ISSN 1831-9424

European Commission

CLEAN ENERGY TECHNOLOGY OBSERVATORY

Advanced Biofuels in the European Union

STATUS REPORT ON TECHNOLOGY DEVELOPMENT, TRENDS, VALUE CHAINS & MARKETS

2024

Joint Research Centre

EUR 40060

Contact information
Name: Nicolae Scarlat
Address: Joint Research Centre, Ispra, Italy
Email: Nicolae.SCARLAT@ec.europa.eu

EU Science Hub
https://joint-research-centre.ec.europa.eu

JRC139335

EUR 40060

PDF ISBN 978-92-68-20959-2 ISSN 1831-9424 doi:10.2760/6538066 KJ-01-24-063-EN-N

Luxembourg: Publications Office of the European Union, 2024

How to cite this report: European Commission, Joint Research Centre, Motola, V .Scarlat, N., Buffi, M., Hurtig, O., Rejtharova, J., Georgakaki, A., Mountraki, A., Letout, S., Salvucci, R., Rózsai, M. and Schade, B., *Clean Energy Technology Observatory: Advanced Biofuels in the European Union - 2024 Status Report on Technology Development, Trends, Value Chains and Markets*, Publications Office of the European Union, Luxembourg, 2024, https://data.europa.eu/doi/10.2760/6538066, JRC139335.

Contents

Abstract

The report provides a detailed examination of the biofuel sector and advanced biofuel sector within the European Union (EU), focusing on its economic, environmental, and technological dimensions. The report is an update of the CETO 2023 report. The EU is highlighted as the central point of view, with specific references to EU Member States showcasing their roles in the sector.

The report is essential for understanding the multifaceted role of advanced biofuels in the EU's strategy to reduce greenhouse gas emissions and enhance energy security. The report underscores the EU's commitment through various policies and directives, such as the Renewable Energy Directive and its amendment, which set sustainability criteria and define advanced biofuels. The report details the EU's leadership in scientific publications and high-value patents in the advanced biofuel sector. It gives insights into the current state of innovation and the areas where the EU is leading. The report delves into technological advancements and challenges in the biofuel sector. It discusses various advanced biofuel technologies currently being developed and commercialised. The report covers the trends in installed capacity and production of biofuels within the EU, providing a comparative analysis with other regions. It details the production capacities and operational plants for bioethanol and biodiesel. The report provides comprehensive data on the economic contributions of the advanced biofuel sector to the EU's economy. The report details the sector's impact on GDP and employment, highlighting the significant contributions from operation and maintenance, feedstock supply, construction, and equipment manufacturing.

The report emphasises the importance of continued investment, technological development, and international collaboration to ensure the advanced biofuel sector's growth and sustainability.

Foreword on the Clean Energy Technology Observatory

The European Commission set up the Clean Energy Technology Observatory (CETO) in 2022 to help address the complexity and multi-faced character of the transition to a climate-neutral society in Europe. The EU's ambitious energy and climate policies create a necessity to tackle the related challenges in a comprehensive manner, recognizing the important role for advanced technologies and innovation in the process.

CETO is a joint initiative of the European Commission Joint Research Centre (JRC), that run the observatory, and Directorate Generals Research and Innovation (R&I) and Energy (ENER) on the policy side. Its overall objectives are to:

- monitor the EU research and innovation activities on clean energy technologies needed for the delivery of the European Green Deal
- assess the competitiveness of the EU clean energy sector and its positioning in the global energy market
- build on existing Commission studies, relevant information & knowledge in Commission services and agencies, and on the Low Carbon Energy Observatory (2015-2020)
- publish reports on the Strategic Energy Technology Plan (SET-Plan) SETIS online platform

CETO provides a repository of techno- and socio-economic data on the most relevant technologies and their integration in the energy system. It targets in particular the status and outlook for innovative solutions as well as the sustainable market uptake of both mature and innovative technologies. The project serves as primary source of data for the Commission's annual progress reports on competitiveness of clean energy technologies. It also supports the implementation of and development of EU research and innovation policy.

The observatory produces a series of annual reports addressing the following themes:

- Clean Energy Technology Status, Value Chains and Market: covering advanced biofuels, batteries, bioenergy, carbon capture utilisation and storage, concentrated solar power and heat, geothermal heat and power, heat pumps, hydropower & pumped hydropower storage, novel electricity and heat storage technologies, ocean energy, photovoltaics, renewable fuels of non-biological origin (other), renewable hydrogen, solar fuels (direct) and wind (offshore and onshore).
- Clean Energy Technology System Integration: building-related technologies, digital infrastructure for smart energy system, industrial and district heat & cold management, standalone systems, transmission and distribution technologies, smart cities and innovative energy carriers and supply for transport.
- Foresight Analysis for Future Clean Energy Technologies using Weak Signal Analysis
- Clean Energy Outlooks: Analysis and Critical Review
- System Modelling for Clean Energy Technology Scenarios
- Overall Strategic Analysis of Clean Energy Technology Sector

More details are available on the CETO web pages

Acknowledgements

The authors would like to thank:

- Maria Georgiadou (DG RDT) for her review and comments.
- Nigel Taylor (CETO project leader), JRC.C.2, for support, review and comments.
- The JRC.C.6 energy system modelling teams for providing energy scenarios:
    - from POTEnCIA: Wegener, M., Jaxa-Rozen, M., Gea Bermudez, J., Neuwahl, F., R., Sikora.
    - from POLES-JRC: Schmitz A., Keramidas, K., Fosse, F., Dowling, P, Russ, P.

Authors:

Vincenzo Motola, Jana Rejtharova, Nicolae Scarlat, Oliver Hurtig, Marco Buffi - JRC Ispra Unit C.2

Aliki Georgakaki, Simon Letout and Aikaterini Mountraki - JRC Petten Unit C.7

Raffaele Salvucci, Máté Rózsai, Burkhard Schade - JRC Seville Unit C.6

Executive Summary

The report provides a comprehensive overview of the biofuel sector in the European Union, highlighting its economic, environmental, and technological aspects. It is an update of the CETO 2023 report. The EU has been actively promoting the production and use of biofuels to reduce greenhouse gas emissions and enhance energy security. This commitment is reflected in various policies and directives, including the Renewable Energy Directive (RED II) and its amendment Directive (EU) 2023/2413, through Commission delegated directive (EU) 2024/1405. These legislative instruments set out sustainability criteria and define advanced biofuels, mitigating negative impacts on land use and biodiversity.

Private RD&I funding and investments are crucial for fostering innovation and economic growth within the EU. Private equity and venture capital are the main forms of private RD&I funding, with global investments in biofuel companies exceeding EUR 2 billion between 2018 and 2023. In 2022 alone, these investments surpassed EUR 500 million, doubling the amount from 2021. This influx of private funding underscores the growing interest and potential in the biofuel sector.

The EU's leadership in scientific publications and high-value patents in the advanced biofuel sector is well-established. The EU consistently produces 40-50 scientific publications annually, with 61 highly cited publications accounting for 32% of the top 10% most cited papers in the field. This success is attributed to the EU's emphasis on high-impact research and international collaborations, particularly with the United States. The EU also holds a 59% share of high-value patents out of 489 applications for the triennium 2019-2021, focusing on climate change mitigation, renewable energy, and the reduction of greenhouse gas emissions in energy generation, transmission, or distribution.

The biofuel sector significantly contributes to the EU's economy. According to economic data from EurObserv'ER, the industry's turnover peaked in 2018 at EUR 13,700 million, saw a decline to EUR 12,070 million in 2021, and experienced a slight recovery to EUR 12,220 million in 2022. A Deloitte (Deloitte, 2022) report estimated that the biofuel sector had a direct GDP impact of EUR 2,304 million in 2020, with an indirect GDP impact of EUR 6,621 million, bringing the total to EUR 8,925 million. The sector's direct contributions are primarily concentrated in operation and maintenance, which accounted for EUR 1,530 million, with other areas of impact including the supply of feedstock, construction, and equipment manufacturing.

The report also highlights the technological advancements and challenges in the biofuel sector. Several advanced biofuel technologies are currently being developed and commercialised. Technologies for obtaining intermediate bioenergy carriers include pre-treatment and enzymatic hydrolysis to sugars, hydrothermal gasification, oil extraction from algae, and hydrothermal liquefaction to bio-crude. Fuel synthesis and upgrading encompass various technologies aimed at converting biomass and other feedstocks into high-quality biofuels. Europe is a leader in Hydrotreated Vegetable Oil and Hydroprocessed Esters and Fatty Acids production, with several commercial plants in operation.

Installed capacity and production of biofuels have been on the rise globally and within the EU. The EU has a higher number of advanced biofuels operational plants compared to other regions. Ethanol production in the EU was around 5 billion litres from 2015 to 2022, with production staying below 60% of nominal capacity on average. In 2022, there were 52 refineries producing conventional ethanol and three refineries producing cellulosic ethanol fuel. Biodiesel production capacity in the EU remained steady at around 16 billion litres per year between 2015 and 2022, with production at around 80% of nominal capacity in 2022. The number of refineries producing biodiesel was 162 in 2022, with 17 refineries producing renewable diesel. The share of renewable diesel produced from feedstocks listed in Annex IX of RED II in the total biodiesel produced in the EU reached 21.69% in 2022, mainly due to the use of used cooking oil. Advanced ethanol accounted for only 0.76% of total ethanol production.

Public investment in Research, Development, and Innovation (RD&I) is also crucial for advancing the EU's objectives in sustainable energy and climate action. From 2020 to 2021, public RD&D investment in liquid biofuels averaged around EUR 50 million annually. In 2022, there was a substantial increase in funding, with around EUR 250 million mostly to classified unallocated biofuels. The unallocated biofuels are not assigned to a specific use or destination, allowing for greater flexibility in their application as technological and market needs evolve. This significant investment supports a wide range of biofuel technologies, covering the entire value chain from feedstock production to pre-treatment, intermediate bioenergy carrier production, liquid fuel synthesis, and upgrading for use in road, maritime, and aviation fuels.

The biofuels sector has contributed to employment within the EU, although there has been a decline in job numbers from 239,600 in 2018 to 149,700 in 2022. The sector's impact on jobs, expressed in Full Time Equivalent (FTE), reached 219,651 in 2019, with significant contributions from equipment manufacturing, construction, supply of feedstock, and operation and maintenance. The EU is addressing challenges such as the rural location of biorefineries and the transition of skilled workers from the fossil fuel industry to the biofuels sector.

Energy intensity and labour productivity are critical indicators for assessing the efficiency and sustainability of the biofuel sector. In 2020, the total biofuel production in the EU was 15,763 kilotonnes of oil equivalent (ktoe), contributing EUR 8,925 million to the GDP, resulting in an energy intensity of 1.77 ktoe per million euros. Labour productivity in the bioenergy sector is approximately 122 thousand euros per FTE per year, with each FTE producing around 10 terajoules of energy annually.

The EU's trade in biofuels shows a strong global presence. In 2023, extra-EU exports of biodiesel increased by 47%, while imports decreased by 27%, leading to a significant reduction in the trade deficit. The EU faces challenges in the bioethanol market, with a stable trade deficit and lower value per quantity of exports. The EU exports biofuels at a higher value per kilo than it imports, indicating a competitive advantage, but production needs to keep up with demand to maintain this advantage.

The report highlights the importance of technological learning and increased production capacities in driving down costs and making advanced biofuels more economically viable. The EU's focus on advanced biofuels is expected to play a crucial role in achieving its energy and climate goals, while also supporting economic development and job creation in the EU.

Table 1. CETO SWOT analysis for the competitiveness of biofuels.

Strengths	**Weaknesses**
• several technologies are available and/or getting close to commercialisation • available option now for the GHG emission reduction of hard to decarbonise sectors such as aviation, shipping, and heavy road freight transport • can be produced from a wide range of sustainable feedstocks like wastes and residues (available in substantial amounts in some areas) • can use existing fuel infrastructure with little or no additional investments needed • can be blended with fossil fuels, or used as drop-in fuels without modifications to engines • high greenhouse gas emission reduction potential	• several technologies like aquatic biomass to advanced biofuels, Dark / light fermentation to hydrogen are not yet demonstrated in commercial operation • limited feedstock resources from residues and waste in some areas • need industrial large-scale facilities to benefit from scale effect • complex logistics for collection, transport and storage related to low energy density and variable characteristics • complex technologies, based on a combination of thermochemical and biological processes at different development levels • high initial investment for plant construction • high fuel production cost compared to fossil fuels • economic viability depends on availability of low-cost feedstock
Opportunities	**Threats**
• contribution to energy supply diversification and energy security • contribution to decarbonisation of transport and the reduction of fossil fuel imports • synergies between traditional fuels and chemicals production in combined biorefineries, with the aim better exploit infrastructures and logistic • employment and business opportunities along the supply chain • potential driver of agriculture, forestry and industrial development in rural areas • potential contribution to the remediation of marginal and degraded land, when feedstock cultivation is made complies with sustainability criteria	• high technological and economic risks • competition with alternative uses of feedstock • reduced availability and affordability of feedstock in the long term • slow market uptake due to insufficient incentives • failure to reach cost competitiveness through technology improvement and scale-up • lack of stable policy framework, lack of long term policy perspectives • low public awareness and public acceptance • lack of adequate incentives for large scale deployment (including for biomass supply chains) • EV technology advances like for heavy duty road transport electrification

Source: JRC 2024 analysis

1 Introduction

1.1 EU legislative context

Directive 2009/28/EC (RED I) introduced a set of sustainability criteria for biofuels, including criteria protecting land with high biodiversity value and land with high-carbon stock. The Directive (EU) 2018/2001 RED II defined reinforced EU sustainability criteria for biofuels used in transport as well as for solid and gaseous biomass fuels for heat and power. The revised Renewable Energy Directive (EU/2023/2413) RED III provides an overarching policy for the promotion and use of energy from renewable sources in the EU. It also reinforces the sustainability criteria of bioenergy through different provisions, including the negative direct impact that the production of biofuels may have due to indirect land use change. The goal is to deliver high greenhouse gas emission savings and not cause deforestation or degradation of habitats or loss of biodiversity, while promoting efficient use and avoid unintended impacts on other uses. Biofuels should not be produced from raw materials originating from: high biodiversity land primary forests; areas designated for nature protection or for the protection of rare and endangered ecosystems or species; highly biodiverse grasslands; high carbon stock land (wetlands, continuously forested land or other forested areas); peatland (as of January 2008).

Sustainability criteria regulate land-use, land-use change and forestry (LULUCF) criteria and changes in carbon stock associated with biomass harvest. Moreover, RED II defines low ILUC-risk biofuels according to the Delegated Regulation (EU) 2019/807, which defines high ILUC-risk fuels and sets out criteria for the certification of low ILUC-risk fuels that should be exempt from the specific and gradually decreasing limit for food- and feed-based biofuels. Therefore, advanced biofuels are those fuels produced using only specific feedstock listed in the Annex IX of the RED II. For example, used cooking oils, waste lipids, residual biomasses, wastes and their derived bio-intermediates (e.g. bio-crudes produced from lignocellulosic material) can be used as feedstock to produce advanced biofuels for the EU market. (European Parliament, 2018)(European Parliament, 2018)(European Parliament, 2018)(European Parliament, 2018)(European Parliament, 2018)(European Parliament, 2018)The list also includes many types of wood- and agro- residues, animal manure, sewage sludge, and algae, as well as other biowaste-derived materials, plus more general lignocellulosic materials. The European Commission may adopt specific delegated acts to expand this list based on scientific advice, while it cannot remove items.

The new RED III rules establish an overall target for transport aiming to 14.5% GHG reduction, or 29%renewable share. Concerning Sustainable Aviation Fuel SAF a target of 6% energy share by 2030, regarding maritime 6% GHG reduction as for 2030. There are binding combined sub-target of 5.5% for advanced biofuels (generally derived from non-food-based feedstocks) and renewable fuels of non-biological origin (mostly renewable hydrogen and hydrogen-based synthetic fuels) in the share of renewable energies supplied to the transport sector. Within this target, there is a minimum requirement of 1% of renewable fuels of non-biological origin (RFNBOs) in the share of renewable energies supplied to the transport sector in 2030.

As regards the sustainability issues, biofuels should comply with the sustainability and GHG emission saving criteria. RED II includes “no-go” areas for which there is no public support to biofuels, to preserve primary forests, highly biodiverse areas, wetlands and protected areas. The use of food and feed crops-based biofuels is capped and, according to the criteria set by RED II, such fuels are required to pass a GreenHouse Gas (GHG) reduction threshold, the same as the other biofuels to be considered eligible. These requirements are 50-65% for biofuels, depending on the date of facility construction, and 70% for RFNBOs & Recycled Carbon Fuels (RCFs).

Finally, advanced biofuels can also contribute to the targets imposed by the ReFuelEU and FuelEU Maritime regulations, which set a target of 63% of Sustainable Aviation Fuels (SAFs) and -75% as GHGs reduction intensity respectively, by 2050.

According to RED III (ANNEX IX Part A), fuels produced from the following feedstocks can be considered as advanced biofuels, last update COMMISSION DELEGATED DIRECTIVE (EU) 2024/1405

- (a) Algae if cultivated on land in ponds or photobioreactors;

- (b) Biomass fraction of mixed municipal waste, but not separated household waste subject to recycling targets under point (a) of Article 11(2) of Directive 2008/98/EC;
- (c) Biowaste as defined in point (4) of Article 3 of Directive 2008/98/EC from private households subject to separate collection as defined in point (11) of Article 3 of that Directive;
- (d) Biomass fraction of industrial waste not fit for use in the food or feed chain, including material from retail and wholesale and the agro-food and fish and aquaculture industry, and excluding feedstocks listed in part B of this Annex;
- (e) Straw;
- (f) Animal manure and sewage sludge;
- (g) Palm oil mill effluent and empty palm fruit bunches;
- (h) Tall oil pitch;
- (i) Crude glycerine;
- (j) Bagasse;
- (k) Grape marc and wine lees;
- (l) Nut shells;
- (m) Husks;
- (n) Cobs cleaned of kernels of corn;
- (o) Biomass fraction of wastes and residues from forestry and forest-based industries, namely, bark, branches, pre- commercial thinning, leaves, needles, treetops, saw dust, cutter shavings, black liquor, brown liquor, fibre sludge, lignin and tall oil;
- (p) Other non-food cellulosic material;
- (q) Other lignocellulosic material except saw logs and veneer logs.
- (r) Fuel oils from alcoholic distillation;
- (s) Raw methanol from kraft pulping stemming from the production of wood pulp;
- (t) Intermediate crops, such as catch crops and cover crops that are grown in areas where due to a short vegetation period the production of food and feed crops is limited to one harvest and provided their use does not trigger demand for additional land, and provided the soil organic matter content is maintained, where used for the production of biofuel for the aviation sector; (u) Crops grown on severely degraded land, except food and feed crops, where used for the production of biofuel for the aviation sector;
- (v) Cyanobacteria.

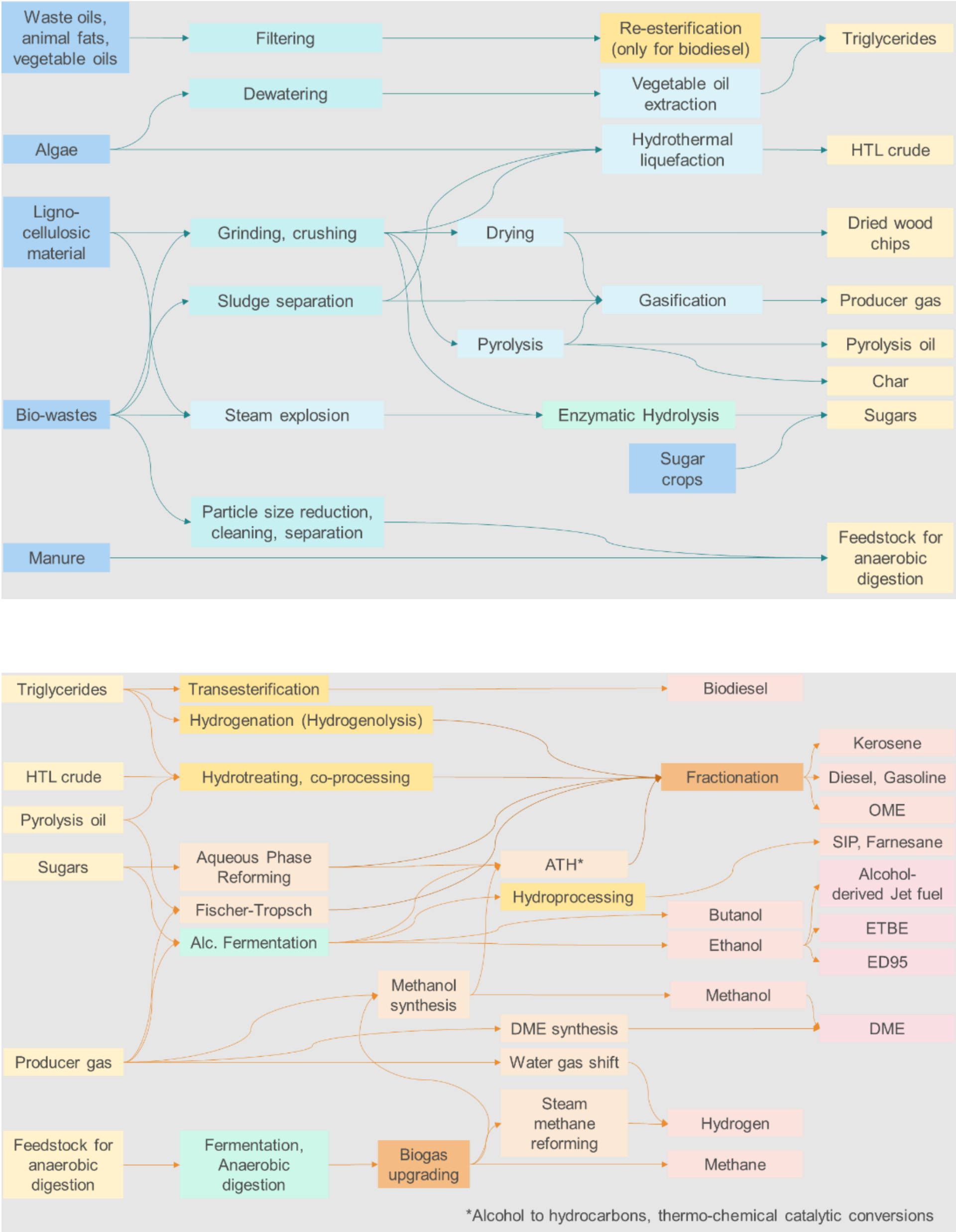
Advanced biofuels from biomass can be obtained by biochemical, thermo-chemical or oleochemical routes. In the following two flowcharts we sum up the most promising conversion pathways from the eligible feedstocks to advanced biofuels. The flowchart is separated in a “pre-treatment” part to obtain intermediate bioenergy carriers (IBC) with a higher energy density and a “conversion” part to the final fuel.

Additionally, recycled carbon fuels (RCFs) which used carbon-containing waste streams can be produced by the same pathways as described below, using carbon containing wastes as feedstock instead of biomass, notably:

- RCF from industrial off-gases (not biogas) processed by bacteria through microbial fermentation into ethanol
- RCF from gasification or hydrothermal liquefaction of waste streams of non-renewable origin which are not suitable for material recovery

Multiple transformations are possible for most of the biomasses to obtain advanced biofuels. In this part, the transformation pathways are split into process steps which are grouped into pre-treatment and processing steps as shown in Figure 1.

Figure 1. Selected pathways to produce advanced biofuels from eligible feedstock



Source: JRC 2024

Colour code: dark blue: eligible biomass, yellow: IBC, turquoise: mechanical, blue: thermal and thermo-chemical, dark yellow: oleochemical, green: biological, orange: thermo-chemical and catalytic, dark orange: separation processes and red-pink: final advanced biofuels.

1.2 Scope and context

The Clean Energy Technology Observatory (CETO) builds on the previous work within the Low Carbon Energy Observatory. The reports provide a repository of techno- and socio-economic data on the most relevant technologies and their integration in the energy system.

This report is an update of the CETO report on advanced biofuels from 2023 and is closely connected with the CETO reports on bioenergy and renewable fuels of non-biological origin [RFNBO].

This report presents an assessment of the state of the art of key technologies for biofuel production. The various technologies were analysed, based on their technological advancement and their potential to provide a significant contribution to decarbonisation of the European energy system in the short-and medium- to long-term period.

These various technologies, although in different stages of development, have undergone significant improvements and technical advances in the last years. However, most of them still face technical and non-technical challenges and barriers that impede on their large-scale commercial application and that will be discussed in the report. Some technologies still require research support to improve their technical, economic and environmental performances to achieve commercial operation.

1.3 Methodology and Data Sources

The methodology for the technology development reports is based on three pillars:

- JRC peer review and expert judgement;
- Monitoring, data compilation; definition and use of indicators, for which the focus is the Technology Readiness Level (TRL) parameter, using the guidelines set out in the 2017 report for DG-RTD;
- Modelling results of long-term deployment trends.

The main data sources used to assess the state of the art of the technologies and to identify the relevant European R&D projects came from several sources of information from literature and R&D project data divided as follows:

- R&D projects in CORDIS database, IEA and Innovation Fund
- Patents statistics, for patents filed on technologies/sub-technologies on PatStat service
- Scientific publishing statistics from the JRC's TIM (Tools for Information Monitoring) software
- Global CETO 2°C scenario 2024 (POLES-JRC model) and *POTEnCIA CETO 2024 scenario* (POTEnCIA model)
- EUROSTAT and Eurobserver
- Existing scientific overviews and compilations

2 Technology status and development trends

2.1 Technology readiness level

In the frame of the SET Plan Action 8 Bioenergy and Renewable Fuels for Sustainable Transport, the Technology Readiness Level (TRL) indicator was applied as recommended by the European Horizon 2020 Research Programme. This indicator offers a classification based on nine levels:

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

Table 2 shows the most promising pathways and TRL are summarized, while detailed description of pathways can be found in annex 5.

