and 775 – 1,500 €/t for biomethanol to be acceptable.

Biofuel production technologies continue to be further developed and optimized. Under current market and regulatory conditions, advanced ethanol, pyrolysis oil, and gasification for production of SNG could already contribute to advanced biofuels production shortly after 2030. Further technologies such as gasification with subsequent Fischer-Tropsch synthesis for SAF production, alcohol-to-jet, and hydrothermal liquefaction are expected to be further developed and demonstrated and to contribute to advanced biofuels production sometime after 2035 under current market conditions.

In addition to these technologies, further innovations include:

- The production of e-methane through addition of hydrogen to biogas production
- The processing of waste-based feedstocks and oils from crops cultivated on marginal lands or intermediate crops in FAME or HVO production
- The production of high-protein food for human consumption along with ethanol production
- The capturing and upgrading or storing of CO2 from ethanol facilities
- The gasification of wastes and residues and subsequent gas cleaning ahead of the synthesis reactions
- The development of catalytic hydrothermal gasification
- The doubling of lipid-based biofuel production through adding depolymerised lignin from pulp production
- The use of CO2 from biofuel production facilities for the production of RFNBOs

Large investments into large-scale advanced biofuels demonstrations will be needed to fully bring these technologies to maturity and further deploy them at commercial scale. Public support through grants and loans as well as equity are needed to trigger these investments. Although there are no EU programs that explicitly support the erection of advanced biofuels installations, many programs would see such projects as eligible. In some member states also national programs are available, but in a high number of member states the project team could not find any such programs.

Investments in large-scale demonstrations as well as in commercial production facilities will be attractive when there is foreseeable market demand and benefit to make over a few decades. Investments in upcoming technologies will start at lowest perceived risk, essentially where CAPEX is rather low, or retrofitting existing facilities where possible. As more technologies reach market maturity, they will start adding to the picture. Technology deployment can be significantly triggered through bold investment incentives or other market mechanisms reducing the risk for investors, as can be seen from the difference in capacity deployment by 2030 in the two different assessments undertaken. Feedstock availability is a pre-requisite to obtain project funding, but will become a deployment limiting factor only once deployment has reached a scale that creates feedstock constraints. Demand from other sectors, e.g. the chemical industry or the decarbonization of gas use or even the aviation and shipping sector, can drive the installation of facilities while concurrently competing for feedstocks and fuels. Note that sectors or countries that have mandates that are based on GHG emission reductions rather than volumes or energy content will have a different merit order of fuels.

With the revised Renewable Energy Directive and ReFuelEU Aviation and FuelEU Maritime becoming effective in the near future, the demand for renewable transport fuels in the EU will continue to increase. Both the aviation and the shipping sector are expected to pull for biofuels and divert them from the road sector, hereby creating no-regret opportunities for investments today even for advanced ethanol production, despite the expected future shrink in market demand for gasoline substitutes.

Under current market conditions, overall biofuel and biomethane[17] production capacity that is assumed available to the transport sector can be ramped up from 18 Mtoe/y in 2023 to 27 Mtoe/y in 2030 and 49 Mtoe/y in 2050. Estimated contributions of specific fuels in 2023 are 13.0 Mtoe/y conventional biofuels, 1.7 Mtoe/y advanced biofuels and biomethane and 3.1 Mtoe/y biofuels based on Annex IX Part B feedstocks; 14.1 Mtoe/y conventional biofuels, 4.3 Mtoe/y advanced biofuels and biomethane and 9.0 Mtoe/y biofuels based on Annex IX Part B feedstocks in 2030; and 10.4 Mtoe/y conventional biofuels, 26.2 Mtoe/y advanced biofuels and biomethane and 12.0 Mtoe/y biofuels based on Annex IX Part B feedstocks in 2050. FAME and HVO/HEFA will continue to provide most of the biofuels in 2030, with other fuels such as FT-SPK, ATJ from advanced ethanol, and biomethane expected to become important by 2050. Conventional ethanol is expected to be phased out by 2050 due to the electrification of the car pool; any production is expected to go to the biochemicals sector, or to ATJ production in case that it would be an eligible feedstock by that time. Production capacities for biomethane could actually contribute more than indicated above, but due to the large competition for natural gas substitutes from other sectors, only 10% of capacity was assumed to be available to the transport sector.