Table 2.TRL levels by sub-technology aspect

	TRL (Technology Readiness Level)								
Sub-Technology	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**
Pre-treatment and enzymatic hydrolysis to sugars								■	■
Pyrolysis of biomass to pyrolysis oil								■	
Gasification of biomass and pyrolysis oil to syngas							■	■	
Hydrothermal liquefaction to bio-crude					■	■			
Oil extraction from algae to triglycerides				■	■	■			
Dark / light fermentation to hydrogen				■	■				
Hydroprocessing of oils, fats and bio-liquid intermediates									■
Fermentation of syngas to biomethane				■	■	■			
Gas fermentation through microorganisms to alcohols								■	■
Aqueous Phase Reforming of sugars to hydrogen					■				
Transesterification of triglycerides									■
Biomethanol synthesis								■	
Methanol to Gasoline synthesis								■	
Biomethane from biogas upgrading									■
Catalytic methanation of syngas for SNG production							■	■	
Fast Pyrolysis & Thermo-Catalytic Reforming to drop-in fuels						■	■		
Lignocellulosic biomass to FT fuels						■	■		
Lignocellulosic biomass to ethanol							■	■	
Aquatic biomass to advanced biofuels			■	■					

Source: JRC 2024

2.2 Installed Capacity and Production

2.2.1 Global biofuel production

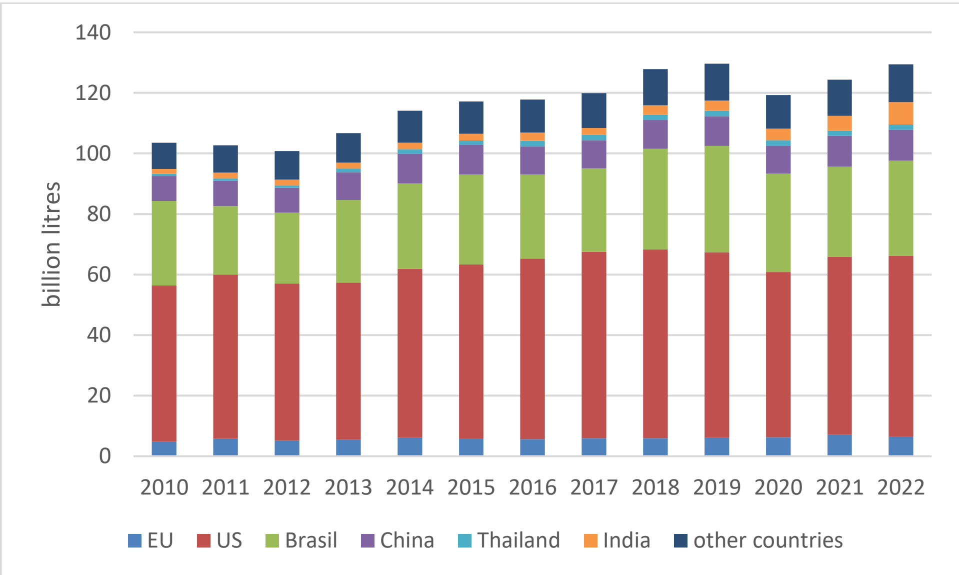
In the EU, the definition of advanced biofuels is a political decision based on specific feedstock categories, while in the rest of the world, this classification is based on the technology deployed. The RED II reinforced the sustainability criteria, including a definition of advanced biofuels to mitigate the negative impacts of biofuels on land use, biodiversity, including deforestation in third Countries. In 2024 an update of the RED II Annex IX by a specific delegated regulation entered into force.

Commission delegated directive (EU) 2024/1405 of 14 March 2024 amending Annex IX to Directive (EU) 2018/2001 of the European Parliament and of the Council as regards adding feedstock to produce biofuels and biogas. The delegated directive favors certain feedstock categories (e.g. intermediate crops and crops from severely degraded lands) to produce SAF only as advanced biofuels.

Statistics on biofuels production are generally divided per biofuel class, or sometimes per feedstock category. This results in a challenging classification for the EU advanced biofuels eligible for the RED III targets Therefore, the aim of this chapter is a quick investigation on statistics on the global production of biofuels, which is mostly conventional, and then on the current advanced biofuels contribution to biofuel supply.

The global biofuel production (bioethanol and biodiesel combined) increased from 123 to over 189 billion litres/year from 2010 to 2022, (OECD, 2022a). Bioethanol production had a rapid increase from 2005 to 2010 when the production more than doubled, afterward it was steady at around 100 billion litres/year for a couple of years and then it grew again at a slower pace to peak at a bit more than 120 billion litres/year in 2019 (Figure 2).

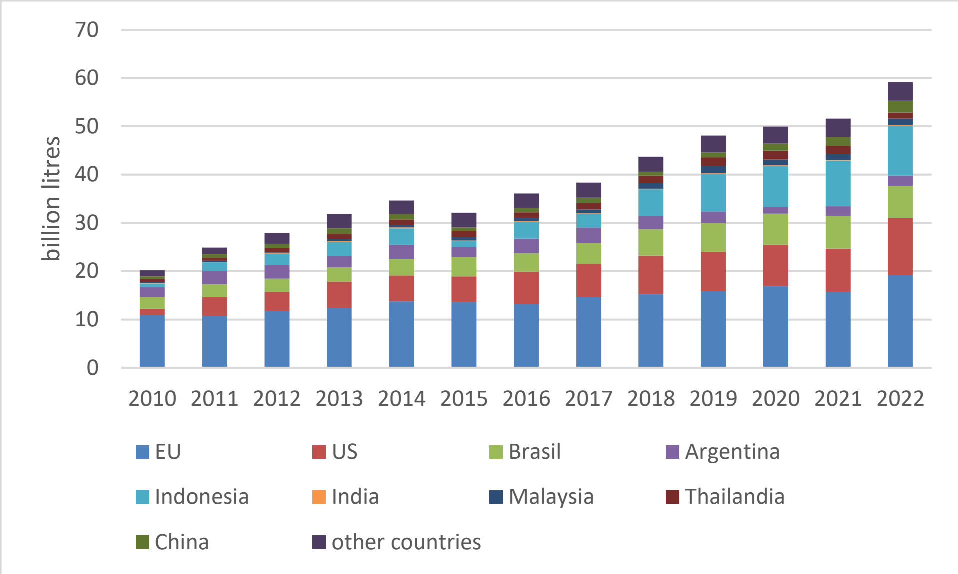
Figure 2. Evolution of bioethanol production in the world



Source: (OECD, 2022a)

Biodiesel production doubled from 2010 to 2018 from around 20 billion litres/year to 40 billion litres/year. After the production stayed almost steadily between 2014 and 2017 at bit less than 40 billion litres/year, then increased and passed the 60 billion litres/year in 2022 (Figure 3).

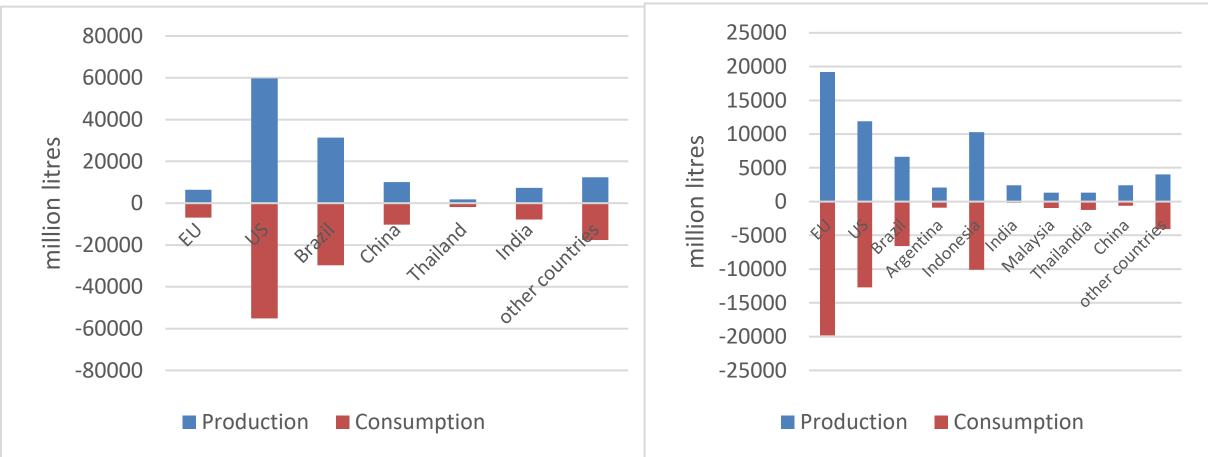
Figure 3. Evolution of biodiesel production in the world



Source: (OECD, 2022a)

For the bioethanol sector, the lead global producer and consumer countries are US and Brazil, for the biodiesel the EU is the lead producer and consumer followed by US and Indonesia (Figure 4).

Figure 4. Leading countries in bioethanol (left) and biodiesel (right) production and consumption in 2022



Source: (OECD, 2022a)

2.2.2 Biofuel production in Europe

EU biofuel production: as of 2023, four technologies have reached market maturity and are widely deployed in Europe: Table 3 shows the capacity of biofuel production in 2023 in Europe

Table 3. Capacity of biofuel production in 2023 in Europe

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 m^3
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

Source: (European Commission et al., 2024)

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.

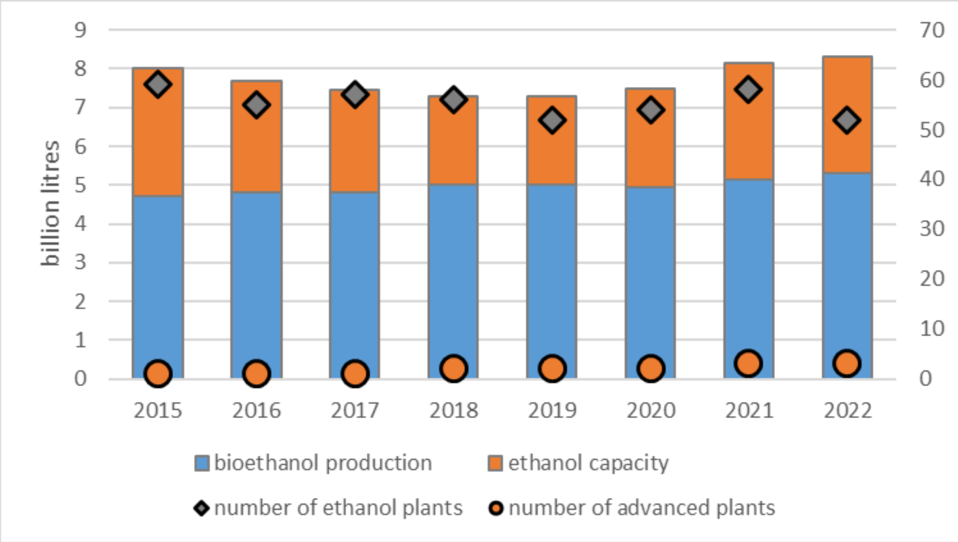
Table 4. Estimated biofuels production in 2023 in Europe

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	
Annex IX Part B		**15**
FAME and HVO	3.09	

Source: (European Commission et al., 2024)

As shown in Figure 5, the ethanol production in the EU, was at around 5 Billion litres from 2015 to 2022. On average the production stays below 60% of nominal capacity. In the EU in 2022, 52 refineries were producing conventional ethanol and 3 refineries were producing cellulosic ethanol fuel.

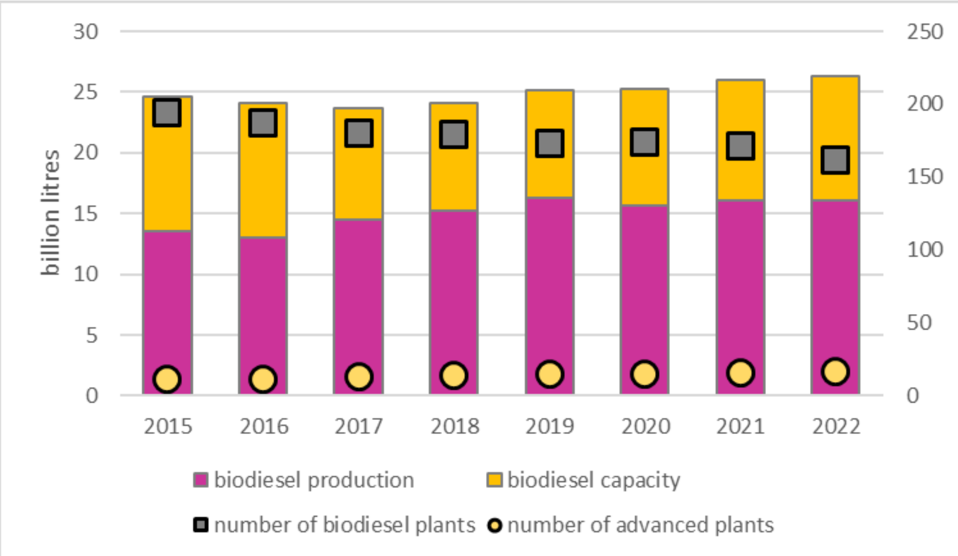
Figure 5. Evolution of bioethanol production and capacity and plants in the EU



Source: (USDA Foreign Agricultural Service et al., 2024)

Figure 6 shows the remarkable biodiesel production capacity was steadily in the EU between 2015 and 2022, at around 16 billion litres/year, combined FAME/HDRD (Hydrogenated-Derived Renewable Diesel), while the production was around 80% of nominal capacity 2022. The number of refineries producing biodiesel was 162 in 2022 and 17 refineries producing renewable diesel(Chandra and Rosmann, 2023). Important to notice is the low use of capacity both for ethanol and biodiesel plants, with an increasing trend for biodiesel plants.

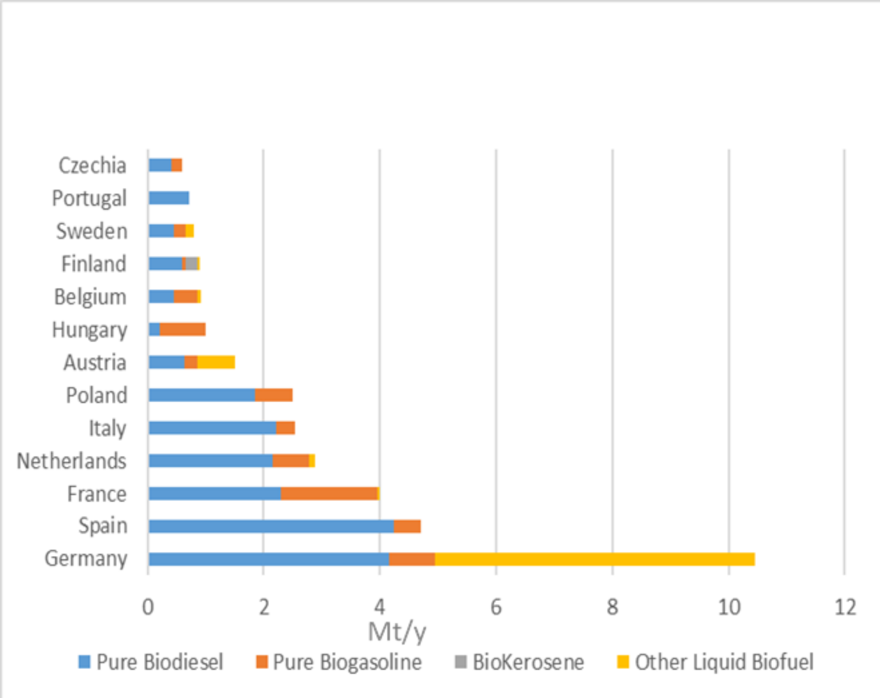
Figure 6. Evolution of biodiesel production and capacity in the EU



Source: (USDA Foreign Agricultural Service et al., 2024)

In 2022 the biofuel production capacity in leading EU member states is resumed in Figure 7. While In the annex 4 we show the list of biofuels plants

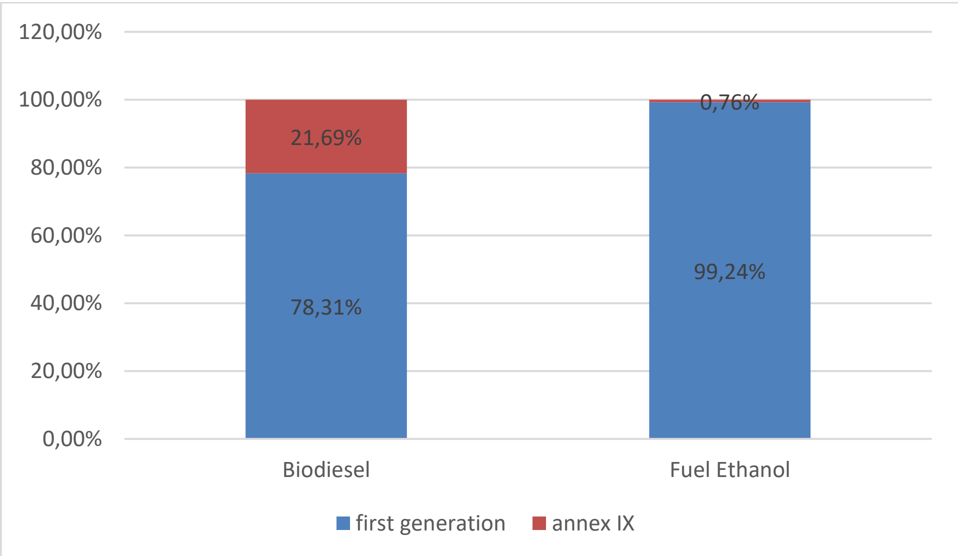
Figure 7. Biofuel production capacity per MS and type in the EU, 2022



Source: (Eurostat., 2024)

As shown Figure 8 the share of renewable diesel (produced from feedstock listed in Annex IX of RED II) in the total biodiesel produced in EU reached 21.69% in 2022, mainly due to the use of used cooking oil (UCO). Advanced ethanol was at only 0.76%.

Figure 8. Share of advanced biofuels in biofuel use the EU in 2022



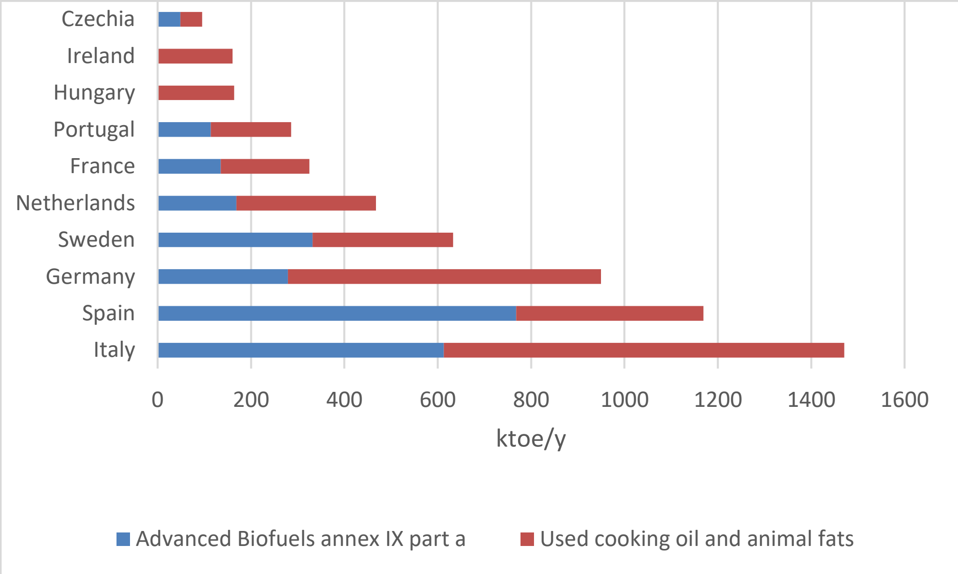
Source: (Eurostat., 2024)

Biofuel consumption

For biofuel produced using feedstock listed in Annex IX of RED II, Italy, Spain and Germany are the consumption leaders in the EU, year 2022, mainly due to the use of HVO from used cooking oil and animal fats. (Figure 9)

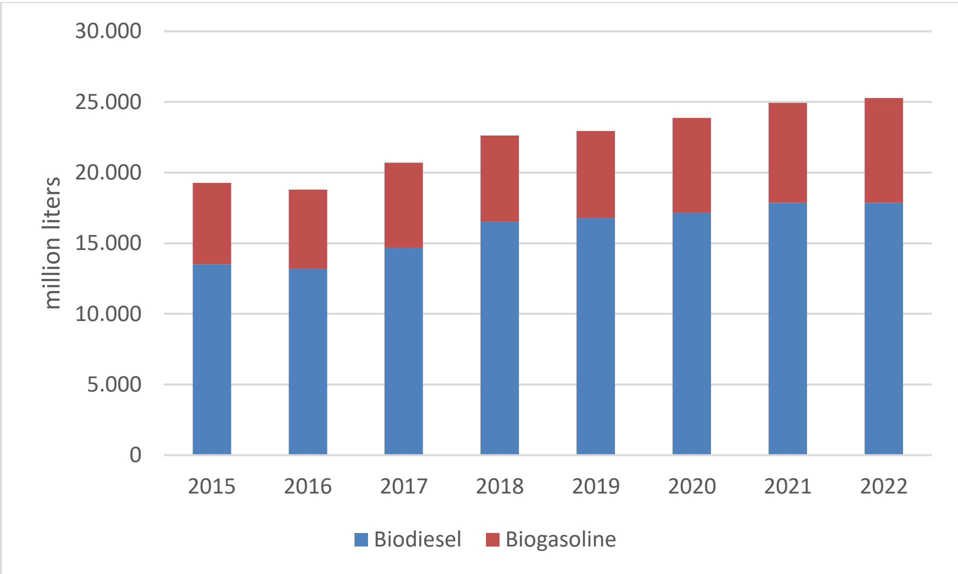
The biofuel consumption in the EU transport sector was 19 Ml in 2015 and surpassed 25 Ml in 2022, biodiesel has around 70% of share (Figure 10).

Figure 9. Leading EU MS in the use of Annex IX biofuels in ktoe 2022



Source: (EurObserv-ER, 2024)

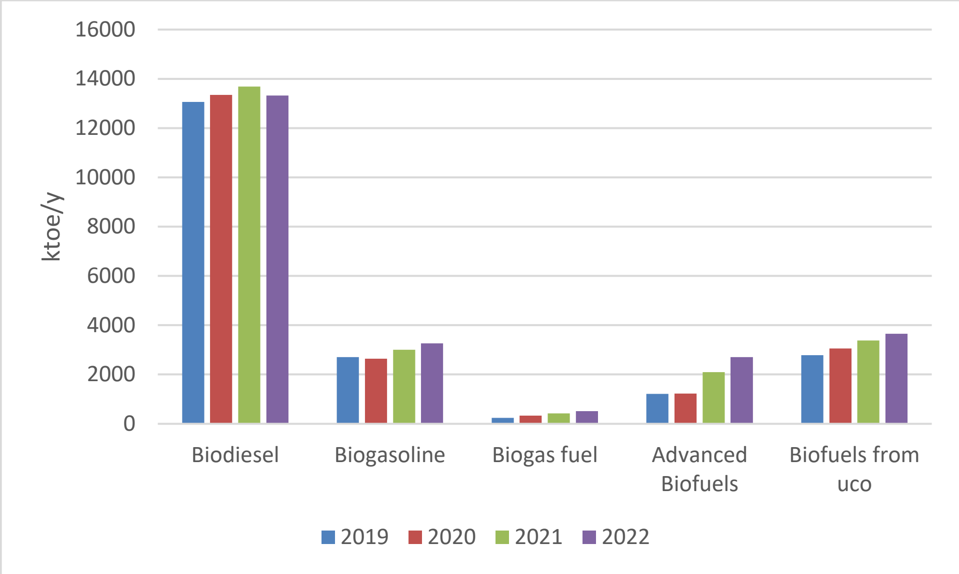
Figure 10. The evolution of the use of biofuels in transport in the EU



Source: (EurObserv-ER, 2024)

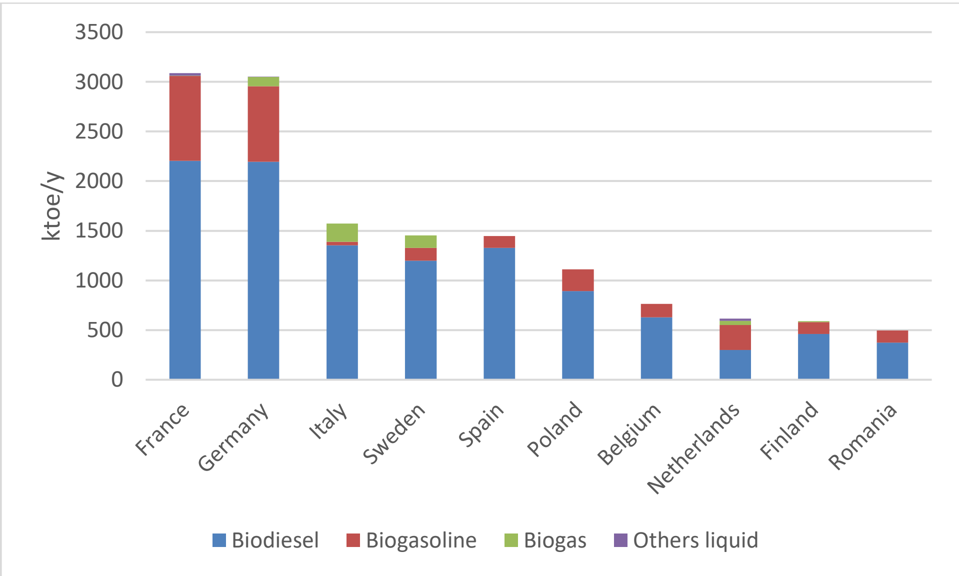
The use of advanced biofuel (biofuels made from feedstock listed in Part A of Annex IX of RED II) has been increasing in the last years and was more than 2 Mtoe in 2022 at around 16% of total biofuel consumption (Figure 11). Germany and France were by far the main biofuel consumer in Europe in 2022, with 3 Mtoe each, followed by Italy with more than 1.5 Mtoe consumed (Figure 12)

Figure 11. The evolution of the use of biofuel, including advanced biofuels in the EU



Source: (eurostat, 2024)

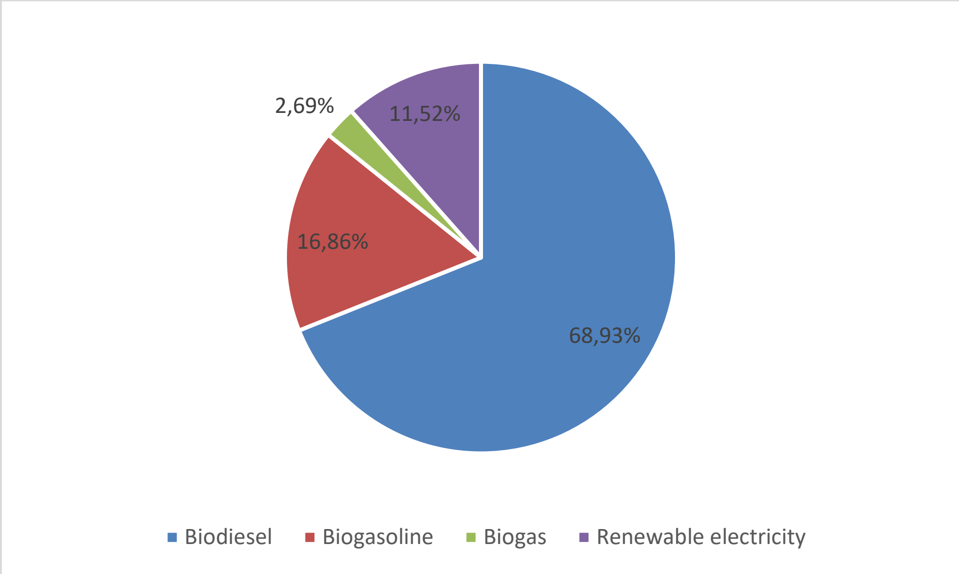
Figure 12. The use of biofuel, including advanced biofuels in the MS of the EU in 2022



Source: (eurostat, 2024)

When we also consider the renewable electricity share used in the transport sector in the EU, biodiesel still had a share of 69% in 2022 (Figure 13).

Figure 13. Distribution of renewable energy by fuel used in the EU in 2022

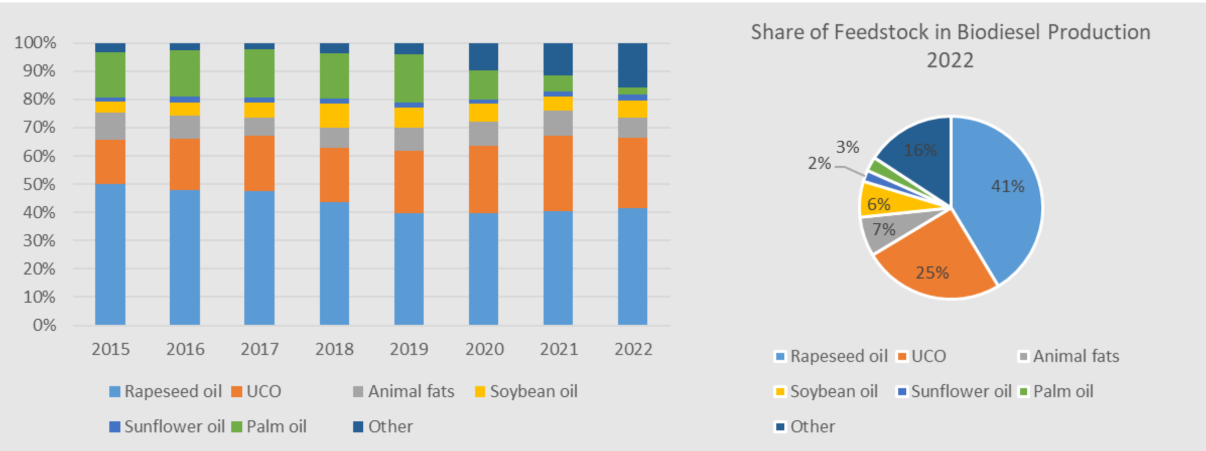


Source: (EurObserv-ER, 2023)

2.2.3 Feedstock Use and Co-product Production

Globally, about 75% of biodiesel is based on vegetable oils (20% rapeseed oil, 25% soybean oil, and 30% palm oil) or used cooking oils (20%) (OECD, 2022b). In the EU, about 52% of the feedstock use for biodiesel came from vegetable oils in 2022 (41% rapeseed oil, 6% soy oil) and 25% from used cooking oils and animal fats (feedstock listed in Part B Annex IX of RED III) for biodiesel and renewable Diesel. (Figure 14) The popularity of rapeseed oil is grounded in its domestic availability as well as in the higher winter stability of the resulting rapeseed methyl ester (RME) compared to other feedstocks. UCO was the second most important feedstock in 2022.

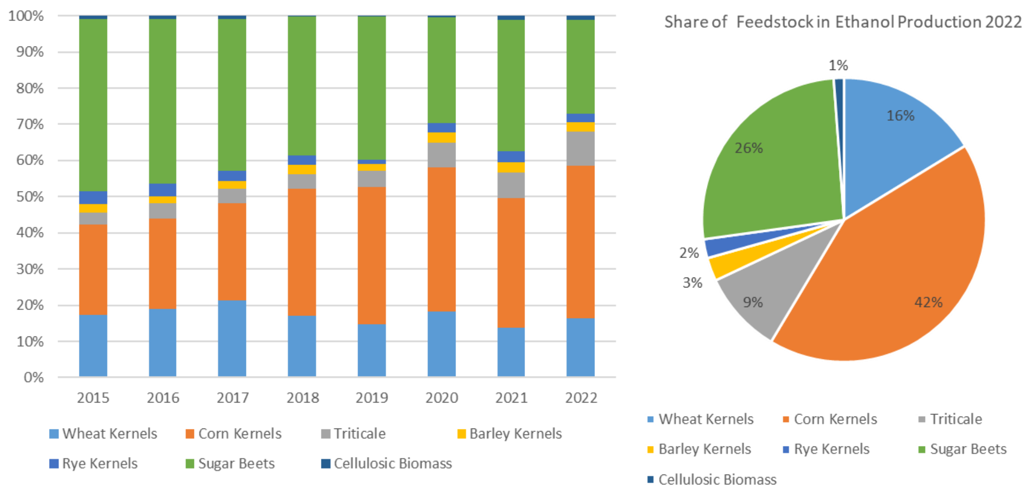
Figure 14. Feedstock use share, Biodiesel in the EU in 2022



Source: (JRC elaboration on USDA Foreign Agricultural Service et al., 2024)

Regarding ethanol in 2022, about 42% of ethanol is produced from maize in the EU, 26% from sugar beet, 16% from wheat, etc. Advanced biofuels from cellulosic feedstock (e.g. crop residues, dedicated energy crops, or wood) account for a very small share of total biofuel production. (Figure 15).

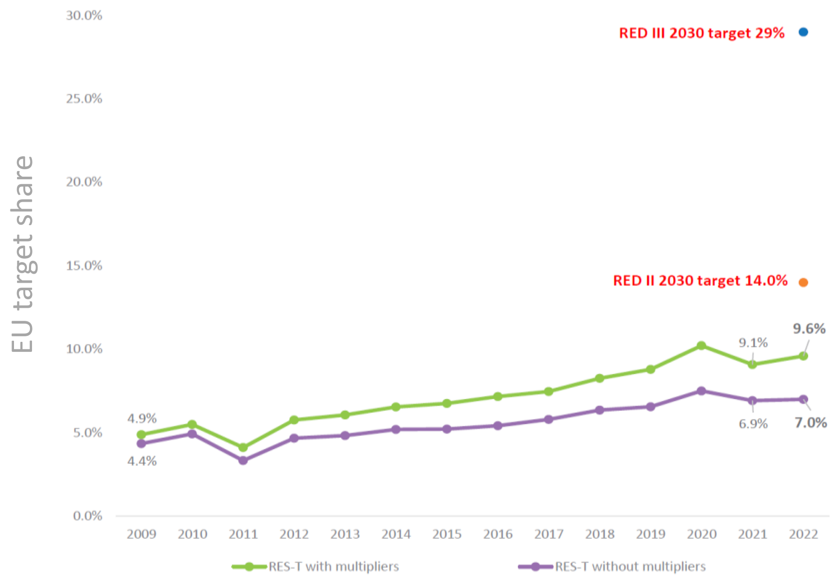
Figure 15. Feedstock use share, Ethanol in the EU in 2022



Source: (JRC elaboration on USDA Foreign Agricultural Service et al., 2024)

The EU reached its 2020 target for the use of renewable energy in transport (10.2 %), with the use of multipliers, which allow for double counting of energy content for Annex IX biofuels and multiplying that of renewable electricity in road transport by four. However, the actual share of renewable energy in transport in 2020 without applying these multipliers was just 7.5 %. According to Eurostat SHARES, in 2022, the RES-T at EU-27 level was 9.6% with multipliers under RED II; ePURE (Saint-Supéry et al., 2020) found that when the multipliers are removed, the real RES-T for EU-27 was only at 7% in 2022, Figure 16.

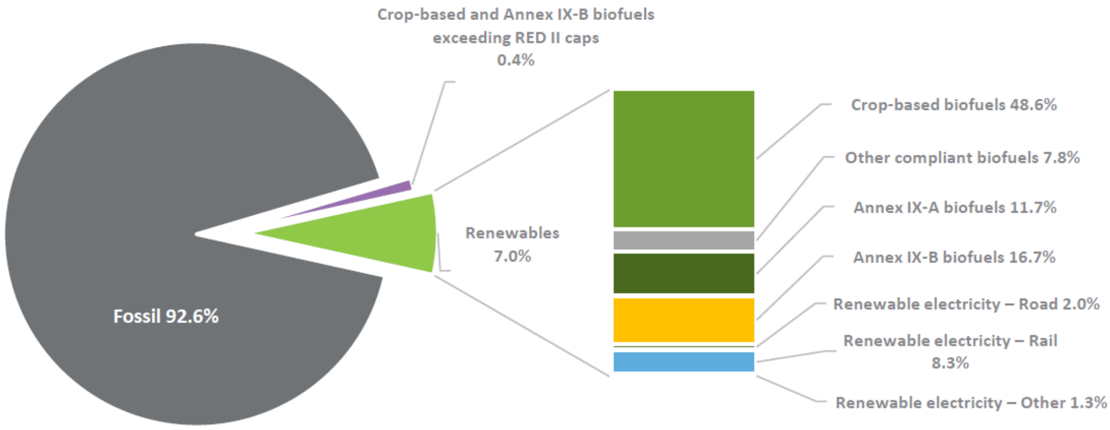
Figure 16. EU Biofuels consumption: the EU target



Source: (epure, Eurostat SHARES)

According to Eurostat SHARES, all biofuels together account for almost 89 % of renewables in transport in the EU, with multiple counting. Crop-based biofuels contribution for renewables in transport is at 57% without considering multipliers. Biofuels produced from REDII Annex IX- A feedstocks, for advanced biofuels, represented 11.7% of the mix whereas biofuels made from Annex IX- B were at 16.7%. Biofuels produced from REDII Annex IX-B feedstock represented 1.4% of the energy used in transport in 2022. (Figure 17)

Figure 17. EU Biofuels in transport 2022



Source: (epure, Eurostat SHARES)

2.2.4 Future scenarios

In the last years, several institutions provided estimates on the possible evolution of biofuels (including advanced biofuels) in scenarios towards 2030 and beyond. For instance, the IEA "Net Zero by 2050" scenario (IEA, 2021) relies largely on advanced biofuels for the decarbonisation of the global transport sector up to 2050. Concawe in 2021 released a study on the European transport sector by modelling elements such as the evolution of the different powertrains and the availability of different alternative fuels over the period 2018-2030 (Yugo et al., 2021).

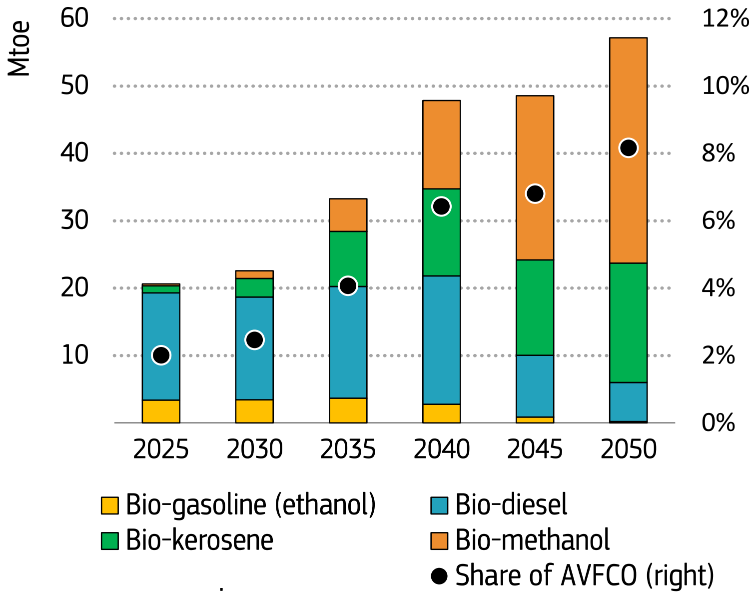
The results show 21.4 Mtoe of biofuels use in EU in 2030. More recently, DG RTD commissioned the study "Development of Outlook for the Necessary Means to Build Industrial Capacity for Drop-in Advanced Biofuels" (European Commission et al., 2024). The scenarios were developed based on the ambitions of the EU Green Deal, which includes a 55% reduction in EU GHG emissions by 2030 and the achievement of climate neutrality by 2050.

The results show that the demand for advanced biofuels in the transport sector is expected to increase significantly by 2030. If the deployment of electric vehicles (EVs), and RFNBOs supply fall short of expectations, biofuels uptake could rise to between 38 and 42 Mtoe/yr to meet the Renewable Energy Directive GHG intensity reduction target in transport. By 2030, advanced biofuels are projected to constitute about half of all biofuel demand, translating to over one-third of all renewable energy consumed in transport. The growth in advanced biofuels is anticipated to be driven by technologies capable of processing lignocellulosic materials.

Within the CETO 2024 exercise, JRC employed the POTEnCIA model to develop the POTEnCIA CETO 2024 Scenario, a technology-oriented scenario exploring the potential role of clean energy technologies, including biofuels and their production pathways, in achieving climate neutrality by 2050. A more detailed description of the POTEnCIA model and scenario is given in Annex 3. This section reports the results of the POTEnCIA CETO 2024 Scenario for total biofuels consumption (Figure 18) and advanced biofuels1 installed capacity and production (Figure 19). Results for biogas are reported separately at the end of the section.

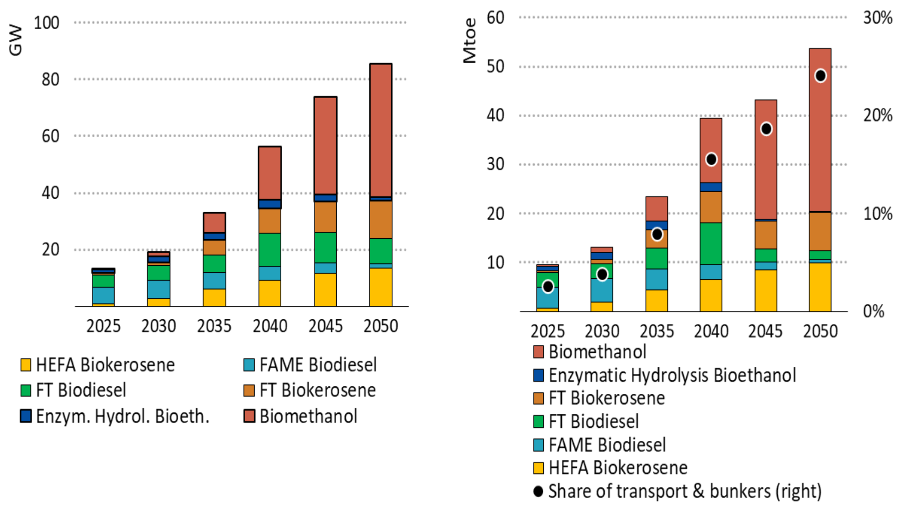
[1] Following the Renewable Energy Directive, the term "advanced biofuels" refers to those biofuels produced from the feedstocks listed in the Annex IX Part A of the same directive. However, here for simplicity, "advanced biofuels" refer to biofuels produced from feedstocks listed in the Annex IX Part A and B.

Figure 18. Total biofuels consumption in EU under the POTEnCIA CETO 2024 Scenario, 2025-2050. AVFCO stands for Available for Final Consumption and includes energy consumption contributions from: final energy, final non-energy and international aviation and shipping.



Source: POTEnCIA model

Figure 19. Advanced biofuels installed capacity (left) and production (right) in the EU under the POTEnCIA CETO 2024 Scenario, 2025-2050. The share of advanced biofuels in energy use in transport and bunkers is also reported in the right graph (black dots, secondary axis).



Source: POTEnCIA model

Besides targeting a progressive decrease in GHG emissions leading to carbon neutrality in 2050, the POTEnCIA CETO 2024 Scenario considers specific penetration targets, caps and eligibility rules for different biofuels types as those defined by the Renewable Energy Directive or by the ReFuelEU Aviation regulation (i.e. SAF definitions and targets), which are reflected in the scenario results shown. Moreover, the resulting consumption of biofuels is also the result of a direct competition with other alternative fuels (e.g. RFNBOs), based on assumed techno-economic projections, to meet the overall GHG reduction target or sector specific targets (for instance the FuelEU Maritime reduction targets for GHG intensity of energy use in vessels). For more details and insights on RFNBOs see the dedicated CETO 2024 report.

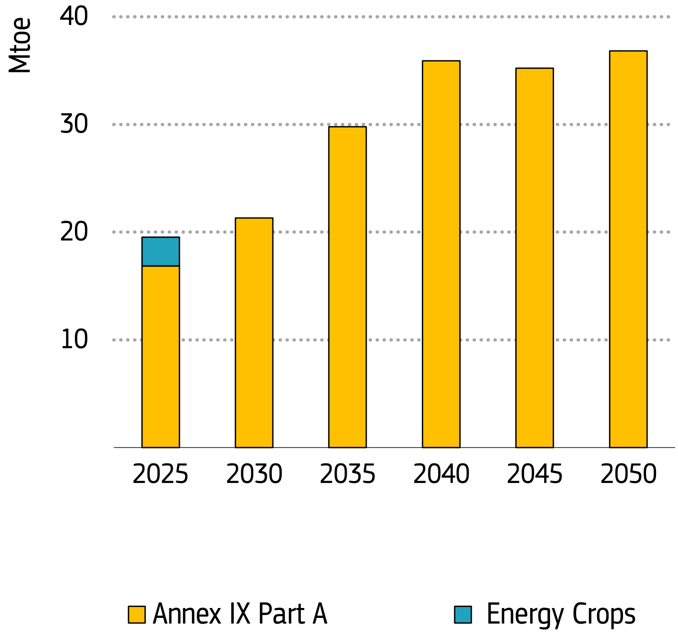
Overall, the biofuels consumption increases across the years (Figure 18, from around 21 Mtoe in 2025 to 57 Mtoe in 2050. Figure 18 shows the consumption of all bio-based fuels that can substitute a specific type of fossil fuel within the specific fuel category, including drop-in biofuels (e.g., from HEFA or FT processes), as well as alcohols (biomethanol and bioethanol) or other esters (such as FAME biodiesel). The production of advanced biofuels increases progressively towards 2050 (Figure 19 right), while the production of biofuels from food and feed crops provides progressively minor contributions.

The increase in biofuels consumption contributes to achieving the progressive reduction in GHG emissions over the years besides fulfilling sector specific targets. In particular, the growing consumption of biokerosene in the aviation sector contributes to the ReFuelEU Aviation targets for SAFs. The increasing consumption of biomethanol in the maritime sector (including bunkers and domestic navigation), especially after 2030, contributes to the targets of the FuelEU Maritime. Besides, a substantial part of the increase in biomethanol consumption takes place in the chemical industry to replace part of the fossil feedstock, resulting in the long-term storage of renewable CO2 in materials and thus contributing to offset the residual GHG emissions from hard-to-abate sectors (as assumed in a number of decarbonisation scenarios including the POTEnCIA CETO 2024 Scenario).

On the other hand, the downward trend in biodiesel and bioethanol consumption after 2040 is mainly driven by the progressive electrification of the road sector triggered by the CO2 emission standards for new vehicles. The progressive phase-out of internal combustion engine vehicles leaves less and less space for biodiesel and bioethanol blends in the road sector leading to a gradual reduction in their consumption, even if the biofuel blending shares, driven by progressively tightening decarbonisation objectives, increase over time.

Figure 20 Biogas contributes also to the pathway towards climate neutrality in 2050. Its production by feedstock type across the years in the POTEnCIA CETO 2024 Scenario is reported in Figure 20.

Figure 20. Biogas production by feedstock type in the EU under the POTEnCIA CETO 2024 Scenario, 2025-2050. Annex IX feedstock meeting RED III sustainability criteria



Source: POTEnCIA model

This modelling exercise assumes the completion by 2030 of the gradual reduction of biogas produced from food and feed crops in favor of a production from feedstocks listed in the RED Annex IX Part A (e.g. manure and agricultural residues). The share of biogas that is upgraded to biomethane increases over the years, allowing for its consumption across different sectors, among which power and heat generation, industries and other end-use sectors, and maritime. Besides contributing in achieveing specific targets defined by the RED, biomethane also contributes to achieve the FuelEU Maritime targets, accounting for over 4% of energy use in the maritime sector by 2050.

2.3 Technology Costs

The fuel production costs are composed of investment (capital) costs (CAPEX), operating costs (OPEX) and feedstock costs. Even if each of those is heavily influenced by plant size and local conditions, some conclusions can be drawn from the spans of available data on demo or commercial plants, research projects and publications.

IEA (Adam Brown *et al.*, 2020) gathered data on all advanced biofuels technologies for low and high cost scenarios and produced one of the most coherent studies on current advanced biofuels technology costs. Those costs will be presented first, followed by EU-centric information and future trends. According to IEA, the production of HVO fuel is mostly influenced by the feedstock costs, which make up 65-80% of the production costs, based on local situations, like refinery upgrade to allow co-processing, logistics, refinery revamps to HVO. The maturity of technology and load factor at around 8000 hours/year result in a low CAPEX (from 3-15 €/MWh) compared to the OPEX (which range from 48-76 €/MWh).

According to IEA, to produce cellulosic bioethanol, it is the capital cost of a production plant that represents the main share of the overall costs. The plants installation cost ranges between 2.8 k€/kW and 3.7 k€/kW depending on plant size, technology complexity and location. The feedstock cost is in a range of 10-20 €/MWh (50-100€/dry tonne) while enzymes are in a range from 15 to 30 €/MWh of ethanol produced. For the lignocellulosic ethanol we have CAPEX of 32-60 €/MWh ethanol produced and OPEX of 53-98 €/MWh ethanol produced.

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. (European Commission 2024) * 12 commodity-price-dashboard_2023-03_en_0.pdf (europa.eu)

The other pathway analysed in IEA (Adam Brown *et al.*, 2020), for the cost assessment is the production of synthetic fuel via thermal gasification, with three main product categories:

- Biomethane,
- Oxygenates such as Methanol, Ethanol and DME,
- Synthetic long chain hydrocarbons such as FT Diesel, Gasoline or Kerosene.

For alcohols and hydrocarbons IEA relies on the SGAB report (Maniatis *et al.*, 2017), survey to producers and scientific literature. In general, the production cost is dependent on plant size, the use of waste or biomass and local market, the technology process, the operational hours. Based on a plant with 200 MW biofuel nominal output, the range of cost for CAPEX varies from 33 to 59 €/MWh fuel produced, and OPEX range from 30 to 63 €/MWh of fuel produced.

In the EU, a good source for technology costs is the SET Implementation Plan (ETIP Bioenergy, 2018) that sets a goal of reducing advanced biofuels production costs from 50 €/MWh in 2020 to less than 35 €/MWh in 2030, and for liquid and gaseous intermediate bioenergy carriers by thermochemical or biochemical processing from 20 €/MWh in 2020 to less than 10 €/MWh (40 and 30 €/MWh respectively for microbial and other higher quality oils). The document also contains a list of current projects and their CAPEX and OPEX, see Table 5 which in detail sometimes differ from the costs shown above, but follow a similar trend and similar overall costs.

Table 5. Current advanced biofuel costs (CAPEX, feedstock and OPEX)

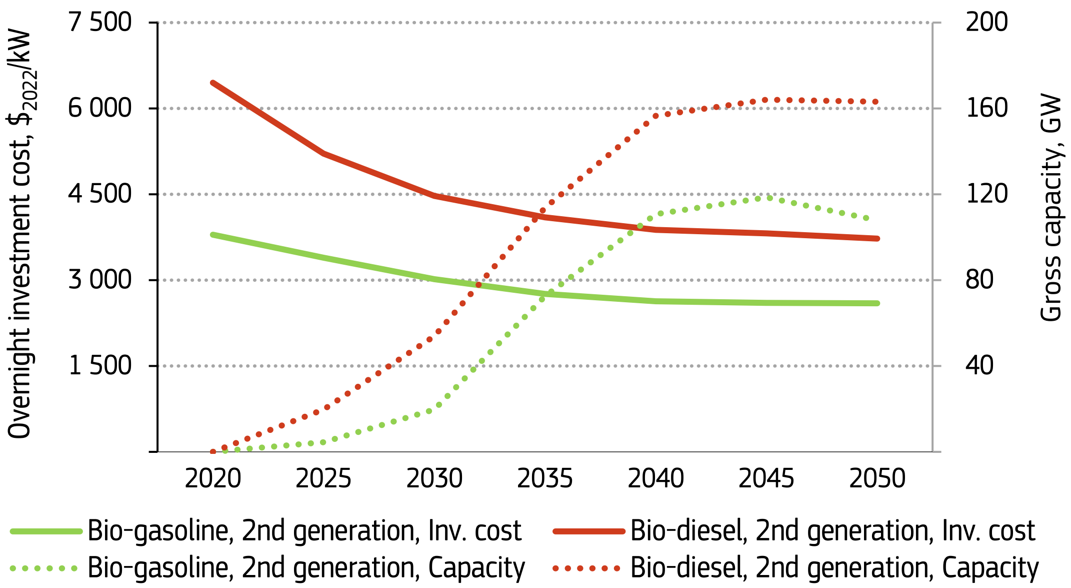
		Costs, EUR/MWh			
Process		**Capital**	**Feedstock cost**	**Operating cost**	**Total**
Cellulosic ethanol	Low	42	33	28	103
	High	60	50	48	158
Cellulosic ethanol "1/2 Gen"	Low	33	0	18	51
	High	38	0	21	59
Methanol and methane - biomass	Low	33	15	14	62
	High	49	33	30	112
Methanol and methane - wastes	Low	43	-25	30	48
	High	59	0	30	89
FT Liquids — Biomass	Low	43	18	14	75
	High	74	50	20	144
	Low	48	-25	30	53

FT Liquids — Wastes	High	74	0	30	104
Bio-oil plus co-processing	Low	40	34	5	79
	High	66	68	5	139
Bio-oil stand alone	Low	38	15	29	82
	High	38	70	59	127
HVO	Low	3	40	8	51
	High	15	60	16	91
AD — Biomethane	Low	25	-13	28	40
	High	33	50	38	120

Source: (Adam Brown et al., 2020)

In addition to the EU scenario of the POTEnCIA model, the *Global CETO 2°C scenario 2024* calculated by the POLES-JRC model (details available in Annex 3), showcases a future where concerted efforts to limit global temperature increases to 2°C yield transformative impacts on the production and economic viability of clean energy technologies. Figure 21 shows the development of investment costs and capacities for 2nd generation diesel and gasoline. For these fuels, overnight investment costs decrease strongly from the end of the 2020's to about 2030, which is a result of endogenous learning induced by the fast deployment of advanced biofuels installations during this period. This initial cost decrease triggers thereafter the expansion of the production, reaching over 160 GW of installed capacity (95 Mtoe of production) for bio-based diesel and 108 GW of installed capacity (41 Mtoe of production) for bio-based gasoline in 2050.

Figure 21. Advanced biofuels global overnight investment cost and production



Source: JRC-POLES model

For all biofuels, including 1st and 2nd generation biofuels as well as biogas, the *Global CETO 2°C scenario 2024* projects by 2050 a global production of 324 Mtoe and a production capacity of 595 GW shows merely 2ndgeneration biofuels). The *Global CETO 2°C scenario 2024* envisage for biofuels a future where increased production and technological learning drive down the costs of advanced biofuels, making them a more economically viable option within the low-carbon transition.

The specific share of advanced biofuels on each country's in the world energy mix will depend on decarbonization targets and the specific applications where advanced biofuels are most needed (geography, biomass availability, costs, etc.). While advanced biofuels will be essential for achieving climate neutrality, especially in hard-to-abate sectors, they are part of a broader set of solutions that include energy efficiency, modal shifts, and direct electrification.