When assessed under the assumption that the regulatory environment is absolutely favorable and money for investments is readily available, technically possible capacity of overall biofuel and biomethane production that is assumed available to the transport sector could even increase to 61 Mtoe/y in 2030 and 207 Mtoe/y in 2050. To this, conventional biofuels will provide 21 Mtoe/y in 2030 and 17 Mtoe/y in 2050, with advanced biofuels and biomethane (produced from Annex IX Part A feedstocks) contributing 30 and 174 Mtoe/y in 2030/2050 respectively and biofuels from Annex IX Part B feedstocks contributing 10 and 16 Mtoe/y respectively.

When capped by feedstock availability, biofuel and biomethane capacity that is assumed available to the transport sector are lower: 57 Mtoe/y of overall biofuel production in 2030 and 129 Mtoe/y in 2050.

Expected biofuel demand in 2030 as calculated by Task 1 is between 23 and 40 Mtoe/y, while our first estimate (based on current market and regulatory conditions) provides 27 Mtoe/y. Most challenging is the provision of biofuels and biomethane produced from Annex IX Part A feedstocks. While the expected Annex IX Part A biofuels and biomethane demand is between 6 and 18.4 Mtoe/y (see Task 1), the estimated production capacity available to the transport sector is 4.3 Mtoe/y. Oil crops cultivated as intermediate crops are expected to be included in Annex IX Part B in the future and when accounting for these on top of UCO and animal fats, Annex IX Part B-based biofuels could contribute 9.0 Mote/y by 2030. It is worth noting that supply chains for such intermediate crops would still need to be developed to cover this demand. Also, note that the estimate only includes 10% of the estimated 15 Mtoe/y of biomethane production capacity from anaerobic digestion; raising the share available to

[17] Note that in the Renewable Energy Directive biogas is defined as biogas for transport, i.e. biomethane. In the revised Renewable Energy Directive of 2023, the expression “biogas for transport” replaces the earlier wording of “biogas”, hereby providing more clarity. In this report, too, biogas refers to biogas for transport, i.e. biomethane.

transport and usable in transport (i.e. sufficient vehicles, most likely LNG trucks) would largely support reaching the 2030 targets for advanced biofuels and biomethane. Finally, it is worth noting that under current market conditions, the contribution of biofuels produced from lignocellulosic materials is only 1.1 Mtoe/y, while the potential contribution (see second estimate) is around 26 Mtoe/y; bold incentives will be required to push this specific set of technologies.

When comparing the expected biofuel demand in 2030 to the second estimate (technically possible capacity), the possible expansion of advanced biofuels and biomethane production capacities from Annex IX A feedstocks that is assumed available to the transport sector of 30 Mtoe/y can easily meet the expected demand, and this doesn´t change when considering EU feedstock availability.

Thus, we can conclude that, if the regulatory environment is adapted and successfully triggers investors' appetite, advanced biofuels production capacities can be expanded as needed to reach the 2030 targets. A high number of companies with background from different sectors (chemicals, pulp & paper, refining) is developing various technologies for the production of transport biofuels. The companies interviewed were all well prepared to support industrial deployment of advanced biofuels production once conditions will be favourable. There is a window of opportunity for such investments right now, since EU regulation is just being finalized, and will remain unchanged until the next cabinet of the European Commission will settle in and probably pursue different priorities towards the end of 2024.

The high diversity of biofuel technologies, the sourcing of feedstocks from different sectors (agriculture, forestry, pulp & paper, agro-processing, wood-processing, waste processing, industrial flue gases and potentially also aquatic biomass/algae) and the flexibility of most technologies in terms of final product is a strong asset, since this will allow to adapt to changing market needs. Also, the multitude of technology providers is an asset, increasing the chances of reaching the advanced biofuels targets even if some of the facilities to be installed will likely fail economically. We as a society must be prepared to lose some money through failures for the benefit of developing and deploying the best-performing technologies.

The development of viable production technologies can take years to decades, as can be seen from the time that many of the actors are already active in the biofuels sector. Also, the lead time for viable projects is quite significant, with up to 2 years for pre-feasibility and feasibility studies often needed to e.g. allow sufficient access to biomass feedstock, and up to 3 years from final investment decision to full operation ability at nameplate capacity of the facility. This leaves us with little time to set up advanced biofuel production facilities that can still contribute to achieving the 2030 targets. It is high time to publish the final regulations and put in place bold incentives to stimulate this deployment.

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Industry declares ready to invest and estimates that the capacity expansion, in EU, for advanced biofuels and biomethane, satisfying demand of all sectors could reach 23.6 Mtoe/y in 2030. Lignocellulosic materials are expected to contribute 1.6 Mtoe/y, while advanced ethanol technology deployment may be limited until 2030. Technically, capacity expansion could be expedited, with numerous technology providers nearing the commercialization of their technologies and ready to support multiple projects.

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