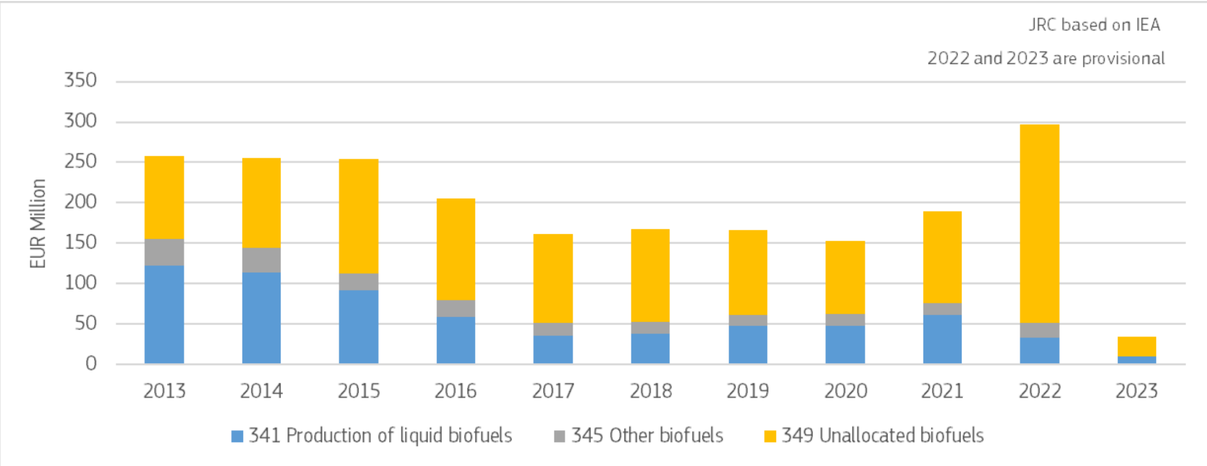
Moreover, it will be challenging to evaluate the resource requirements for biomass, biowastes and bioresidues for advanced biofuels production, since technologies are still under development and sustainability requirements are currently under evolution to ensure only sustainable feedstock supply. In order to cope with these challenges, the POLES-JRC model takes into account potentials of bio-resources and sustainable development goals by soft-coupling with the *GLOBIOM-G4M* model. As a result, POLES-JRC projects in the *Global CETO 2°C scenario 2024* that advanced biofuels rely vastly on 2nd generation biomass (i.e. Annex IX part A, RED) to cover the overall demand.

The transition to bio-based fuels economy will require coordinated effort among national governments, companies, and international organizations to ensure that production is ramped up sustainably and equitably, including collaborative efforts in developing infrastructures.

2.4 Public RD&I Funding and Investments

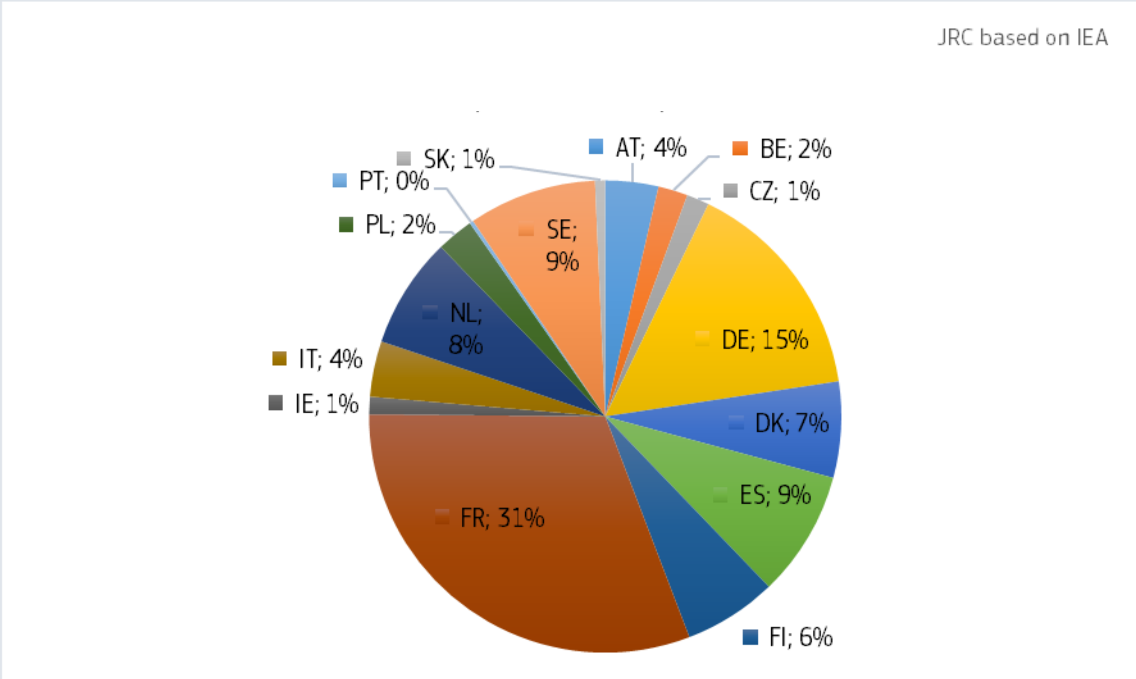
The JRC, based on IEA (IEA, 2024) Energy Technology RD&D Budgets codification, found that public RDD (Research Development and Demonstration) investment on production of liquid biofuels averaged at around 50 EUR Million yearly from 2020 to 2021.However the majority of funding, at around 250 EUR Million in 2022, concerned unallocated biofuels (refers to biofuels that are not currently assigned to a specific use or destination) as shown in Figure 22. France with 31% share , followed by Germany with 15% share were the EU countries getting more public RDD investment from 2013 to 2023. (Figure 23).

Figure 22. RDD public investment on biofuels projects in the EU



Source: JRC elaboration based on IEA 2024

Figure 23. EU countries share for public RDD bioenergy investment 2013-2023



Source: JRC elaboration based IEA 2024

The projects cover most of the described technologies with a focus on gasification and fuel synthesis, but also include biogas, pyrolysis, fermentation and hydrothermal liquefaction. The whole value chain is represented from feedstocks like algae, oil plants and biomass from degraded land, over pre-treatment and intermediate bioenergy carrier production to liquid fuel synthesis to upgrading to road, maritime and aviation fuels.

The Emission Trading System (ETS) Innovation Fund supports the commercial demonstration and deployment of innovative low-carbon technologies, encompassing biofuel refineries under its energy-intensive industries focus. Across the 2020 and 2021 small and large scale calls, the Innovation Fund has selected three projects for support (BECCS Stockholm, FirstBio2Shipping and Waga 4 World) with a contribution of EUR 133 million.

2.5 Private RD&I funding

Private Equity (PE) refers to capital investments (ownership or interest) made into companies that are not publicly traded. Venture capital (VC) is a form of private equity and a type of financing that investors provide to start-up companies and small businesses that have long-term growth potential.

The early and later stages indicators that aggregate different types of equity investments in a selection of companies and along the different stages of their growth path. We only include pre-venture companies (that have received Angel or Seed funding, or are less than 2 years old and have not received funding) and venture capital companies (companies that have been part of the portfolio of a venture capital investment firm at some point).

The early stages indicator include Pre-Seed, Accelerator/Incubator, Angel, Seed and Early stage VC investments; it also include public grants. At the time they raise such investments, those companies can usually be considered as start-ups. But while those companies often rely on innovative solutions and business models, such investments aim at financing the companies' operational expenditures and investment needs until they can scale their revenues and cannot be assimilated to R&I funding.

The later stages indicator reflect growth investments for the scale-up of start-ups or larger SMEs. It include Late Stage VC, Small M&A and Private Equity Growth/Expansion. Very large early stage deals (outliers) are also re-classified as later-stage deals. Small M&A refers to the acquisition by an operating company of a non-control stake in a pre-venture or VC company. Later stages investments do not include Buyout Private Equity and Public investments. The lists of companies include two distinct populations: VC and corporate companies.

Corporate companies is a selection of companies with a relevant patenting activity among the subsidiaries of top R&D investors from the EU Industrial R&D investment Scoreboard.

VC companies are selected based on their activity description (specific keyword selection for each technology and expert inputs) and this selection does not rely on patents. This selection tries to focus on companies that develop and manufacture technological solutions as much as possible. It does not e.g. include operators, project developers, and specific applications.

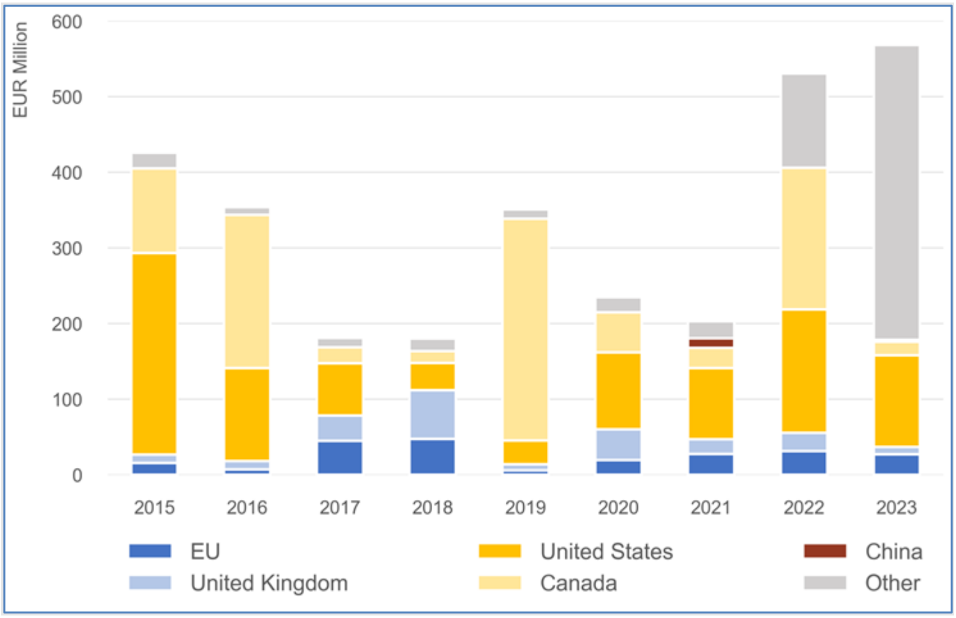
Those selections include all identified companies for each technology, irrespectively of their current operational status or of the fact that they have relevant investments or patenting activities over the current period. VC companies may e.g. currently be start-ups, may have been start-ups or larger SMEs that grew into larger private companies, went public or were acquired by larger companies. They may also currently be out of business.

As they focus on two specific populations, those lists only represent subsets of all market players in each value chains. The aim is however to illustrate the dynamics of emerging innovators with growth potential and large corporate innovators (that are responsible for most private R&I investments).

To support that analysis, the count of companies corresponds to the number of active companies over the current period. Active corporate companies have High Value Patents over the current period. Active VC companies either have been founded (irrespectively of received investments) or have received investments (irrespectively of their founding year) over the current period

The number of VC companies corresponds to the count of active VC companies that have been founded over the period (irrespectively of the investments they have received) or have received investments over the period (irrespectively of the year they have been founded). VC companies that have not been founded or have not received investments over the period are not considered as active. In 2022, global VC/PE investments in biofuel firms surpassed to EUR 500 million, which represents a two-fold increase (x 2.6) as compared to 2021 and slightly increased in 2023. Over the period 2018-23, global VC/PE investments in biofuel firms exceeded EUR 2 Billion, (Figure 24).

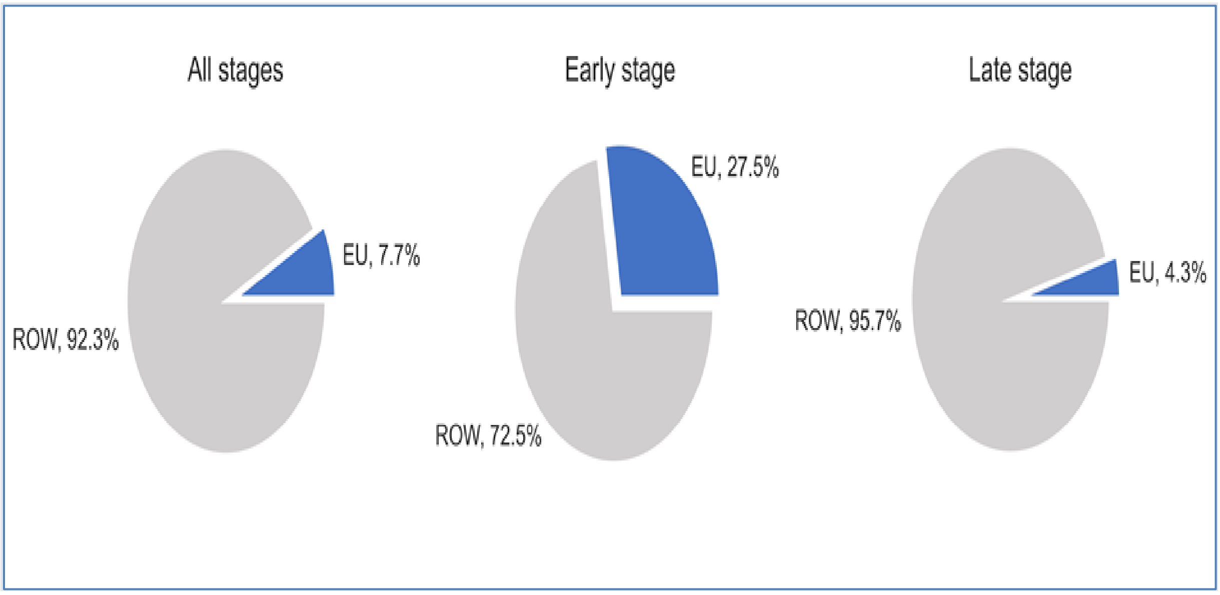
Figure 24. Global VC/PE investments by region



Source: JRC elaboration based on Pitchbook

According to the Figure 25, between 2018 and 2023 the VC share of capital invested in the EU was at 7.7 % compared to the Rest of World (RoW) with the EU early stage at .27.5% and late stage at 4.3%

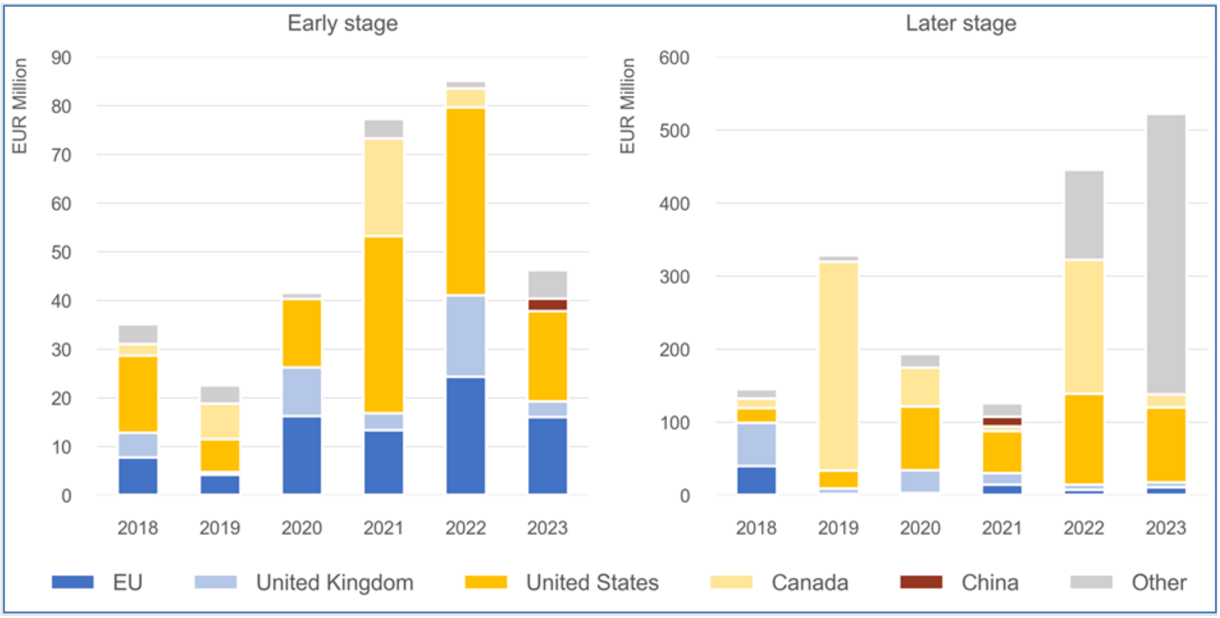
Figure 25. Share of VC investments by region



Source: JRC elaboration based on Pitchbook

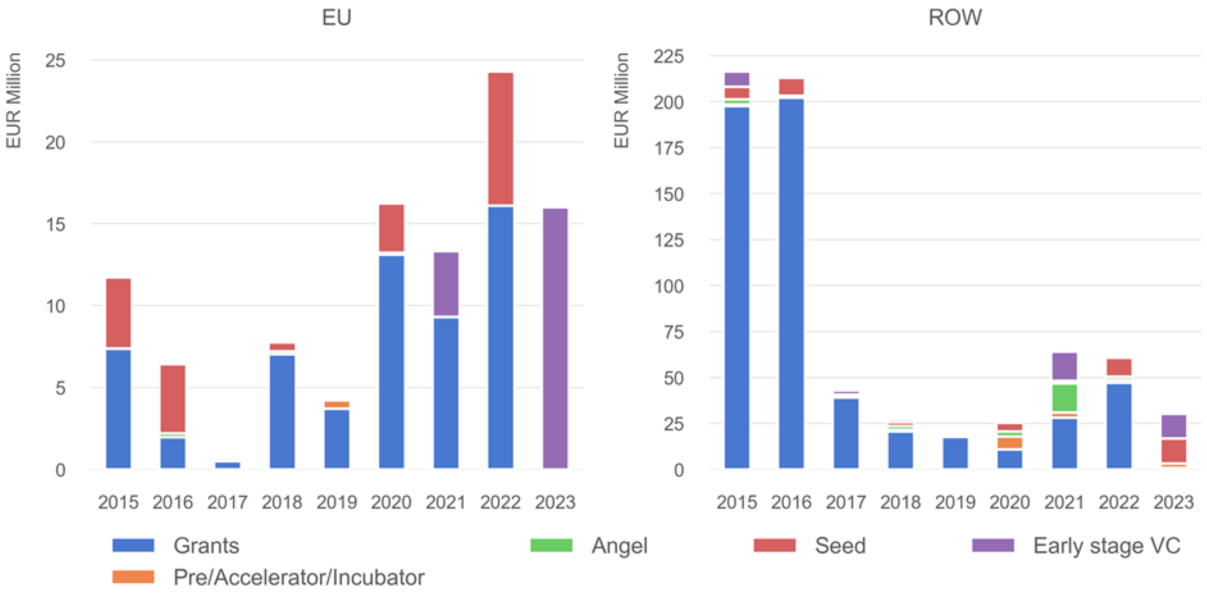
As shown in Figure 23, the amount of early stage investment in the EU was around 20 EUR Million in 2022 and 2023. As shown in Figure 27, in the EU, grants were the mostly used financing in the early stage investments

Figure 26. Share of VC capital investments by region and stage



Source: JRC elaboration based on Pitchbook

Figure 27. Share of early-stage VC capital investments by region and type



Source: JRC elaboration based on Pitchbook

2.6 Patenting trends

For the assessment of the technical progress achieved in the field of advanced fuel, the performed analysis focused on the world distribution of patent filings for the time period between 2018 and 2020 as extracted from PATSTAT database (JRC based on data from the European Patent Office - EPO, 2019; (Fiorini *et al.*, 2017; Pasimeni, 2019; Pasimeni, Fiorini and Georgakaki, 2019, 2021; Pasimeni and Georgakaki, 2020). In order to estimate the share in total inventions a fractional count should be adopted, where inventions tagged with more than one code contribute with an equal fraction to all the codes (classes) involved. Patents related to advanced fuel sector are identified by using the relevant code families of the Cooperative Patent Classification (CPC) for the technologies or applications for mitigation or adaptation against climate change, reduction of greenhouse gases emission related to energy generation, transmission or distribution. The Y codes are designed to facilitate the identification of inventions relevant to renewable energy and climate mitigation technologies. Within this classification, the set of technical classes of inventions that can be related to the biomass technologies, are patent families with code Y02E related to energy generation, transmission or distribution and the Y02E 50 code that include CPC classes referred as 'technologies for the production of fuel of non-fossil origin, in addition the code 'Y02P 30 'related to production or processing of goods. Data for 2021 is not complete.

The relevant patents are grouped under the following classes of patents:

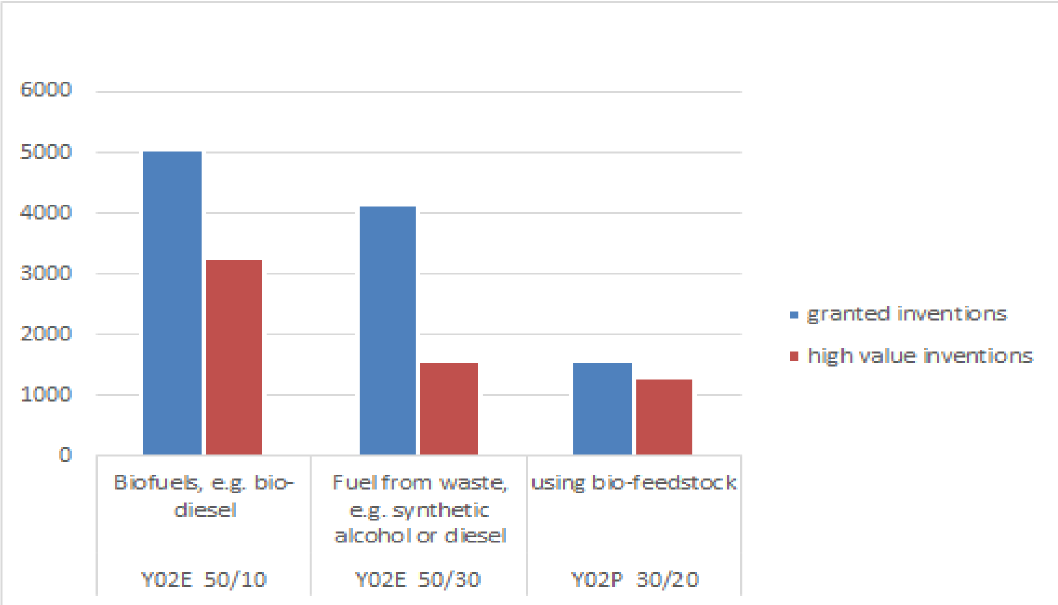
- CPC: Y02E 50/10 biofuels, e.g. biodiesel
- CPC: Y02E 50/30 'Fuel from waste, e.g. synthetic alcohol or diesel'
- CPC: Y02P 30/20 'production or processing of goods using bio-feedstock

For having a representative classification, 3 patent categories have been grouped with the following terminology:

- Patent families (or inventions) measure the inventive activity. Patent families include all documents relevant to a distinct invention (e.g., applications to multiple authorities), thus preventing multiple counting. A fraction of the family is allocated to each applicant and relevant technology.
- High-value inventions (or high-value patent families) refer to patent families that include patent applications filed in more than one patent office.
- Granted patent families represent the share of granted applications in one family. The share is then associated to the fractional counts in the family.

As shown in Figure 28, most granted patents are in the "biofuels" class, followed by "fuels from wastes".

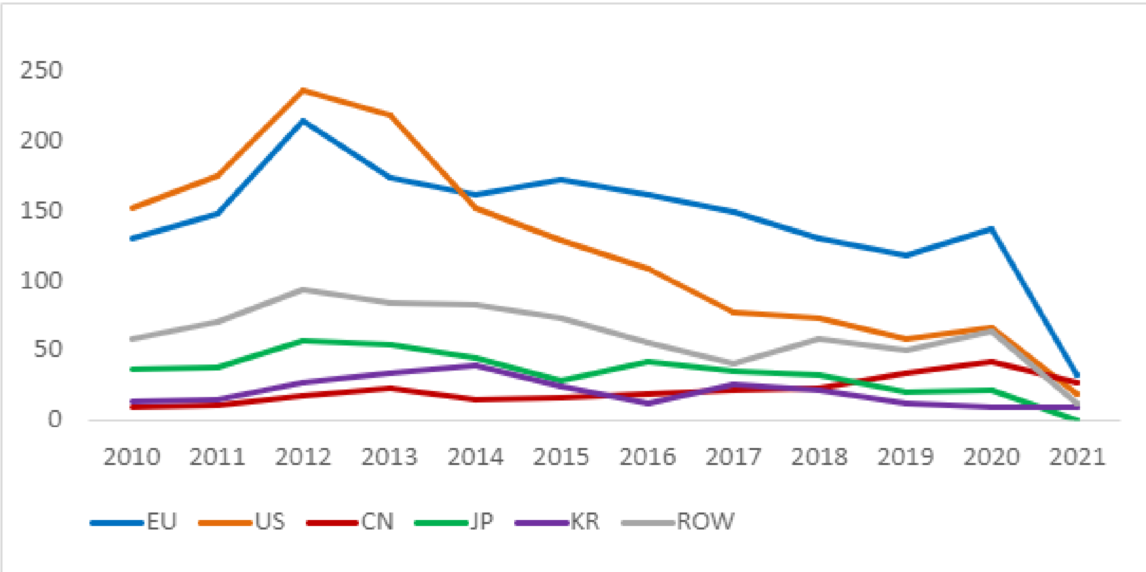
Figure 28. Number of patents granted from 2010 to 2021



Source: JRC elaboration based on data from the European Patent Office (EPO), PATSTAT database 2022

From 2010 to 2021 the EU and the US kept constantly the lead in terms of high value inventions averaging, both reaching more than 200 inventions each in 2012 (Figure 29).

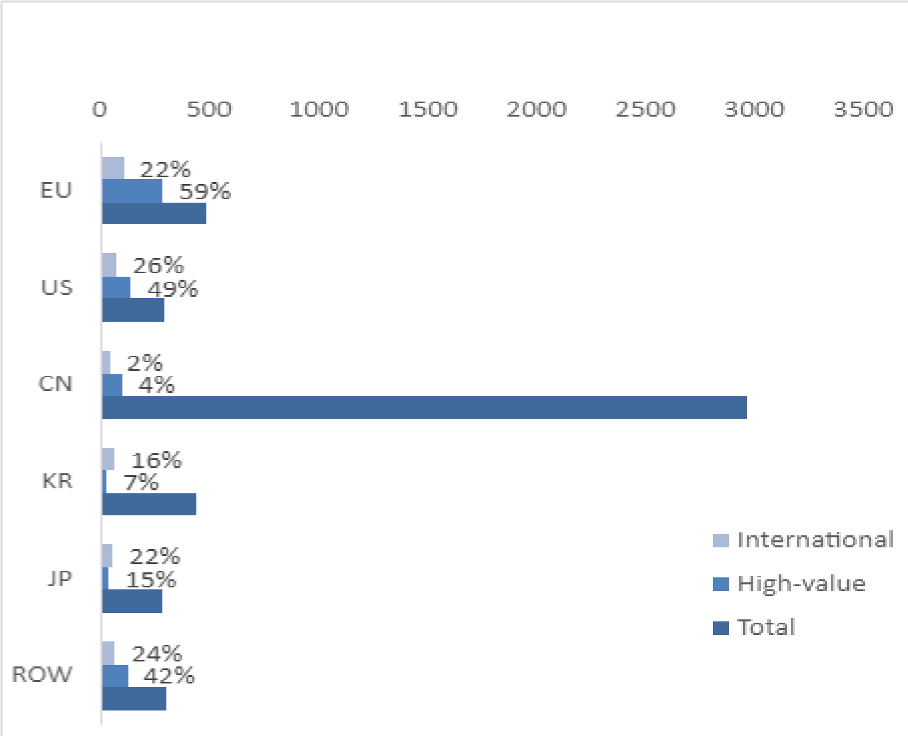
Figure 29. Number of high value inventions advanced fuel globally, 2010-2021



Source: JRC elaboration based on data from the European Patent Office (EPO), PATSTAT database 2022

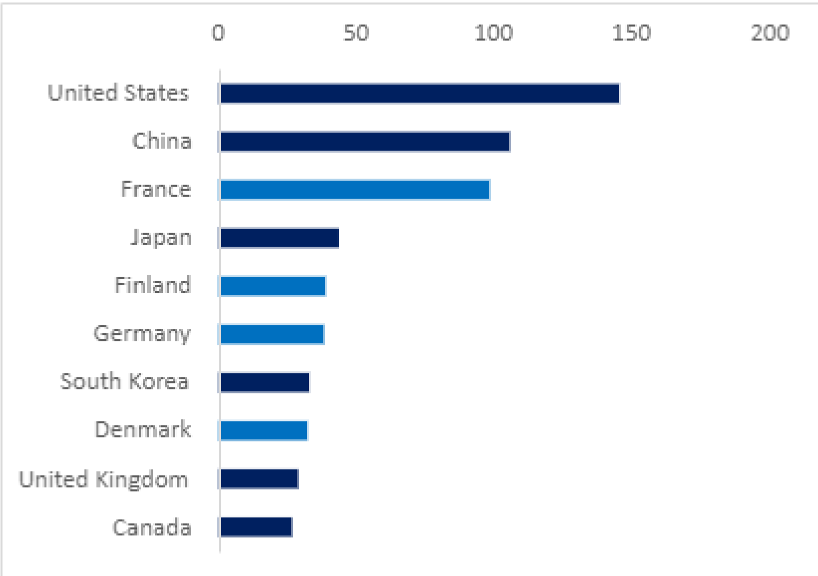
Figure 30 shows that for the triennium 2019-2021 the EU had 59% share of high-value patents out of a total 489 patent applications, while for example China received a total of 2972 patents with only 4% high-value. Figure 31 shows the situation for the same triennium 2019-2021 but at country level. The US is the leading country with 145 high-value patents, while France and China follow with 106 and 98 patents application.

Figure 30. Number of inventions and share of high value and international activities, 2010-2021



Source: JRC elaboration based on data from the European Patent Office (EPO), PATSTAT database 2022

Figure 31. High value inventions, top 10 countries globally, 2010-2021



Source: JRC elaboration based on data from the European Patent Office (EPO), PATSTAT database 2022

Concerning the situation at individual company level, EU based companies Neste Oy, Air Liqid with 14 inventions each, and Novozymes, with 10 high-value inventions, are in the first and sixth position of the top 10 world entities with high value inventions ranking for the triennium 2019-2021 (Table 6).

Table 6. Top 10 companies for high-value inventions in the EU and Global 2019-2021

High-value inventions - Global Top 10 entities (2019-2021)	
	High-value
Lair Liquide Societe Anonyme Pour Letude Et Lexploitation Des Procedes Georges Claude (FR)	14
Neste Oy (FI)	14
Lanzatech Inc (US)	12
Eastman Chemical Company (US)	11
Danisco Us Inc (US)	10
Novozymes As (DK)	10
Indian Oil Corporation Limited (IN)	7
Exxonmobil Research And Engineering Company (US)	7
Upm Kymmene Corporation (FI)	7
Valmet Oy (FI)	7
High-value inventions - EU Top 10 entities (2019-2021)	
	High-value
Lair Liquide Societe Anonyme Pour Letude Et Lexploitation Des Procedes Georges Claude (FR)	14
Neste Oy (FI)	14
Novozymes As (DK)	10
Upm Kymmene Corporation (FI)	7
Valmet Oy (FI)	7
Lallemand Hungary Liquidity Management Llc (HU)	6
Suez Groupe (FR)	5
Basf Aktiengesellschaft (DE)	5
Haldor Topsoe As (DK)	4
Steeper Energy Aps (DK)	3

Source: JRC elaboration based on data from the European Patent Office (EPO), PATSTAT database 2023

The inventions granted decreased in the triennium 2019-2021 from a total of 605 in 2019 to 450 in 2021. China leads this category with 63% share in 2019 and 78 % in 2021 (Table 7).

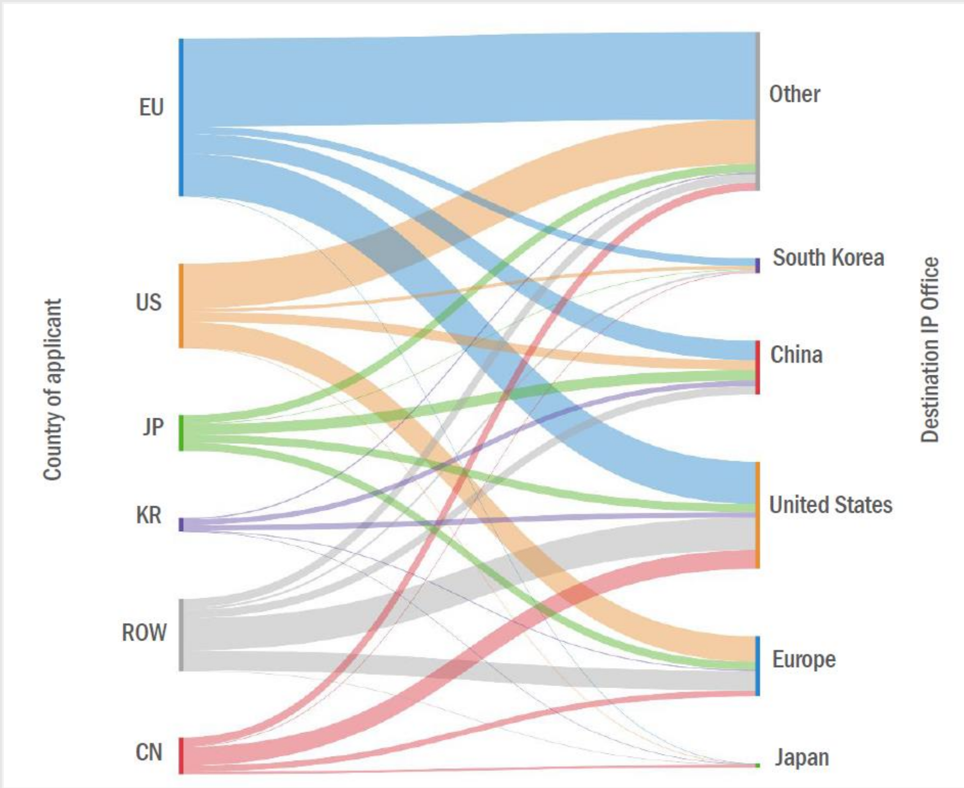
Table 7. Invention granted 2019-2021

World_players	2019	2020	2021
EU	36.4	41.0	6.2
CN	382.9	384.4	351.2
JP	23.1	18.4	10.8
KR	98.7	100.1	59.0
US	20.7	16.6	10.7
ROW	43.1	22.1	12.5
	605	582.6	450.3

Source: JRC elaboration 2024

The flow of inventions (or destination of patent families) indicates where (in which national patent office) inventions are filed. This can be used to analyse the international flow of inventions, the stream, cumulated inventions from 2018 to 2020. Almost 50% of inventions from the EU flows to the US and China. The overall picture about invention flow is presented in the (Figure 32)

Figure 32. Total invention stream from 2019-2021

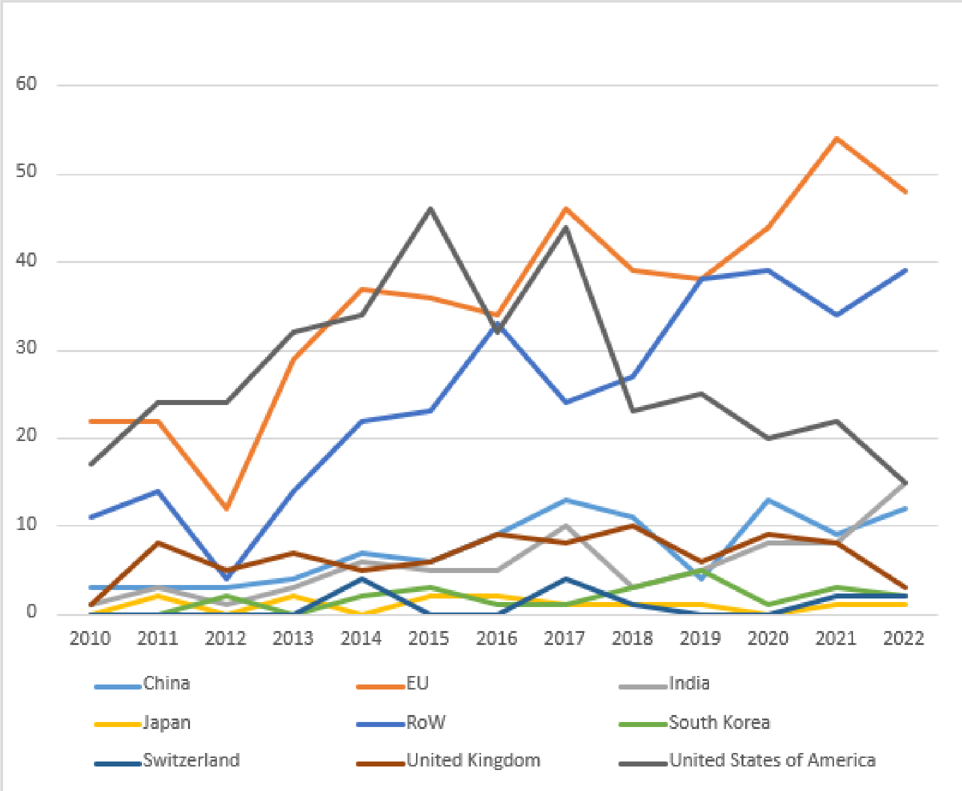


Source: JRC elaboration based on data from the European Patent Office (EPO), PATSTAT database 2021

2.7 Scientific publication trends

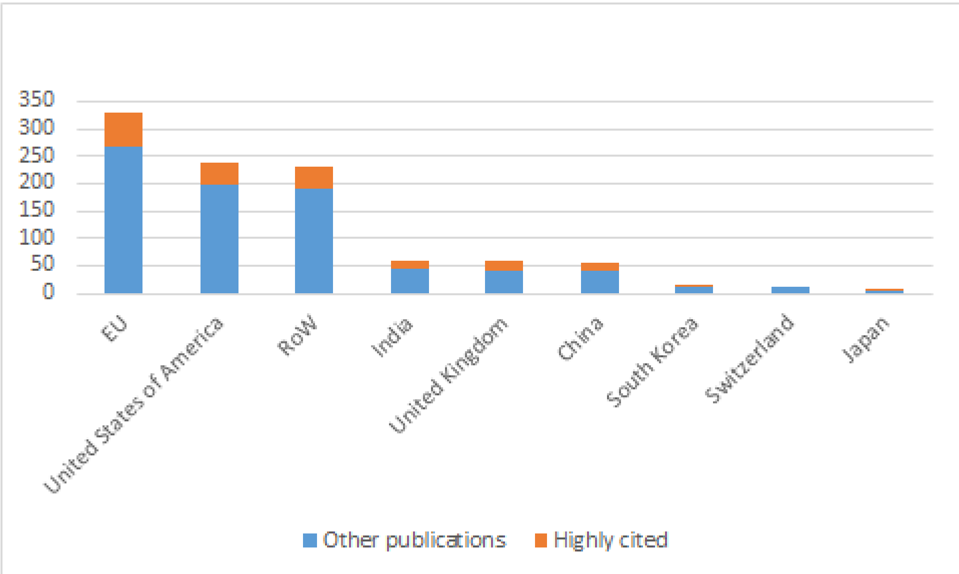
At global level the EU is the top publisher in the sector with 40-50 publications annually since 2017. The second biggest publishing region (besides the “rest of the world”) is the US but with a declining trend, (Figure 33). The EU has 61 highly cited publications, which amounts to 32% of all 10% most cited publications in the field. (Figure 34).

Figure 33. Number of published papers for world regions (2010-2022)



Source: JRC 2024

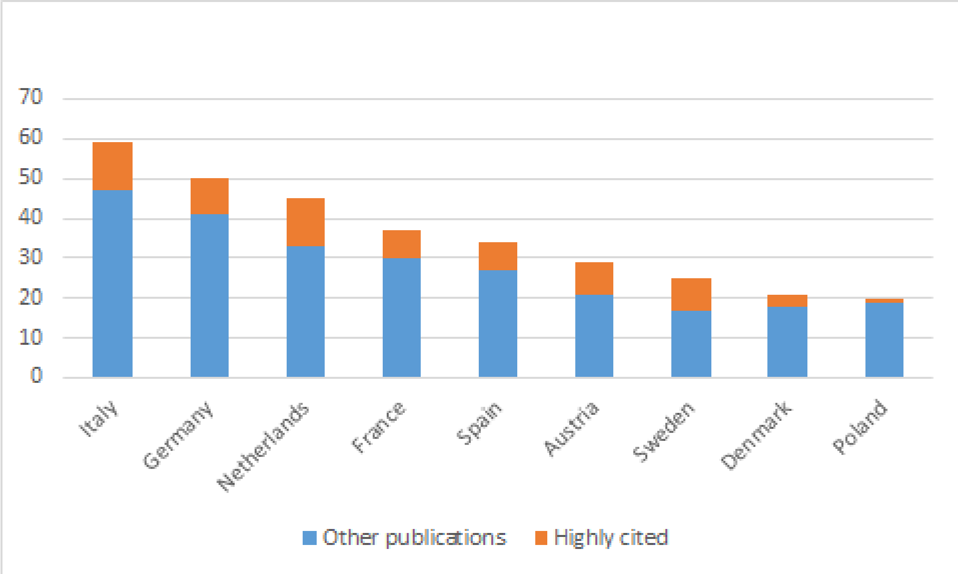
Figure 34. Number of published papers (highly cited and others) for world regions, (2010-2022)



Source: JRC 2024

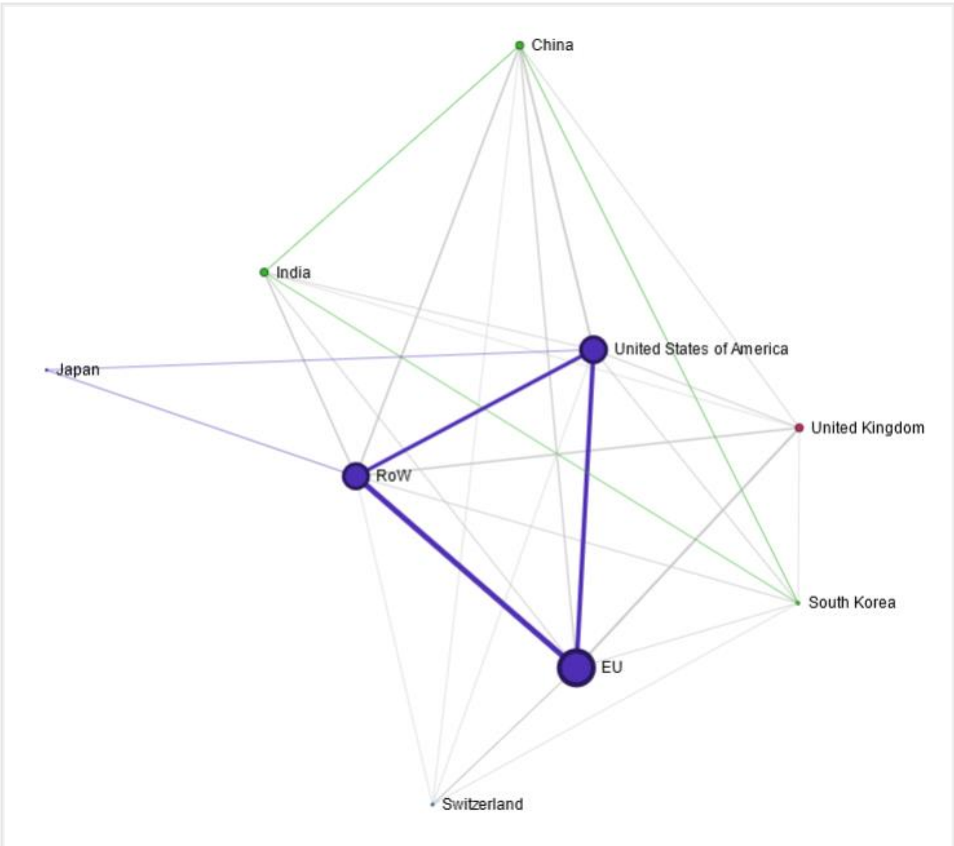
Within Europe, again Italy, Germany and the Netherlands have the highest number of publications and highly cited publications, (Figure 35). When assessing the scientific connection in the field, there is a strong relation between EU, US and the RoW, (Figure 36)

Figure 35. Number of published papers (highly cited and others) for EU countries (2010-2022)



Source: JRC 2024

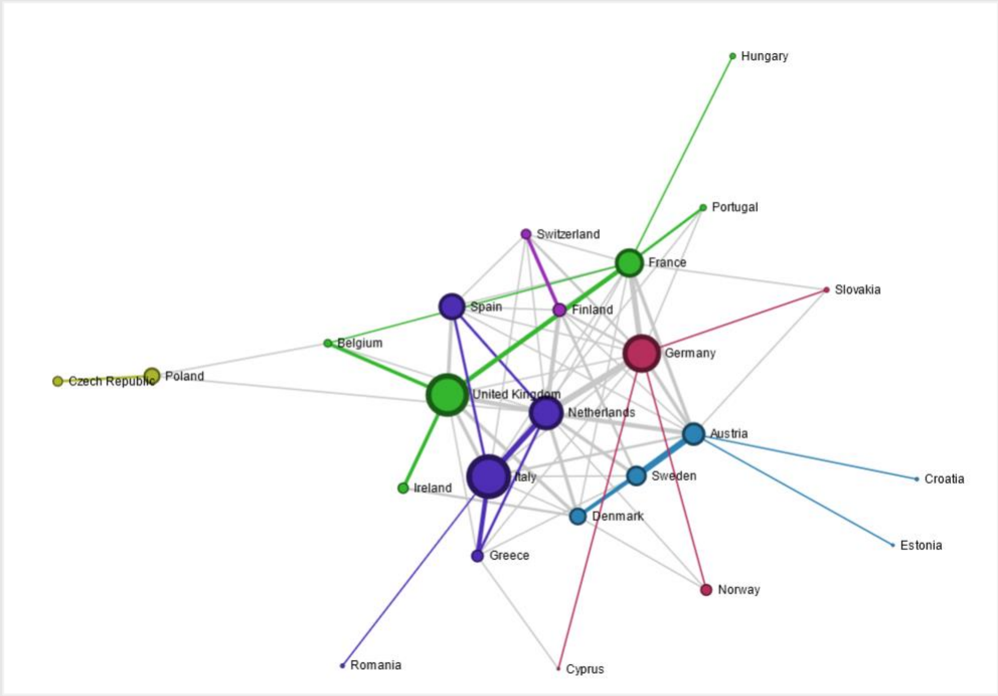
Figure 36. Collaborations on biofuels publications by world regions 2010-2022



Source: JRC 2024

At the EU level Italy, Nederland and Spain show having consolidated network, while Germany that is strong in the field, has many small connections with other EU MS institutions. (Figure 37)

Figure 37. Collaborations on biofuels publications by EU countries 2010-2022



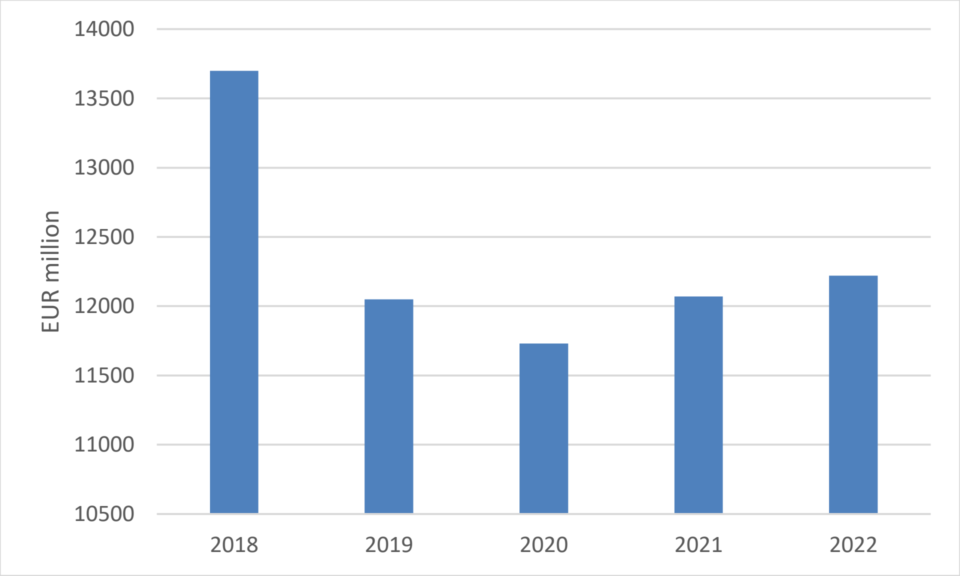
Source: JRC 2024

3 Value Chain Analysis

3.1 Turnover

As shown in Figure 38, the turnover in the EU concerning the biofuel industry peaked in 2018 reaching 13700 M€ then decreasing to EUR 12070 million in 2021 with a slight recover at EUR 12220 million in 2022.

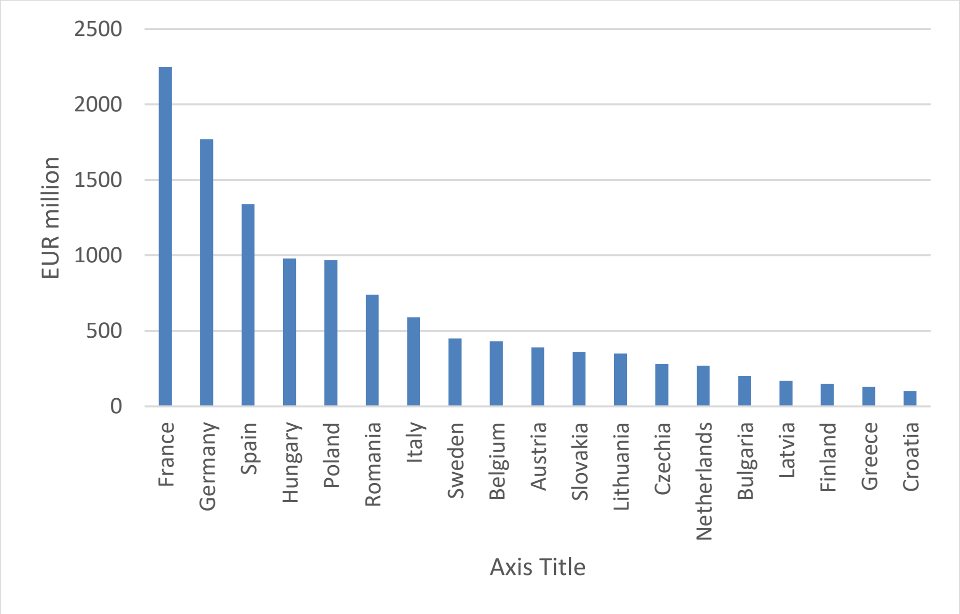
Figure 38. Biofuel industry turnover in the EU



Source: (EurObserv-ER, 2024)

Figure 39 presents the situation at MS level, in 2022 France had the highest turnover for the biofuel industry in the EU, with a bit more EUR 2250 million, followed by Germany with around EUR 1800 million turnover.

Figure 39. Biofuels turnover in EU in 2022



Source: (EurObserv-ER, 2024)

3.2 Gross value added

Deloitte (Deloitte, 2022) estimated the biofuel sector's contribution to EU27 economy using three approaches recognised by the European System of National and Regional Accounts (ESNRA). They gathered data (added value, expenditure, jobs) from publicly disclosed financial statements, regarding EU companies active in the biofuel industry, searching additional info surveying biofuel industry players. The biofuel sector in 2020 had a direct Gross Domestic Product (GDP) impact of EUR 2304 million and indirect at 6621 M€ with a total 8925 M€

According to Deloitte (Deloitte, 2022), the sectorial breakdown on GDP direct impact of biofuel in EU is mainly on operation and maintenance with EUR 1530 million as shown in Table 8.

Table 8. GDP impact of biofuel in EU in M€

<table>
<tr><th colspan="4">Biofuel EU</th></tr>
<tr><th>Impact on GDP (EUR million)</th><th>Direct</th><th>Indirect</th><th>total</th></tr>
<tr><td>Equipment Manufacturing</td><td>142</td><td rowspan="5">6621</td><td rowspan="5">8925</td></tr>
<tr><td>Construction</td><td>144</td></tr>
<tr><td>Supply of feedstock</td><td>488</td></tr>
<tr><td>Operation and maintenance</td><td>1530</td></tr>
<tr><td>Total</td><td>2304</td></tr>
</table>

Source: (Deloitte, 2022)

3.3 Environmental and socio-economic sustainability

The different dimensions of sustainability of advanced biofuels are described as harmonized tables throughout the different CETO reports, and attached as annex 2 in this report.

3.4 Role of EU Companies

Many EU companies involved in the production of biofuels are also players in the traditional fossil energy business; it is not possible allocating the value chain of those companies exclusively to biofuels production.

Neste (Finland) opened in 2011 (investment of EUR 670 million) a renewable diesel plant with a capacity of 910,000 klpa (hereinafter, "kilo litres per annum") in Rotterdam. Current maximum production capacity is of 1,280,000 klpa.

In May 2023, Neste expanded its refinery in Singapore to a production capacity of 1000 ktpa (hereinafter, "kilo tonne per annum") of sustainable aviation fuel (hereinafter, "SAF"), making it the world's largest SAF production facility. In May 2024, Neste expanded its supply capabilities of SAF to Europe; Neste commissioned terminal capacity at VTTI's ETT terminal in Rotterdam, the most important hub for world trade in biofuels, to store and blend Neste MY Sustainable Aviation Fuel™ produced in Singapore. In August 2022, Neste started to expend by 1300 ktpa its refinery in Rotterdam producing renewable diesel. The commercial operations are planned for 2026 with an increased Neste's production capacity of Renewable Diesel (800 ktpa) and SAF (500 ktpa) to a total of 2700 ktpa renewables production capacity.

UPM opened in 2015 a renewable diesel plant in Lappeenranta (FI) producing wood-based renewable diesel and naphtha from crude tall oil, a residue of UPM's own pulp production. The capacity is 130 ktpa of advanced biofuels (renewable diesel and naphtha). UPM is in a basic engineering phase to build a new-generation biofuel refinery in Rotterdam with a capacity of 500 ktpa of renewable fuels, including SAF. In Q4 2023, UPM Biofuels started a registration process for tall oil-based biofuels for jet engine use with ASTM (American Society for Testing and Materials), a necessary step to produce SAF.

Green Fuel Nordic's bio-oil refinery in Lieksa (GFN Lieksa), Finland, started operation in December 2020 to refine forest biomass (sawmill by-products and biostem) into fast pyrolysis bio-oil. The production capacity of the refinery is 24 ktpa of bio-oil.

NordFuel bioproduct factory in Haapavesi, Finland, produces 70 ktpa of bioethanol for transportation use. NordFuel is preparing a next generation bioproduct plant in Haapavesi to produce from domestic sawdust and forestry by-products sustainable biofuels and bioproducts such as bioethanol, biogas, and lignin. The production start is planned for 2028. In March 2024 NordFuel announced Chempolis as the technology provider. In December 2023, Kanteleen Voima, Liquid Wind, and Piipsan Tuulivoima announced a cooperation agreement to prepare a feasibility study for an electrofuel (eFuel) plant producing eMethanol in Haapavesi (FI) and adjacent to NordFuel's planned next generation biorefinery. The electrofuel (eFuel) plant will be powered by renewable energy from a new onshore wind park (built and operated by Piipsan Tuulivoima). Liquid Wind's technology enables to utilise the carbon dioxide that will come out of the biorefinery's process.

BioEnergo plans to build BioEnergo I, a cellulosic second-generation bioethanol plant, for advanced biofuels in Pori (FI), a EUR 200 million investment. The plant will use the by-products of the sawmill industry, softwood sawdust and woodchips sourced from local sawmills. It will processes 60,000 cubic meters of advanced bioethanol into passenger cars and 130,000 MWh of advanced liquefied biogas as biomethane fuel for transport. BioEnergo I technology and process are based on Praj Industries's Enfinity 2nd generation cellulosic ethanol technology, and on Sekab BioFuels & Chemicals's proven CelluAPP® enzymatic hydrolysis technology.

Fintoil's biorefinery in Hamina started operations in 2022, an investment of EUR 130 million, the processing capacity of 200 ktpa. It refines crude tall oil, a by-product of the kraft pulp process, into crude fatty acids products to produce second-generation renewable diesel and for other biochemicals. Fintoil's refinery uses Neste Engineering Solutions' patented NEXPINUS™ technology which enables a 40 percent lower energy consumption compared to a traditional tall oil refinery.

Eni bio-refinery in Venice in Porto Marghera produces Hydrogenated Vegetable Oil (HVO) with EcofiningTM technology. The biorefinery uses waste raw materials, such as waste cooking oil, animal fats and residues from the agro-food industry to produce biofuels, HVO diesel, bio-LPG, bio-jet and bio-naphtha. In 2020, with a capacity of 400 ktpa it processed around 220 ktpa of raw materials of which more than 25% consisted of used cooking oils, animal fats and other waste vegetable oils. Production is forecasted to increase from 2024, a further upgrading of the plant will increase the processing capacity up to 560 ktpa with a production of biodiesel of 420 ktpa .

Eni converted its Gela refinery in Sicily into a renewable diesel production facility with capacity of 750 ktpa. The biorefinery in Gela opened in 2019 to produces biofuel (HVO) from organic raw materials. Construction of the plant to produce SAF in Gela is underway.

Eni plans to open a new biorefining lines in 2026 in Livorno. The project includes a construction of three new facilities to produce hydrogenated biofuels: a biogenic feedstock pre-treatment unit; a 500 ktpa Ecofining™ plant; and a facility to produce hydrogen from methane gas. The plants will process biogenic feedstocks, mainly vegetable waste and residue, to produce HVO diesel, HVO naphtha and bio-LPG. **Preem**'s Gothenburg, Sweden, biorefinery had, in 2023, an annual production capacity of 530 000 m3, and produced its first-ever 100% renewable HVO diesel.

In 2024, **Preem** started to rebuild the ICR (IsoCracker) plant adjacent to its refinery in Lysekil. The diesel plant will after the conversion have an annual production capacity of 600,000 m3 of biojet/SAF, and 600,000 m3 of renewable diesel (HVO-100). An investment of SEK 5.5 billion (≈ EUR 490 million). Start of production in 2027. The investment enables Preem to become the largest producer of SAF in Northern Europe, and one of the largest producers of renewable fuels for road transportation. The plant is designed to source vegetable and animal oils and fats (e.g., rapeseed oil (RSO), used cooking oil (UCO) and rendered fat (Tallow)).

St1 (Finland) and **SCA** (Sweden), a joint venture, started-up, in April 2024, Gothenburg Biorefinery, an investment of 4 billion SEK (≈ EUR 360 million). The biorefinery has a design capacity of 200 ktpa of renewable fuel production. It produces SAF, biodiesel (HVO), bio-naphtha, and bio-LPG. The design of the biorefinery brings flexibility to the process by allowing the use of a wide range of feedstocks (e.g., used cooking oil, animal fats, and tall oil fatty acids).

BioTFuel project, a cooperation of six companies (Avril, Axens, French Alternative Energies and Atomic Energy Commission (CEA), IFP Energies Nouvelles (IFPEN), ThyssenKrupp, and Total Energies) aims to produce 230000 klpa of advanced biodiesel and biojet from lignocellulosic biomass (straw, forest residues and crops). The demonstration-scale plant is located at Total Energies' former Flandres petroleum refinery in Dunkerque. The aim of the project is to validate technologies and to create a complete production chain for second-generation biodiesel and bio-kerosene.

Galp announced, in September 2023, to build, in a joint venture with Mitsui (25%), an advanced biofuels unit adjacent to its refinery in Sines (Portugal), with a production capacity of 263 ktpa of biodiesel and 193 ktpa of biojet from bio-feedstock and waste materials, such as used cooking oils and animal fats, to start up in 2025, an investment of € 400 million.

Cepsa's and **Bio-Oils'** started, in February 2024, construction of new second-generation biofuels plant for SAF and renewable diesel in Palos de la Frontera, the province of Huelva (Spain), to be commissioned in 2026, an investment of EUR 1.2 billion, an annual production capacity of 500 ktpa of SAF and renewable diesel. Topsoe will deliver its HydroFlex™ technology, which enables the production of SAF and renewable diesel from renewable feedstocks including agricultural waste, fats, oils and greases.

Cepsa produces 100% renewable diesel (HVO) in its La Rábida Energy Park (Huelva) from used cooking oils or agricultural waste. By implementing a waste-to-value approach, Cepsa optimizes its integrated supply chain to access broad range of agricultural waste and residues feedstock and upcycle them into renewable fuels such as SAF. Since 2022, Cepsa has been producing and marketing 2G biofuels to its customers in the aviation, maritime, and land sectors. In 2023, Cepsa became the first company to permanently offer SAF (produced in its facilities from agricultural waste and used cooking oils) at five of Spain's main airports: Madrid, Barcelona, Palma de Mallorca, Seville and Malaga, and to offers biofuels in 60 Spanish ports.

Repsol, in 2024, invested EUR 250 million in the construction of a new biofuel production plant in Cartegena (Spain), a production capacity of 250 ktpa of renewable diesel and SAF. It will process 300 ktpa of organic waste (e.g., used cooking oil).

Solarig announced, in April 2024, the plan to build a SAF plant in Soria, Spain with €780m investment, a production capacity of 60 ktpa of SAF. The project is based on the combination of two technological routes, biomethane and renewable electricity, for the SAF production. The plant will promote the circularity and use of local resources (sun, wind, water) and farming waste (biomethane and biogenic CO2).

Sasol, the global chemicals and energy company, and Topsoe, leader in carbon emission reduction technologies, have announced in March 2024 their joint venture project "Zaffra" (headquarters based in Amsterdam) to decarbonise aviation focusing on the development and delivery of SAF.

Versalis, Eni's chemical company started-up, in February 2022, a plant in Crescentino (Italy) with a production capacity of 25 ktpa of bioethanol, from lignocellulosic biomass using proprietary Proesa® technology. In December 2022, Versalis acquired from DSM a technology to produce enzymes for second-generation ethanol. **Clariant** announced, in December 2023, to shut down its sunliquid® bioethanol production in Podari, Romania, and to downsize related activities of the business line Biofuels & Derivatives in Germany (Straubing, Planegg and Munich). The plant in Podari began producing bioethanol in the second quarter of 2022. In July 2023, Clariant started a strategic evaluation of the options for the plant after it became clear that the plant did not achieve targeted operational parameters. Given continued losses, the economics of the plant in Podari cannot justify for Clariant to continue ramp up which would require significant additional capital expenditure.

BioMCN: In 2015, Dutch natural gas-based fertilisers and chemicals producer OCI NV acquired BioMCN. In 2023, OCI shut down European facility, BioMCN.

Södra started up, in 2020, a biomethanol plant at Södra's pulp mill in Mönsterås (Sweden) with a production capacity of 5.25 ktpa of biomethanol, technology Liquid Forest™ Biomethanol. Biomethanol is made from the crude methanol derived from the manufacturing process at pulp mill.

Veolia plans to start-up in 2024 a crude methanol refinery adjacent to Metsä Fibre's Äänekoski (Finland) bioproduct pulp mill to produce 12 ktpa of biomethanol, a EUR 50 million investment.

OMV started up, in June 2024, its co-processing plant at the Schwechat refinery in Austria which integrates renewable components during the refining process. An investment of EUR 200 million, processing capacity of 160 ktpa of liquid biomass being converted into renewable hydrogenated vegetable oil (HVO) components. The plant has feedstock flexibility for waste-based and advanced feedstocks.

In 2024, OMV will start using a patented process developed inhouse to produce the bio-based alcohol propanol from waste glycerol and use it as an advanced biofuel component in gasoline. OMV is set to invest € 36 million to reach production capacities of 1250 klpa of propanol.

Petrom announced, in June 2024, it will invest EUR 750 million at Petrobrazi (Romania) to transform the refinery into a facility with a production capacity of 250 ktpa of SAF and HVO. Petrobrazi is the first refinery in Romania certified to produce SAF and HVO through the co-processing of biological raw materials.

BASF, Thyssenkrupp, OMV, DLR and **ASG** form a consortium Methanol-to-SAF (M2SAF), a development project funded EUR 3.1 million for the period 2022-2025 by the Federal Ministry for Digital and Transport (BMDV) in Germany. The aim is to develop a novel process technology to produce SAF that can be used as a drop-in fuel up to 100%. The starting point of the process is sustainably produced methanol from CO2 and green hydrogen.

European Energy (Denmark) and Metafuels AG (Swiss aviation tech **OMV** company) announced, in May 2024, its plans to set up a synthetic sustainable aviation fuel (eSAF) facility near Padborg (Denmark) with a production capacity of 12,000 litres of eSAF daily (≈ 4,000 klpa).

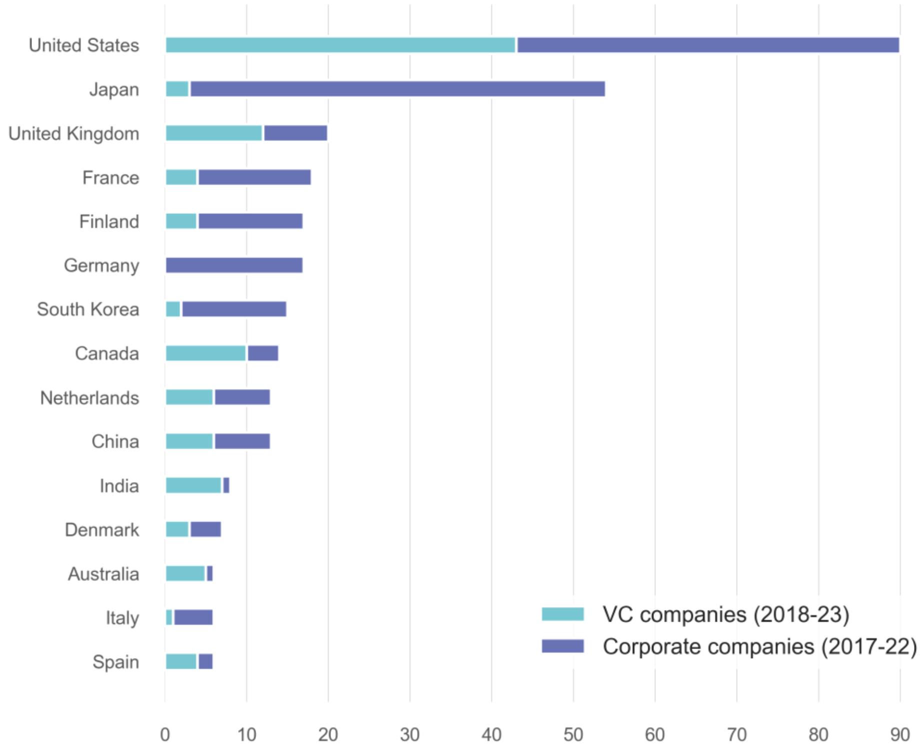
AustroCel`s biorefinery in Hallein (Austria) produces bio-ehtanol since December 2020, an investment of € 42 million, a capacity of 30,000 klpa. Bioethanol is produced from residual materials from its wood-based pulp production. The principal consumer is OMV (a multi-year agreement with AustroCel) which adds bioethano to petrol fuels.

ORLEN Południe announced, in September 2023, to build oilseed processing plant in Kętrzyn (Poland), an investment of PLN 850 million (≈200 million euro), a processing capacity of 500 ktpa of rapeseed (in 2022, Poland's rapeseed crop yielded a total of 3600 ktpa), yielding a production output of 200 ktpa of oil to manufacture biofuels. The principal consumer will be ORLEN Południe, which operates a biodiesel plant in Trzebinia. The construction of the facility is to commence in 2024, with completion expected by mid-2026.

in March 2023, Orlen Poludnie announced to invest PLN 1.12 billion (≈ € 260 million) to build a (second-generation) bioethanol plant in Jedlicze Petroleum Refinery (Poland), to be completed in 2025, a capacity production of 25 ktpa of bioethanol from crop residues, (e.g.,cereal straw). The demand for feeding stock of 150 ktpa.

As advanced biofuels is still a young sector, it is interesting to look at innovating companies instead of market leaders. Figure 40 shows that U.S. and Japan have the highest number of innovating companies at 145 the EU leaders in this ranking are France, Finland and Germany totalling 52 companies.

Figure 40. Number of innovating companies by type, ranking of top 15 countries

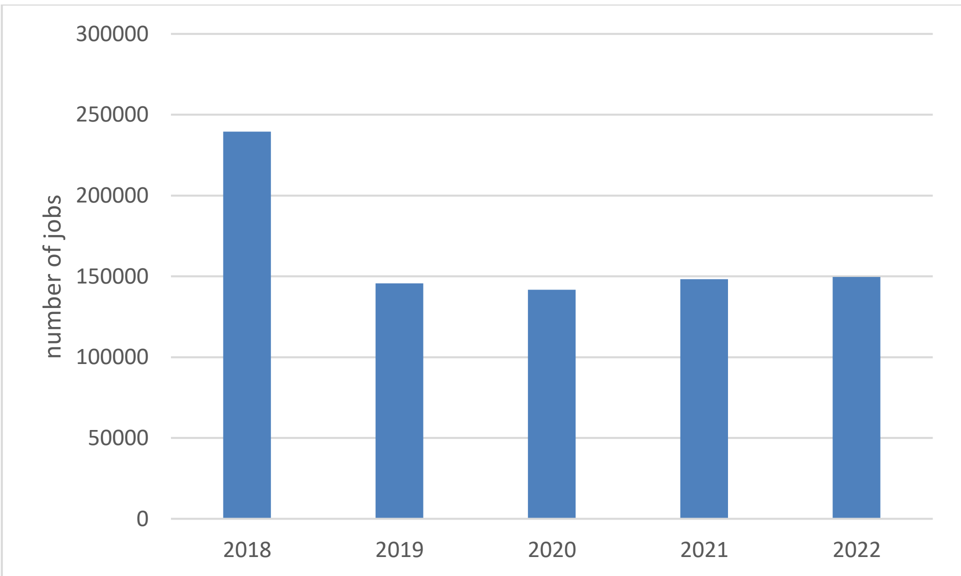


Source: JRC elaboration based on EU Industrial R&D investment Scoreboard and other sources

3.5 Employment

According to EurObserv-ER (EurObserv-ER, 2024) the number of direct and indirect jobs generated for the biofuels sector in EU was 239600 in 2018 then dropped and reached 149700 in 2022 (Figure 41).

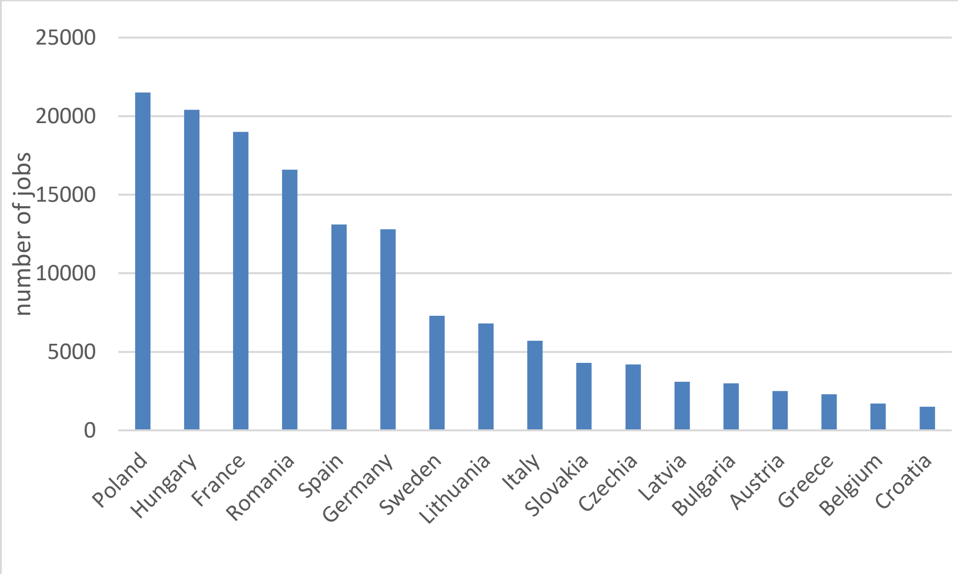
Figure 41. Number of direct and indirect jobs in the biofuels sector in the EU



Source: (EurObserv-ER, 2024)

As shown in Figure 42 at EU country level, Poland with 21500 jobs is the country with the highest employment for the biofuel sector in 2022.

Figure 42. Number of direct and indirect jobs in EU countries, 2022



Source: (EurObserv-ER, 2024)

Deloitte (Deloitte, 2022) estimated the biofuel sector's contribution to jobs in EU27. According to this study, along the whole value chain the impact on jobs expressed in FTE (Full Time Equivalent) reached 219651 in 2019, of which 57216 direct jobs (Table 7).

Table 9. Impact of biofuels sector on jobs in the EU, 2019

<table>
<tr><th colspan="4">Biofuel EU</th></tr>
<tr><th>Impact on Jobs</th><th>Direct</th><th>Indirect</th><th>total</th></tr>
<tr><td>Equipment Manufacturing</td><td>3403</td><td rowspan="5">162434</td><td rowspan="5">219651</td></tr>
<tr><td>Construction</td><td>1678</td></tr>
<tr><td>Supply of feedstock</td><td>35313</td></tr>
<tr><td>Operation and maintenance</td><td>16821</td></tr>
<tr><td>Total</td><td>57216</td></tr>
</table>

Source: (Deloitte, 2022)

The number of skilled workers required highly depends on the technology. A fossil refinery is employing about 2000 workers, plus workers for maintenance at the same order of magnitude. There is potential to keep a similar amount in biorefineries, which also require petrochemicals skilled workers. Potential is seen in the shift from skilled workers from the oil industry to the biorefinery sector. However, biorefineries are often located on the countryside, which makes them less attractive for workers.

3.6 Energy intensity and labour productivity

3.6.1 Energy intensity

Fossil energy inputs to produce advanced biofuels can range anywhere from close to 0% to nearly 50% of the energy in the fuel according to JECv5 (Prussi *et al.*, 2020). With the exception of the energy content of the (waste) biomass, the Energy Return On Energy Invested (EROEI) can be anywhere from 2 to nearly infinite.

Energy intensity is one of the indicators to measure the energy needs of an economy, Eurostat (eurostat, 2020) calculates the indicator as units of energy per unit of GDP. The total biofuel produced in EU (source Statista) was 15763 ktoe in 2020 while the impact on GDP of the Biofuel sector (Deloitte, 2022) was EUR 8925 million, the Energy intensity is estimated at 1.77 ktoe/M€.

3.6.2 Labour productivity

Labour productivity can be defined in several ways (Borychowski, 2018). If combining the total direct employment of 57216 FTE in the bioenergy sector with the 609 billion MJ of biofuels produced, a rough number of 10 TJ of energy is produced by every FTE. In monetary terms, the production is approximately EUR 7 billion (see chapter 4.2), so the labour productivity is roughly 122 k€ per FTE and year. Using the turnover at EUR 12 billion and job data at 57216 FTE, the turnover per job was at 211 k€/Job and year. On energy basis the biofuel production was 15763 ktoe, putting the energy production per job at 275 toe/job and year.

3.7 EU Production Data

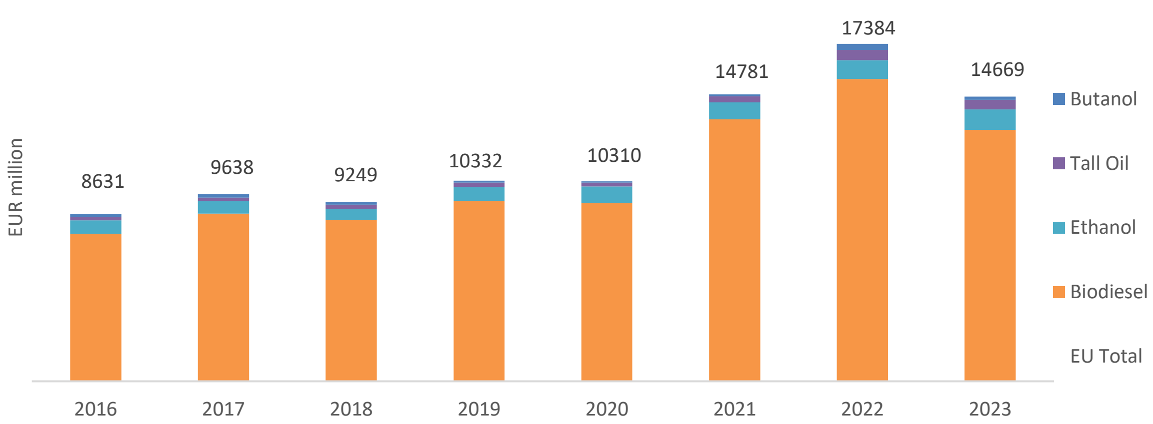
Advanced biofuel products are hard to separate from other biofuels, as the trade and PRODCOM codes only cover general categories. This chapter gives an overview of biofuels production and tries to complement with some information on the share of advanced biofuels in that production.

PRODCOM provides statistics on the production of manufactured goods carried out by enterprises on the national territory of the reporting countries. PRODCOM statistics aim at providing a full picture at EU level of developments in industrial production for a given product or for an industry in a comparable manner across countries. For consistency with the trade codes, the following codes for PRODCOM have been used:

20142230	Butan-1-ol (n-butyl alcohol)
20147130	Tall oil; whether or not refined
20147500	Denatured ethyl alcohol and other denatured spirits; of any strength
20595800	Biodiesel and mixtures thereof not containing or containing < 70 % by weight of petroleum oils or oils obtained from bituminous minerals
20595990	Biofuels (diesel substitute) other chemical products n.e.c. (for period 2009-2011)
20595997	Biofuels (diesel substitute) (for period 2012-2015)

In 2023, the total EU production of biofuels decreased by 16% compared to the previous year, reaching almost EUR 15 billion, Biodiesel represents the vast majority of the EU production, followed by ethanol, (Figure 43)

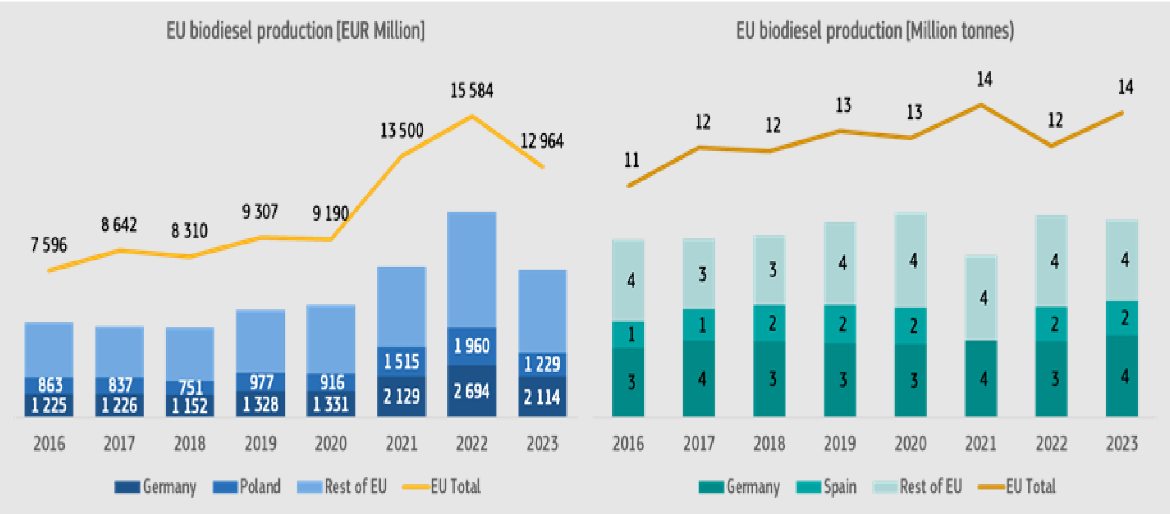
Figure 43. EU Biofuels Production value biofuels in EUR million



Source: JRC elaboration on Prodcom 2024

Figure 44 Focusing on biodiesel, the EU production decreased by 17% in 2023, reaching almost EUR 13 billion Germany and Poland were the top producers holding together more than one-quarter of the EU production. Italy has significantly increased its biodiesel production since 2021 and holds 12% of the total EU production value for 2021-2023. Spain follows as fourth producer without disclosing its production for 2021. In terms of quantities, the EU production increased by 12% in 2023, reaching almost 14 million tonnes of biodiesel Germany and Spain were the top EU producers with more than one-third of the EU production, followed by Poland and Italy.

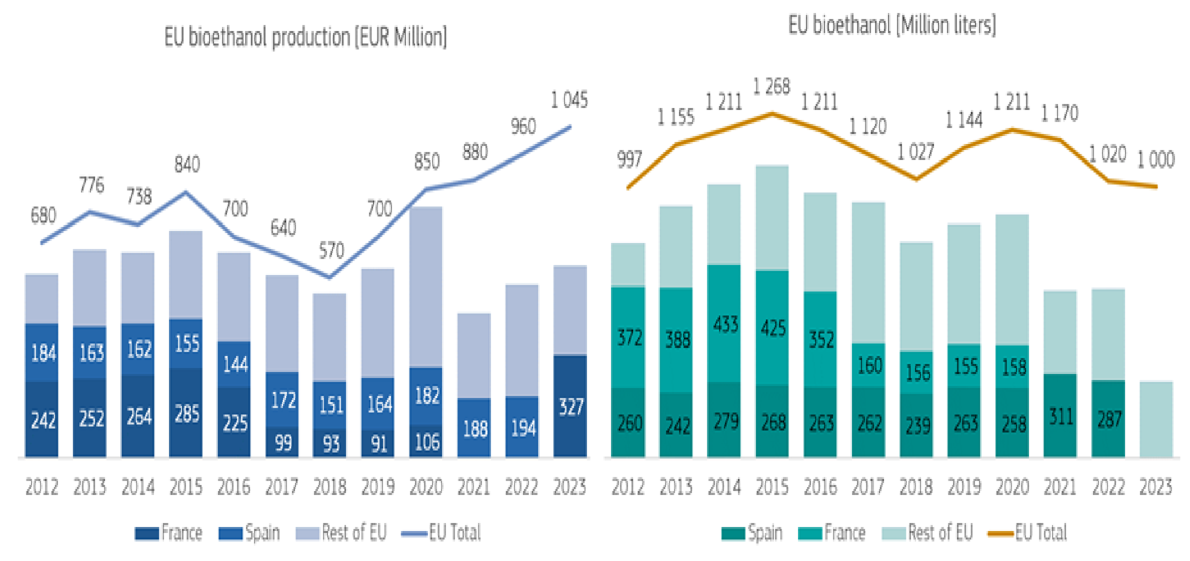
Figure 44. EU Biodiesel production



Source: JRC elaboration on Prodcom 2024

Focusing on bioethanol, the EU production increased by 9% in 2023, reaching more than EUR 1billion France and Spain were the top producers holding together almost one-quarter of the EU production, followed by Hungary and Germany. In terms of quantities, the EU production remained the stable at 1billion litres of bioethanol Spain and France were the top EU producers followed by Hungary and Czechia. Germany has not disclosed its ethanol production in quantities. (Figure 45)

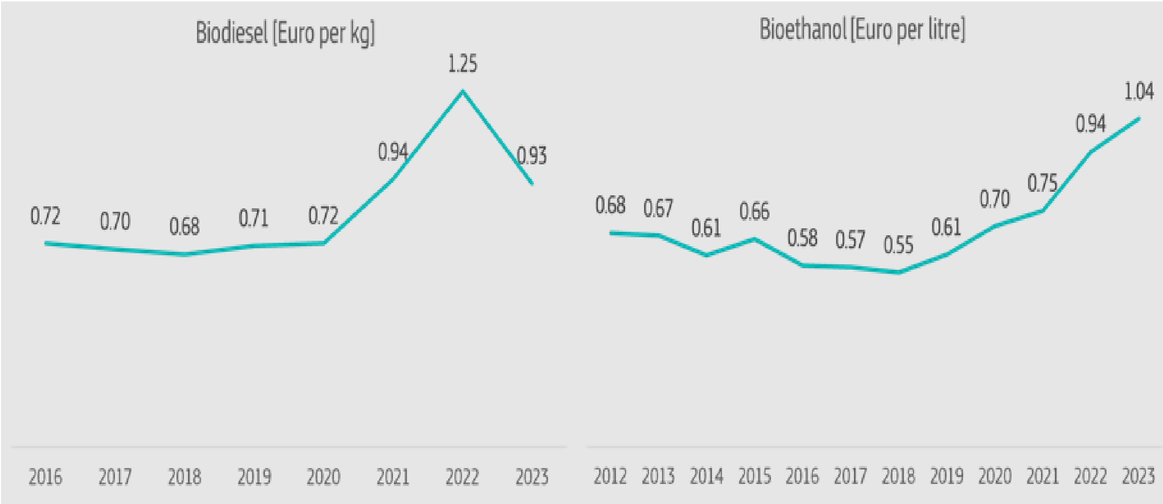
Figure 45. EU Bioethanol production



Source: JRC elaboration on Prodcom 2024

The EU biodiesel production value per quantity spiked in 2022, reaching 1.25 EUR/kg, and it rolled back to its previous cost of 0.93 EUR/kg in 2023 The EU bioethanol production value per quantity has been increasing steadily since 2018, reaching 1.04 EUR/lt in 2023. (Figure 46)

Figure 46. EU Bioethanol production value per quantity



Source: JRC elaboration on Prodcom 2024

As described in section 2.2.2 the share of advanced biodiesel in EU reached 21.7% in 2022, while for advanced ethanol it was at only 0.76%. Assuming the same price for conventional and advanced biofuels, then advanced biodiesel had a production value of EUR 1.4 billion and advanced bioethanol of EUR 4 million.

4 EU Market Position and Global Competitiveness

4.1 Global & EU market leaders

The sector of advanced biofuels is just emerging, and the number of commercial plants is still quite low, while international trade is very limited. International trade is nearly inexistent for advanced biofuels, which do not still have a harmonized definition at International level. In EU, the definition of advanced biofuels is a political decision based on specific feedstock categories, while in the rest of the World, this classification is based on the technology deployed.

The list of operational, commercial plants for advanced biofuels is dominated by the EU, the clear market leader. As shown in Table 10, inside the EU, Sweden and Finland have the highest number of plants.

Table 10. Global list of plants at TRL 9 producing advanced biofuels

Company	Plant	Country	Region
Green Fuel Nordic	GNF Lieksa	Finland	EU
St1	Etanolix Vantaa	Finland	EU
St1	Etanolix Lahti	Finland	EU
St1	Etanolix Hamina	Finland	EU
Total	La Mede	France	EU
Eni SPA	Eni Taranto refinery	Italy	EU
Eni SPA	HVO plants in Gela and Venice	Italy	EU
Versalis / Eni	Crescentino Biorefinery	Italy	EU
Twence	Hengelo	Netherlands	EU
Borregaard Industries AS	ChemCell Ethanol	Norway	EU
BP	Co-processing Castellon	Spain	EU
Repsol	Co-processing Puertollano	Spain	EU
Domsjoe Fabriker	Domsjoe Fabriker	Sweden	EU
Honeywell UOP and Preem	Co-processing trial	Sweden	EU
Preem	Preem HVO diesel and biojet	Sweden	EU
Pyrocell (JV of Setra and Preem)	pyrolysis oil upgrading	Sweden	EU
Sodra	Sodra biomethanol	Sweden	EU
St1	Etanolix Gothenburg	Sweden	EU
SunPine	SunPine HVO addition	Sweden	EU
SunPine	SunPine HVO 100 mio litres	Sweden	EU
ECO Biochemical Technology	HVO plant	China	RoW
DINS Sakai Co.,Ltd.	Construction waste timber to ethanol	Japan	RoW
Pertamina	Pertamina refinery	Indonesia	RoW
BP	Cherry Point refinery	United States	U.S.
Marathon Petroleum	Dickinson Renewable Diesel Facility	United States	U.S.

Source: IEA Bioenergy Task 39 database (BEST GmbH, 2024; ETIP Bioenergy, 2024)

4.2 Trade (Import/export) and trade balance

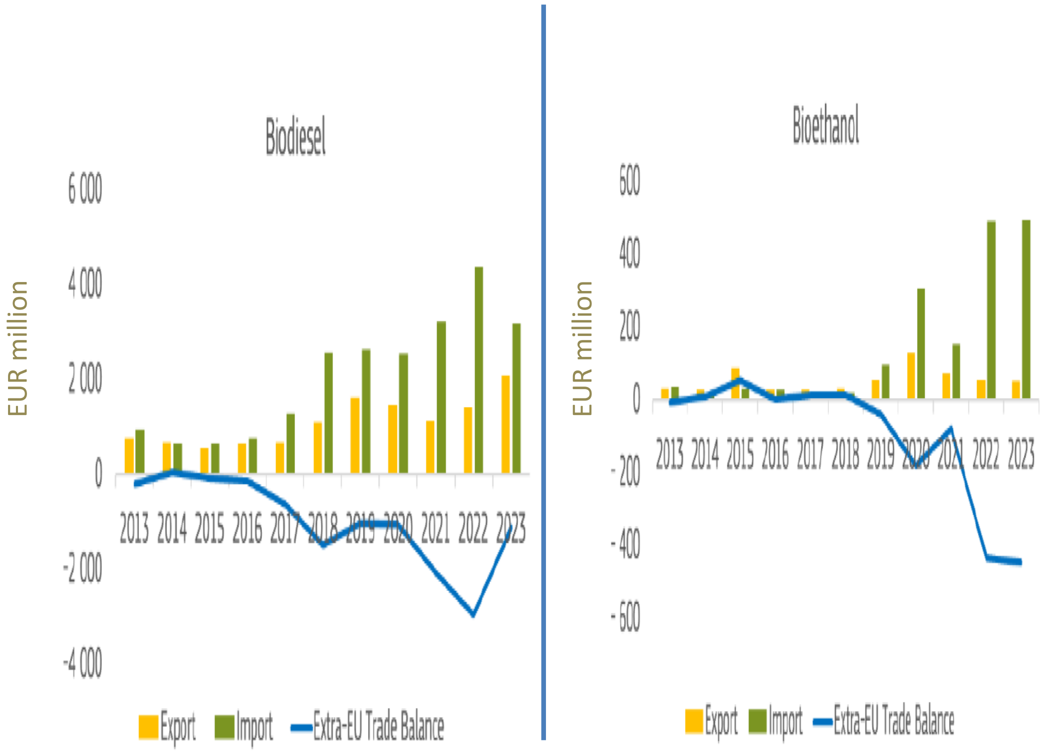
The European Climate Neutral Industry Competitiveness Scoreboard does not include biofuels, therefore the following elaborations are not comparable with other CETO reports.

Statistics on trade have been performed by using the COMEXT Eurostat's reference database for detailed statistics on international trade in goods. It provides access on recent and historical data of the EU and its individual Member States, but also covers a significant number of non-EU countries.

International trade in advanced biofuels is monitored using four different six-digit codes of the Harmonised System (HS) classification. More specifically, the codes used are 220720 [Denatured ethyl alcohol and other spirits of any strength], 290513 [n-butyl alcohol], 382600 [Biodiesel and mixtures thereof, not containing or containing < 70 % by weight of petroleum oils or oils obtained from bituminous minerals] and 380300 [Tall oil, whether or not refined]. However, the current classification system does not permit the differentiation between biofuels and advanced biofuels

As seen in Figure 47 the majority of EU biofuels imports and exports consists of biodiesel followed by bioethanol. This year trade analysis focuses on biodiesel and bioethanol to examine the trends in those markets the extra-EU exports of biodiesel increased by 47% compared to 2022, reaching almost EUR 2.1 billion, while extra-EU imports shrank by -27%, reaching around EUR3.2 billion. The trade deficit shrank from almost EUR-3 billion in 2022 to EUR-1.1 billion in 2023. The extra-EU exports of bioethanol decreased by -10% at EUR 51 million, while extra-EU imports remained stable at EUR 0.5 billion, maintaining the trade deficit at EUR-0.4 billion.

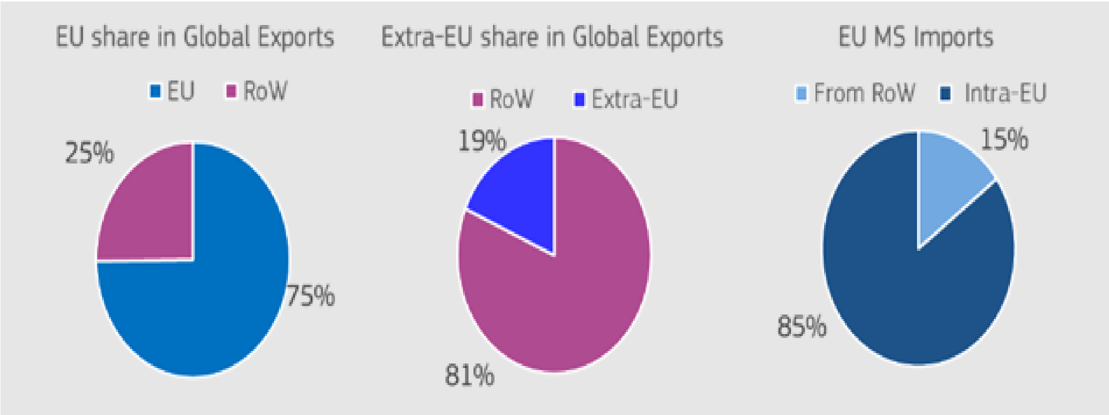
Figure 47. Extra-EU trade for biodiesel (left) and bioethanol (right) [EUR Million]



Source: JRC based on COMEXT data 2024

Figure 48 shows Germany, Netherlands and Spain were the Member States with the biggest trade surpluses in biodiesel (EUR Billion +1.7, +1.5, +1.2, respectively, in 2023), and France, Poland and Hungary in bioethanol (EUR Million +48, +31, +16, respectively in 2023). The Member States with the biggest trade deficits in biodiesel were France, Italy and Sweden (EUR Billion -2.2, -0.7, -0.5, respectively) and Germany, Czechia and Greece in bioethanol (EUR Million -123, -78, -51, respectively).In 2021-2023, the EU share in global exports of biodiesel was 75%, but when excluding trade among Member States, the extra-EU share was 19%. The share of imports coming from outside the EU was 15%.

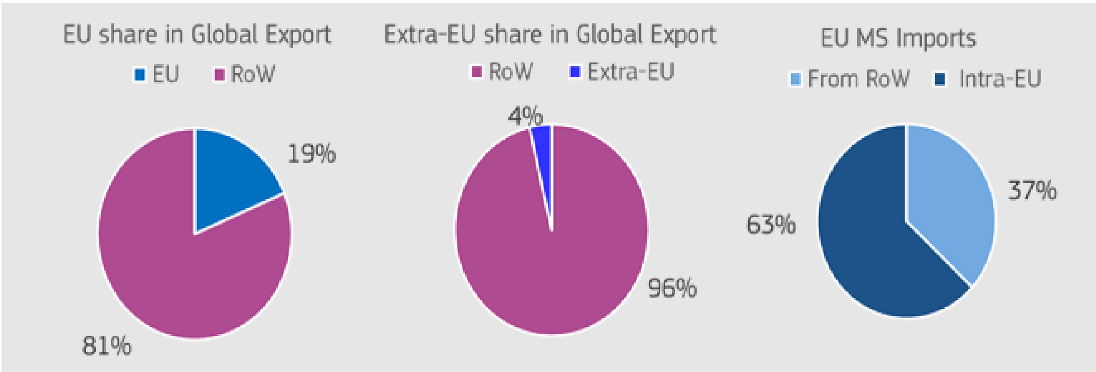
Figure 48. EU share in global export (left), extra-EU share in global export (middle) and EU imports (right) of biodiesel [2021-2023]



Source: JRC based on UN Comtrade data 2024

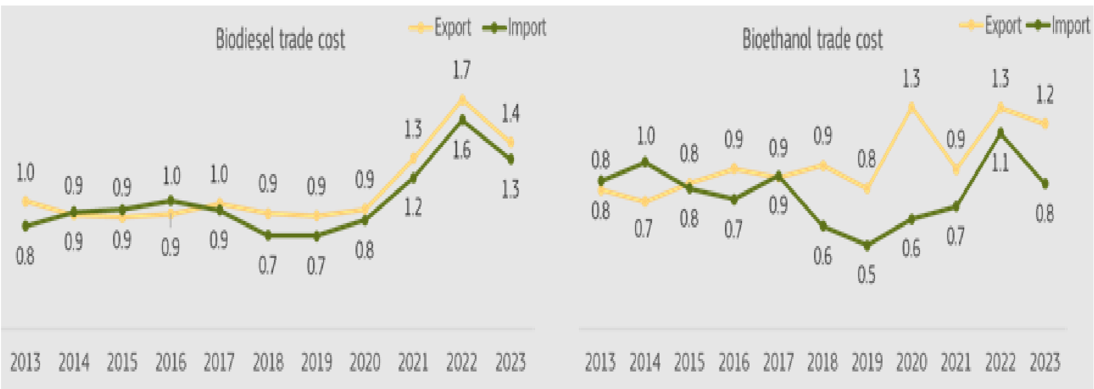
For the same period, the EU share in global exports of bioethanol was 19%, and the extra-EU share was 4%. The share of imports coming from outside the EU was 15% (Figure 49). The EU covered 63% of its imports needs through trading amongst its Member States. The EU exports at higher value per kilo than what it imports. This shows that the EU has a competitive advantage, yet the EU production need to keep up, (Figure 50).

Figure 49. EU share in global export (left), extra-EU share in global export (middle) and EU imports (right) of bioethanol [2021-2023]



Source: JRC based on UN Comtrade data 2024

Figure 50. : Value per quantity of extra-EU trade for biodiesel (left) and bioethanol (right) [EUR per kilo]]



Source: JRC based on UN Comtrade data 2024

Overall, bioethanol and biodiesel trade trends are different. The EU appears to have a stronger global presence in export shares and trade flows. The EU trade of bioethanol has lower value per quantity, which could rise if the imports and the EU production do not keep up with the demand

4.3 Resource efficiency and dependence in relation to EU competitiveness

The dependence on critical materials is very low (see also annex 3). Depending on the feedstock and assumed fuel consumption, the main critical impact is the availability of sustainable biogenic resources. RED II limits the use of food-based feedstocks to avoid competition with food as well as indirect land use changes. Biomass grown on purpose generally needs land, water and nutrients and is thus limited in availability, while residues are also a limited resource, as their amount cannot be increased to meet an increasing demand. Whether the availability of sustainable biomass is able to meet the demand mainly depends on the expected demand of advanced biofuels, based on assumptions of penetration of electric vehicles, transport demand and industrial use.

5 Conclusions

The EU has been actively promoting the production and use of biofuels as part of its strategy to reduce greenhouse gas emissions and enhance energy security. Biofuels, which include biodiesel and bioethanol, are seen as sustainable alternatives to fossil fuels. The Renewable Energy Directive, reinforced by EU delegated directive (EU) 2024/1405, sets out sustainability criteria and defines advanced biofuels to mitigate negative impacts on land use and biodiversity. The directive favours certain feedstock categories for the production of advanced biofuels and Sustainable Aviation Fuels (SAF). The EU's approach to defining advanced biofuels, based on specific feedstock categories rather than technology, underscores EU's focus on sustainability and resource efficiency.

The use of advanced biofuels, made from feedstocks listed in Annex IX of the Renewable Energy Directive, has been increasing in recent years, reaching more than 2 million tonnes of oil equivalent (Mtoe) in 2022, accounting for around 16% of total biofuel consumption. In 2022, the share of advanced biodiesel in the EU reached 21.69%, while advanced ethanol accounted for 0.76%. The production value of advanced biodiesel was EUR 1.4 billion, and advanced bioethanol was EUR 4 million.

Biodiesel continues to represent the vast majority of the EU biofuels production. In 2023, the EU production value of biodiesel decreased by 17%, amounting to nearly EUR 13 billion. Germany and Poland were the top producers, together holding more than one-quarter of the EU production value. In terms of quantities, the EU biodiesel production increased by 12% in 2023, reaching almost 14 million tonnes.

The EU bioethanol production value per quantity has been increasing steadily since 2018, reaching 1.04 EUR/litre in 2023. This steady increase indicates a growing market for bioethanol within the EU. Bioethanol production in the EU showed a positive trend in 2023, with a 9% increase in production value, surpassing EUR 1 billion. France and Spain were the top producers, together holding almost one-quarter of the EU production value.

The biofuel sector is a significant economic driver within the EU, contributing substantially to GDP and generating employment. The biofuel consumption in the EU transport sector increased from 19 million litres in 2015 to over 25 million litres in 2022, with biodiesel having around 70% of the share.

The biofuels sector has been a significant contributor to employment within the EU, generating both direct and indirect jobs across various segments of the industry. According to EurObserv'ER, the number of direct and indirect jobs in the biofuels sector was 239,600 in 2018. However, this number saw a decline, reaching 148,300 in 2021. Efforts are being made to facilitate the transition of skilled workers from the fossil fuel industry to the biofuels sector, ensuring that expertise is retained and utilised effectively. Additionally, the EU is working to make biorefineries more attractive to workers, despite their rural locations.

The EU's trade in biofuels, specifically biodiesel and bioethanol, has shown distinct trends and challenges over the past few years. In 2023, the majority of EU biofuels imports and exports consisted of biodiesel, followed by bioethanol. Extra-EU exports of biodiesel increased by 47% compared to 2022, reaching almost EUR 2.1 billion. On the other hand, extra-EU imports of biodiesel decreased by 27%, amounting to around EUR 3.2 billion. This led to a significant reduction in the trade deficit, which shrank from nearly EUR 3 billion in 2022 to EUR 1.1 billion in 2023.

The EU's POTEnCIA CETO 2024 Scenario projects that biofuels consumption will increase from around 21 million tonnes of oil equivalent (Mtoe) in 2025 to 57 Mtoe in 2050. The production of advanced biofuels is expected to progressively increase towards 2050, while the production of biofuels from food and feed crops will provide progressively minor contributions.

References

Al-Sabawi, M. and Chen, J. (2012) 'Hydroprocessing of Biomass-Derived Oils and Their Blends with Petroleum Feedstocks: A Review', *Energy & Fuels*, 26(9), pp. 5373–5399. Available at: https://doi.org/10.1021/ef3006405.

Attia, M., Farag, S. and Chaouki, J. (2020) 'Upgrading of oils from biomass and waste: Catalytic hydrodeoxygenation', *Catalysts*, 10(12), pp. 1–30. Available at: https://doi.org/10.3390/catal10121381.

Basu, P. (2018) *Biomass Gasification, Pyrolysis and Torrefaction*. Elsevier. Available at: https://doi.org/10.1016/C2016-0-04056-1.

BEST GmbH (2024) *Database on facilities for the production of advanced liquid and gaseous biofuels for transport*. Available at: https://demoplants.best-research.eu/ (Accessed: 29 June 2022).

Bioenergy, I.E.A., Gasification, T. and Workshop, B. (2014) 'Thermal biomass gasification in small scale', pp. 1–27.

Brown, Adam *et al.* (2020) 'Advanced Biofuels - Potential for Cost Reduction, IEA Bioenergy: Task 41: 2020:01', *IEA Bioenergy*, pp. 1–88. Available at: https://task39.sites.olt.ubc.ca/files/2020/02/Advanced-Biofuels-Potential-for-Cost-Reduction-Final-Draft.pdf.

Brown, A *et al.* (2020) 'The Role of Renewable Transport Fuels in Decarbonizing Road Transport- Production Technology and Costs', (November), pp. 1–134.

Buffi, M. *et al.* (2024) 'Energy and GHG emissions assessment for biochar-enhanced advanced biofuels value chains', *Energy Conversion and Management*, 309, p. 118450. Available at: https://doi.org/10.1016/j.enconman.2024.118450.

Chandra, A. and Rosmann, M. (2023) *Biofuels Annual European Union*. Available at: https://apps.fas.usda.gov/newgainapi/api/Report/DownloadReportByFileName?fileName=Biofuels Annual_The Hague_European Union_E42023-0033.pdf.

Chatzipanagi, A. *et al.* (2023) 'Clean Energy Technology Observatory: Photovoltaics in the European Union - 2023 Status Report on Technology Development, Trends, Value Chains and Markets', (KJ-NA-31-691-EN-N (online)). Available at: https://doi.org/10.2760/732675 (online).

Cherubini, F. *et al.* (2009) 'Energy- and greenhouse gas-based LCA of biofuel and bioenergy systems: Key issues, ranges and recommendations', *Resources, Conservation and Recycling*, 53(8), pp. 434–447. Available at: https://doi.org/10.1016/j.resconrec.2009.03.013.

Deloitte (2022) *Towards an Integrated Energy System : Assessing Bioenergy's Socio-Economic and Environmental Impact*.

Despres, J. *et al.* (2018) 'POLES-JRC model documentation'. Luxembourg: Joint Research Centre (Seville site). Available at: https://doi.org/10.2760/814959.

Dimitriadis, A. and Bezergianni, S. (2017) 'Hydrothermal liquefaction of various biomass and waste feedstocks for biocrude production: A state of the art review', *Renewable and Sustainable Energy Reviews*, 68(October 2016), pp. 113–125. Available at: https://doi.org/10.1016/j.rser.2016.09.120.

Drake, H.L., Großner, A.S. and Daniel, S.L. (2008) 'Old Acetogens, New Light', *Annals of the New York Academy of Sciences*, 128, pp. 100–128. Available at: https://doi.org/10.1196/annals.1419.016.

ETIP Bioenergy (2018) *SET Plan Implementation Plan Action 8: Bioenergy and Renewable Fuels for Sustainable Transport*. Available at: https://www.etipbioenergy.eu/set4bio/set-plan-and-its-implementation.

ETIP Bioenergy (2024) *IEA Bioenergy Task 39 2nd Generation Biofuels Demonstration Facilities*. Available at: https://www.etipbioenergy.eu/databases/reports/15-iea-bioenergy-task-39-2nd-generation-biofuels-demonstration-facilities.

EurObserv-ER (2023) *RES in Transport barometer 2023*. Available at: https://www.eurobserv-er.org/res-in-transport-barometer-2021/.

EurObserv-ER (2024) *Employment & Turnover 2022*. Available at: https://www.eurobserv-er.org/online-database/.

European Commission *et al.* (2024) *Development of outlook for the necessary means to build industrial capacity for drop-in advanced biofuels : final report.* Available at: https://doi.org/10.2777/858956.

European Parliament (2018) 'DIRECTIVE (EU) 2018/2001 on the promotion of the use of energy from renewable sources (recast)', *OJ L 328, 21.12.2018*, 2018(21.12.2018), pp. 82–209.

European Parliament and the Council of the European Union (2023) *Directive 2023/2413 amending Directive (EU) 2018/2001, Regulation (EU) 2018/1999 and Directive 98/70/EC as regards the promotion of energy from renewable sources*. European Parliament and European Council. Available at: https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A32023L2413.

eurostat (2020) 'Glossary:Energy intensity', *Statistics Explained*. Available at: https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Glossary:Energy_intensity.

eurostat (2024) *Use of renewables for transport - details (nrg_ind_urtd)*. Available at: https://ec.europa.eu/eurostat/databrowser/view/nrg_ind_urtd/default/table?lang=en.

Fiorini, A. *et al.* (2017) *Monitoring R&I in Low-Carbon Energy Technologies*. Available at: https://doi.org/10.2760/434051.

Fritsche, U.R. *et al.* (2017) *Energy and Land Use*.

G., K., Van Gerpen, J. and Krahl, J. (2005) *The Biodiesel Handbook*. AOCS Press.

Gerbens-Leenes, P.W., Hoekstra, A.Y. and van der Meer, T. (2009) 'The water footprint of energy from biomass: A quantitative assessment and consequences of an increasing share of bio-energy in energy supply', *Ecological Economics*, 68(4), pp. 1052–1060. Available at: https://doi.org/10.1016/j.ecolecon.2008.07.013.

Gill, M. *et al.* (2021) 'Biomass and Bioenergy Thermo-catalytic reforming of alberta-based biomass feedstock to produce biofuels', *Biomass and Bioenergy*, 152(August), p. 106203. Available at: https://doi.org/10.1016/j.biombioe.2021.106203.

Gollakota, A.R.K., Kishore, N. and Gu, S. (2018) 'A review on hydrothermal liquefaction of biomass', *Renewable and Sustainable Energy Reviews*, 81(April 2017), pp. 1378–1392. Available at: https://doi.org/10.1016/j.rser.2017.05.178.

Grimalt-Alemany, A., Skiadas, I. V. and Gavala, H.N. (2018) 'Syngas biomethanation : state of the art review and perspectives', *Biofuels, Bioproducts and Biorefining*, 12(1), pp. 139–158. Available at: https://doi.org/10.1002/bbb.1826.

Hamelinck, C.N. and Faaij, A.P.C. (2006) 'Outlook for advanced biofuels', *Energy Policy*, 34(17), pp. 3268–3283. Available at: https://doi.org/10.1016/j.enpol.2005.06.012.

Hao, B. *et al.* (2021) 'Chemical reactions in the hydrothermal liquefaction of biomass and in the catalytic hydrogenation upgrading of biocrude', *Green Chemistry*, 23(4), pp. 1562–1583. Available at: https://doi.org/10.1039/d0gc02893b.

Hiederer, R. *et al.* (2010) 'Biofuels: a New Methodology to Estimate GHG Emissions from Global Land Use Change'. Available at: https://doi.org/10.2788/48910.

Hornung, A. *et al.* (2022) 'Thermo-Catalytic Reforming (TCR)–An important link between waste management and renewable fuels as part of the energy transition', *Applications in Energy and Combustion Science*, 12, p. 100088. Available at: https://doi.org/10.1016/j.jaecs.2022.100088.

HYTIME (2015) *Low temperature hydrogen production from second generation biomass*. Available at: https://cordis.europa.eu/project/id/278855/reporting.

IEA (2021) 'Net Zero by 2050: A Roadmap for the Global Energy Sector', p. 70. Available at: https://www.iea.org/reports/net-zero-by-2050.

IEA (2024) *Energy Technology RD&D Budgets*. Available at: https://www.iea.org/data-and-statistics/data-product/energy-technology-rd-and-d-budget-database-2 (Accessed: 12 September 2024).

IIASA (2024) *GLOBIOM documentation*, *International Institute for Applied Systems Analysis*. Available at: https://globiom.org/documentation.html (Accessed: 15 October 2024).

IRENA (2016) *Innovation Outlook. Advanced liquid biofuels*.

Joanneum Research (2016) *Improving the Sustainability of Fatty Acid Methyl Esters (FAME – Biodiesel), European Commission funded report, tender No. ENER/C2/2013/628*.

Karatzos, S., Mcmillan, J. and Saddler, J. (2014) *The potential and challenges of 'drop in' biofuels*, *IEA Bioenergy*

- *Task 39*.

Kumar, M., Olajire Oyedun, A. and Kumar, A. (2018) 'A review on the current status of various hydrothermal technologies on biomass feedstock', *Renewable and Sustainable Energy Reviews*, 81(November 2016), pp. 1742–1770. Available at: https://doi.org/10.1016/j.rser.2017.05.270.

Liu, H. *et al.* (2012) 'Soot Emissions of Various Oxygenated Biofuels in Conventional Diesel Combustion and Low-Temperature Combustion Conditions', *Energy & Fuels*, 26(3), pp. 1900–1911. Available at: https://doi.org/10.1021/ef201720d.

Maniatis, K. *et al.* (2017) *Building up the future - Cost of Biofuel - Sub group on advanced biofuels (SGAB): final report*.

Mantzos, L. *et al.* (2017) 'POTEnCIA: A new EU-wide energy sector model', in *2017 14th international conference on the {European} {Energy} {Market} ({EEM})*. IEEE, pp. 1–5.

Mantzos, L. *et al.* (2019) *The POTEnCIA Central scenario: An EU energy outlook to 2050*, *Distribution*. Luxembourg. Available at: https://doi.org/10.2760/32835.

Matayeva, A. *et al.* (2019) *Development of Upgraded Bio-Oil Via Liquefaction and Pyrolysis*. 1st edn, *Studies in Surface Science and Catalysis*. 1st edn. Elsevier B.V. Available at: https://doi.org/10.1016/B978-0-444-64127-4.00012-4.

Mercer, P. and Armenta, R.E. (2011) 'Review Article Developments in oil extraction from microalgae *', pp. 539–547. Available at: https://doi.org/10.1002/ejlt.201000455.

Munasinghe, P.C. and Khanal, S.K. (2010) 'Syngas Fermentation to Biofuel : Evaluation of Carbon Monoxide Mass Transfer Coefficient (kLa) in Different Reactor Configurations', *Biotechnol. Prog.*, 26(6), pp. 1616–1621. Available at: https://doi.org/10.1002/btpr.473.

Neuwahl, F. *et al.* (2024) *The POTEnCIA CETO 2024 Scenario*. Forthcoming.

OECD (2022a) *Agri-Environmental other indicators : Energy use and biofuel production (direct linking not working)*, *OECD.Stat*. Available at: https://stats.oecd.org/index.aspx?r=765398# Global biofuel.

OECD (2022b) *OECD-FAO Agricultural Outlook 2022-2031*. Available at: https://doi.org/10.1787/4bde2d83-en.

Ogunkunle, O. and Ahmed, N.A. (2021) 'Overview of biodiesel combustion in mitigating the adverse impacts of engine emissions on the sustainable human–environment scenario', *Sustainability (Switzerland)*, 13(10). Available at: https://doi.org/10.3390/su13105465.

Ouadi, M. *et al.* (2017) 'Thermo-Catalytic Reforming of municipal solid waste', *Waste Management*, 68(2017), pp. 198–206. Available at: https://doi.org/10.1016/j.wasman.2017.06.044.

Paniagua, S., Lebrero, R. and Munoz, R. (2022) 'Bioresource Technology Syngas biomethanation : Current state and future perspectives', 358(April). Available at: https://doi.org/10.1016/j.biortech.2022.127436.

Pasimeni, F. (2019) 'SQL query to increase data accuracy and completeness in PATSTAT', *World Patent Information*, 57, pp. 1–7. Available at: https://doi.org/10.1016/j.wpi.2019.02.001.

Pasimeni, F., Fiorini, A. and Georgakaki, A. (2019) 'Assessing private R&D spending in Europe for climate change mitigation technologies via patent data', *World Patent Information*, 59, p. 101927. Available at: https://doi.org/10.1016/j.wpi.2019.101927.

Pasimeni, F., Fiorini, A. and Georgakaki, A. (2021) 'International landscape of the inventive activity on climate change mitigation technologies. A patent analysis', *Energy Strategy Reviews*, 36, p. 100677. Available at: https://doi.org/10.1016/j.esr.2021.100677.

Pasimeni, F. and Georgakaki, A. (2020) *Patent-Based Indicators: Main Concepts and Data Availability*. Available at: https://setis.ec.europa.eu/patent-based-indicators-main-concepts-and-data-availability_en.

Phillips, J.R., Huhnke, R.L. and Atiyeh, H.K. (2017) 'Syngas Fermentation : A Microbial Conversion Process of Gaseous Substrates to Various Products', *Fermentation* [Preprint]. Available at: https://doi.org/10.3390/fermentation3020028.

Pragya, N., Pandey, K.K. and Sahoo, P.K. (2013) 'A review on harvesting , oil extraction and biofuels production technologies from microalgae', *Renewable and Sustainable Energy Reviews*, 24, pp. 159–171. Available at: https://doi.org/10.1016/j.rser.2013.03.034.

Prussi, M. *et al.* (2020) *JEC Well-to-Tank report v5 | EUR 30269 EN*. Luxembourg. Available at: https://doi.org/10.2760/959137.

Rawat, I. *et al.* (2011) 'Dual role of microalgae : Phycoremediation of domestic wastewater and biomass production for sustainable biofuels production', *Applied Energy*, 88(10), pp. 3411–3424. Available at: https://doi.org/10.1016/j.apenergy.2010.11.025.

Redwood, M.D., Paterson-Beedle, M. and Macaskie, L.E. (2009) 'Integrating dark and light bio-hydrogen production strategies : towards the hydrogen economy', *Rev Environ Sci Biotechnol*, pp. 149–185. Available at: https://doi.org/10.1007/s11157-008-9144-9.

Reißmann, D., Thrän, D. and Bezama, A. (2018) 'Hydrothermal processes as treatment paths for biogenic residues in Germany: A review of the technology, sustainability and legal aspects', *Journal of Cleaner Production*, 172, pp. 239–252. Available at: https://doi.org/10.1016/j.jclepro.2017.10.151.

Rocca, S. *et al.* (2015) *Biofuels from algae : technology options , energy balance and GHG emissions Insights from a literature review*. Available at: https://doi.org/10.2790/125847.

Rózsai, M. *et al.* (2024) 'JRC-IDEES-2021: the Integrated Database of the European Energy System – Data update and technical documentation', (KJ-NA-31-940-EN-N (online)). Available at: https://doi.org/10.2760/614599 (online).

Saint-Supéry, M.V. *et al.* (2020) *Overview of biofuels policies and markets across the EU-27 and the UK*.

Scarlat, N. and Dallemand, J.F. (2018) 'Future role of bioenergy', in *The Role of Bioenergy in the Emerging Bioeconomy: Resources, Technologies, Sustainability and Policy*. Elsevier Inc., pp. 435–547. Available at: https://doi.org/10.1016/B978-0-12-813056-8.00010-8.

Schmidt, P. *et al.* (2018) 'Power-to-Liquids as Renewable Fuel Option for Aviation: A Review', *Chemie Ingenieur Technik*, 90(1–2), pp. 127–140. Available at: https://doi.org/10.1002/CITE.201700129.

Schmitz, A. *et al.* (2024) *Impacts of enhanced learning for clean energy technologies on global energy system scenarios*. Forthcoming.

Sims, R.E.H. *et al.* (2010) 'An overview of second generation biofuel technologies', *Bioresource Technology*, 101(6), pp. 1570–1580. Available at: https://doi.org/10.1016/j.biortech.2009.11.046.

Sönnichsen, N. (2022) *Global biofuels market size 2020-2030*, *Statista*. Available at: https://www.statista.com/statistics/217179/global-biofuels-market-size/.

Swanson, R.M. *et al.* (2010) 'Techno-economic analysis of biomass-to-liquids production based on gasification', *Fuel*, 89, pp. S11–S19. Available at: https://doi.org/10.1016/j.fuel.2010.07.027.

Thamizhakaran Stanley, J. *et al.* (2022) 'Potential pre-treatment of lignocellulosic biomass for the enhancement of biomethane production through anaerobic digestion- A review', *Fuel*, 318, p. 123593. Available at: https://doi.org/10.1016/j.fuel.2022.123593.

US eia (2022) *Biofuels explained - Biofuels and the environment*. Available at: https://www.eia.gov/energyexplained/biofuels/biofuels-and-the-environment.php.

USDA Foreign Agricultural Service *et al.* (2024) *EU Biofuels Annual*. Available at: https://apps.fas.usda.gov/newgainapi/api/Report/DownloadReportByFileName?fileName=Biofuels Annual_The Hague_European Union_06-18-2021.

Vásquez, M.C., Silva, E.E. and Castillo, E.F. (2017) 'Hydrotreatment of vegetable oils: A review of the technologies and its developments for jet biofuel production', *Biomass and Bioenergy*, 105, pp. 197–206. Available at: https://doi.org/10.1016/j.biombioe.2017.07.008.

Wan-Ting, C. (2017) *Upgrading hydrothermal liquefaction biocrude oil from wet biowaste into transportation fuel*. University of Illinois.

Yugo, M. *et al.* (2021) 'Concawe's Transport and Fuel Outlook towards EU 2030 Climate Targets', *CONCAWE Reports*, 21(2), pp. 1–72.

Zhu, Y. *et al.* (2019) 'Techno-economic analysis of alternative aqueous phase treatment methods for microalgae hydrothermal liquefaction and biocrude upgrading system', *Algal Research*, 39(January), p. 101467. Available at: https://doi.org/10.1016/j.algal.2019.101467.

List of abbreviations and definitions

AD	Anaerobic digestion
APR	Aqueous Phase Reforming
ATR	AutoThermal Reforming
BtL	Biomass to liquid
CAPEX	Capital expenditure
CETO	Clean Energy Technology Observatory
CID	Cycle Inventory Database
CFP	Catalytic Fast Pyrolysis
CPC	Cooperative Patent Classification
DME	Dimethyl ether
EC	European Commission
ELCD	European Reference Life Cycle Database
ETS	Emission Trading System
EPO	European Patent Office
ETS	Emissions Traing System
EU	European Union
FAEE	Fatty Acid Ethyl Ester
FAME	Fatty Acid Methyl Ester
FPBO	Fast Pyrolysis Bio-Oil
FT	Fischer-Tropsch
GDP	Gross Domestic Product
GEMIS	Global Emission Model for Integrated Systems
GHG	GreenHouse Gas
H2020	Horizon 2020 Programme
HDO	Hydro-deoxygenation
HEFA	Hydroprocessed Esters and Fatty Acids
HTC	HydroThermal Carbonization
HTG	Hydrothermal Gasification
HTL	HydroThermal Liquefaction
HVO	Hydrogenated Vegetable Oil
IBC	Intermediate Bioenergy Carrier
IEA	International Energy Agency
ILUC	Indirect Land Use Change
IBC	Intermediate bioenergy carriers
IPC	International Patent Classification
IPCC	Intergovernmental Panel on Climate Change
IRENA	International Renewable Energy Agency
LCA	Life Cycle Analysis

LCOE	Levelised Cost of Electricity
LHV	Lower Heating Value
MS	Member State
MSW	Municipal Solid Waste
MtG	Methanol-to-Gasoline
OME	Oxymethylene ether
OPEX	Operational expenditure
PWS	Pressurised Water Scrubbing
PSA	Pressure Swing Adsorption
RCF	Recycled Carbon Fuel
RED	Renewable Energy Directive
RFNBO	Renewable Fuel of Non-Biological Origin
R&D	Research and Development
R&I	Research and Innovation
SAF	Sustainable Aviation Fuel
SCR	Selective Catalytic Reduction
SETPlan	Strategic Energy Technology Plan
SNG	Synthetic Natural Gas
SMR	Steam Methane Reforming
SNG	Synthetic Natural Gas
TCR	Thermo-Catalytic Reforming
Toe	tonnes oil equivalent
TRL	Technology Readiness Level
UCO	Used Cooking Oil
VC	Venture Capital
WGS	Water Gas Shift
WTT	Well To Tank

List of figures

List of tables

Annexes

Annex 1. Summary Table of Data Sources for the CETO Indicators

Theme	Indicator
Technology maturity status, development and trends	Technology readiness level
	Installed capacity & energy production
	Technology costs
	Public and private RD&I funding
	Patenting trends
	Scientific publication trends
	Assessment of R&I project developments
Value chain analysis	Turnover
	Gross Value Added
	Environmental and socio-economic sustainability
	EU companies and roles
	Employment
	Energy intensity and labour productivity
	EU industrial production
Global markets and EU positioning	Global market growth and relevant short-to-medium term projections
	EU market share vs third countries share, including EU market leaders and global market leaders
	EU trade (imports, exports) and trade balance
	Resource efficiency and dependencies (in relation EU competiveness)

Annex 2. Sustainability Assessment Framework

Parameter / Indicator	***Input***
Environmental	
LCA standards, best practice, LCI databases	Life Cycle Assessments (LCA) are commonly used to quantify the GHG emissions savings of bioenergy, by comparing the bioenergy system with a reference (fossil) energy system following a life cycle approach. The utilization of by-products that can displace other materials, having GHG and energy implications, must also be considered in the analysis. The RED II established the methodology for the calculation of greenhouse gas emissions from the production and use of biofuels, bioliquids and biomass fuels based on a life cycle approach, which includes all emissions, from the extraction or cultivation of raw materials, emissions from processing, transport and distribution and emissions from carbon stock changes caused by direct land-use change. RED II determined the typical and default values of greenhouse gas emissions savings for biofuels if produced with no net-carbon emissions from land-use change. Several LCA models are available for GHG emission estimation, such as Biograce, E3 Database in Europe, the Argonne National Laboratory GREET model in the US and the GHGenius model in Canada. LCA requires large amounts of data on a specific product or service for assessing the complete supply chain. The wide range of results of LCA studies depends on the data that are generally valid for certain regions and conditions. Several LCA databases for the GHG and energy balance of bioenergy systems are available worldwide, such as ECOINVENT, ELCD (European reference Life Cycle Database), GEMIS (Global Emission Model for Integrated Systems), CPM LCA Database or US Life Cycle Inventory Database (LCI) from NREL (Scarlat and Dallemand, 2018). **Sustainability criteria** RED II established the sustainability and greenhouse gas emissions saving criteria for biofuels, bioliquids and biomass fuels. The standard ISO 13065:2015 on Sustainability criteria for bioenergy provides a practical framework to facilitate the assessment of environmental, social

	and economic aspects and the evaluation and comparability of bioenergy production and products, supply chains and applications. ISO 13065:2015 provides sustainability principles, criteria and measurable indicators to provide objective information for assessing sustainability.
GHG emissions	According to the RED II, the GHG emissions savings from the use of biofuels, bioliquids and biomass fuels had to meet a minimum requirement for GHG savings of 50% relative to fossil fuels for plants in operation before 2015, which increased to to 60% for plants in operation after October 2015 and to 65% for plants in operation after January 2021, in comparison to the fossil fuel comparator of 94 g CO_2eq/MJ. The calculation of the GHG emissions has been performed by the JRC (WTT v5, (Prussi *et al.*, 2020)) for a large number of advanced biofuel pathways. The GHG emissions for a selection of pathways is presented here: **GHG footprint for advanced biofuels (g CO_{2eq}/MJ)** • F-T diesel from farmed wood: 13.5 - 14.4 g CO_{2eq}/MJ • F-T diesel from wood residue (waste): 9.3 - 9.9 g CO_{2eq}/MJ • Syndiesel from wood residue via HTL: 27.2 - 27.7 g CO_{2eq}/MJ • Syndiesel from wood chips from SRF via HTL: 29.9 - 30.4 g CO_{2eq}/MJ • Syndiesel from waste wood via black liquor: 5.2 - 5.3 g CO_{2eq}/MJ • Pyrolysis-based gasoline from farmed wood: 26.3 - 27.4 g CO_{2eq}/MJ • Pyrolysis-based gasoline from waste wood: 22.7 - 23.5 g CO_{2eq}/MJ • MeOH from biomass residual wood: 10.0 - 11.1 g CO_{2eq}/MJ • MeOH from farmed wood: 14.1 - 15.9 g CO_{2eq}/MJ • MeOH from waste wood via black liquor: 6.1 - 6.3 g CO_{2eq}/MJ • DME from residual wood: 9.8 - 11.0 g CO_{2eq}/MJ

	• DME from farmed wood: 14.0 - 15.7 g CO_{2eq}/MJ • SNG via waste wood gasification and methanation: 20.1 - 21.6 g CO_{2eq}/MJ • SNG via farmed wood gasification: 23.5 - 25.1 g CO_{2eq}/MJ The GHG intensity of bioenergy depends on the fossil energy for biomass production, harvesting, transport feedstock processing and conversion to energy. If energy supply is progressively decarbonised, the GHG emissions from the use of fossil energy in the bioenergy supply chain will be reduced and thus the GHG chain emissions from bioenergy will decrease (Cherubini *et al.*, 2009).
Energy balance	JRC performed the balance of the energy expended in different advanced biofuel pathways (WTT, v5, (Prussi *et al.*, 2020)). The energy expended ratio for a selection of advanced biofuel pathways is presented here: **Energy expended (MJ/MJ final fuel)** • F-T diesel from farmed wood: 1.25 - 1.41 MJ/MJ final fuel • F-T diesel from wood residue (waste): 1.13 - 1.29 MJ/MJ final fuel • Syndiesel from wood residue via HTL: 0.82 MJ/MJ final fuel • Syndiesel from wood chips from SRF via HTL: 0.89 MJ/MJ final fuel • Syndiesel from waste wood via black liquor: 0.11 MJ/MJ final fuel • Pyrolysis-based gasoline from farmed wood: 1.18 - 1.36 MJ/MJ final fuel • Pyrolysis-based gasoline from waste wood: 1.07 - 1.26 MJ/MJ final fuel • MeOH from biomass residual wood: 1.12 - 1.42 MJ/MJ final fuel • MeOH from farmed wood: 1.22 - 1.54 MJ/MJ final fuel • MeOH from waste wood via black liquor: 0.15 - 0.16 MJ/MJ final fuel • DME from residual wood: 1.11 - 1.39 MJ/MJ final fuel

	• DME from farmed wood: 1.22 - 1.53 MJ/MJ final fuel • SNG via waste wood gasification and methanation: 1.04 - 1.08 MJ/MJ final fuel • SNG via farmed wood gasification: 1.13 - 1.17 MJ/MJ final fuel
Ecosystem and biodiversity impact	The major issue related to the use of biomass crops for energy and biofuels is that they compete for water, land and nutrients crops with food and feed crops, and that they could cause land use changes, ecosystems damage and loss of habitats. Excessive crop residues and forest residue extraction might lead to loss of biodiversity through the reduction of soil organic matter, nutrient availability and increased erosion risks. The application of Sustainable Forest Management practices, together with guidelines for sustainable extraction rates can alleviate certain negative impacts. The use of perennial energy crops can have a positive impact on biodiversity and carbon stock, especially when grown on marginal and degraded land, as well as additional benefits such as soil protection, improved water retention and water purification and ecosystem services (Scarlat and Dallemand, 2018). RED II established the sustainability and the greenhouse gas emissions saving criteria for the energy from biofuels, bioliquids and biomass fuels. Biofuels, bioliquids and biomass fuels produced from waste and residues, other than agricultural and forestry residues, are required to fulfil only the greenhouse gas emissions saving criteria. Secondary agricultural, industrial and wood residues including residues from the wood processing industry, are utilised in the wood industry, while the remaining part is already used for energy generation with no impact on ecosystems and biodiversity. The RED II excludes several land categories with recognised high biodiversity value from being used for biofuels, bioliquids and biomass fuels production: a) primary forests and other wooded land; b) highly biodiverse forests and other wooded land; d) areas designated for nature protection or for the protection of rare, threatened or endangered ecosystems or species; c) highly biodiverse grassland, either natural or non-natural. Biofuels, bioliquids and biomass fuels shall not be made from material coming from peatland and

	land with high carbon stock, such as: a) wetlands; b) continuously forested areas; c) land covered by trees higher than 5 m and a canopy cover between 10% and 30%. Biofuels, bioliquids and biomass fuels produced from forest biomass shall meet the following criteria: (a) national or sub-national laws or (b) management systems are in place ensuring: (i) legality of harvesting operations; (ii) forest regeneration of harvested areas; (iii) protection of designated areas; (iv) maintenance of soil quality and biodiversity; and (v) maintenance or improvement of long-term production capacity of the forest.
Water use	In the case of biofuels, water is used for biomass growth as well as for biomass processing, fermentation, and distillation of biofuels. The water use for first generation biofuels might be significant, mostly due to the water use for food and feed plant growth. In the case of the advanced biofuels, produced from feedstock listed in annex IX of RED II (e.g. wastes and residues from agriculture, forestry and forest-based industries, food industry waste, biowaste, etc.) the water is used mostly in the processing. The water consumption for waste and residues can be very low, because the water consumption is allocated between the main crop and the crop residues (Gerbens-Leenes, Hoekstra and van der Meer, 2009). • crop residues: 8-10 m^3/GJ • energy crops: 20-64 m^3 /GJ The water consumption for biofuel processing can be in comparison low, with a much higher water consumption for processes involving fermentation in aqueous environment (Spang et al 2014): • Ethanol: 0.092 - 0.290 m^3/GJ • Biodiesel: 0.031 m^3/GJ
Air quality	Air pollutants such as carbon monoxide, nitrogen oxides, hydrocarbons and particulate matter are found to be major exhaust emissions from fossil fuels combustion in vehicles. Excessive exposure to these pollutants can have significant impact on air quality and human health. Biofuel combustion produce emissions in the form of carbon monoxide, hydrocarbons, and particulates. The quantity of emissions from biofuels combustion is lower than fossil fuel (gasoline and diesel). Generally,

	oxygenated biofuels produce lower nitric oxide and soot emissions than fossil fuels (Liu *et al.*, 2012). Biodiesel combustion results in lower gaseous pollutants hydrocarbons, aromatic hydrocarbons, carbon, and sulfur emissions (Ogunkunle and Ahmed, 2021). Biodiesel combustion may result in slightly higher amounts of nitrogen oxides relative to petroleum diesel (US eia, 2022). Advanced biofuels in the form of drop-in fuels have the same chemical structure and thus the same air emissions like the fossil fuels.
Land use	**Land use / land use change** Increased demand of biomass crops for biofuels could lead to both direct and indirect land use change. Direct land use change accounts for changes in land use associated with the expansion of biomass production on cropland, the displacement of food or feed crops, and the possible conversion of other land use types into cropland. The increased demand of biomass crops for energy might have multiple effects: substitution of food and feed; food crop price increase inducing reduced demand; crop area expansion; multiple cropping and yield increase through agriculture intensification. Depending on the previous use of the land, land use change can have a positive or a negative impact. If high soil carbon stocks land (e.g. grassland, forest land) is converted into cropland, this might lead to high carbon emissions. When marginal or degraded land, with low carbon stock is used, or when perennial grasses or forest plantations are established on cropland, this leads to an increase in the carbon stock (Hiederer *et al.*, 2010). To limit certain negative impacts, the RED II excludes several land categories, with recognised high biodiversity value and land with high carbon stock, from being used for biofuel production. Wastes and residues from agriculture and forestry, or the use of agricultural or industry waste can be important sources for bioenergy production with no land use impacts. **Indirect land use change** Indirect land use change (ILUC) includes the change in land use outside a biomass production area that is induced by changing the use or production quantity of a feedstock that was previously produced in that area. Since ILUC is not empirically observable, the estimates are determined mostly

	through modelling and few studies have been conducted to find evidence of ILUC in historical data. Since the ILUC impact cannot be unequivocally determined with an adequate level of precision, criteria were developed to mitigate the risk for ILUC. The highest risks of ILUC have been identified for the feedstock for which a significant expansion of the production area into land with high-carbon stock was observed (the high ILUC-risk biofuels, bioliquids and biomass fuels). In order to mitigate ILUC, the ILUC Directive 2015/1513 and the RED II limited the share of high ILUC-risk biofuels produced from food and feed crops and reduced the share of high ILUC-risk biofuels, bioliquids or biomass fuels down to zero in 2030. Low ILUC-risk biofuels, bioliquids and biomass fuels are exempt from the specific and gradually decreasing limit. Low ILUC-risk biofuels, bioliquids and biomass fuels are fuels produced from feedstock within schemes which avoid displacement effects through improved agricultural practices as well as through the cultivation of crops on areas which were previously not used for cultivation of crops. Commission Delegated Directive (EU) 2024/1405 of 14 March 2024 amending Annex IX to Directive (EU) 2018/2001 of the European Parliament and of the Council as regards adding feedstock for the production of biofuels and biogas
Soil health	The use of agricultural or forestry residues offers good opportunities for biofuel production with low or no land use competition. In the past, most of the crop residues was not collected from land and was instead burned in the fields. During the last years, crop residue burning in the field has been banned for air quality protection reasons. Biomass left on land is an important source of organic carbon in soil and play a key role for the maintenance of the soil organic matter balance, the improvement of soil structure and nutrients in soil. On 17 November 2021, the European Commission presented, as part of the EU biodiversity strategy for 2030, a new EU soil strategy. The strategy, encompassing non-legislative and legislative actions, aims to bring all EU soil ecosystems in good condition by 2050. One flagship initiative announced in the strategy is a new Soil health law to address transboundary impacts of soil degradation and achieve policy coherence at EU and national level

	Excessive residue removal from the field can reduce the carbon input into soil, soil organic carbon, which may reduce the long-term productive capacity of the soils. The fate of soil organic carbon in soil and the magnitude of soil carbon loss depends on biomass input, the farming practices (tillage, crop rotation, nutrients input, etc.), soil characteristics (soil texture and structure) and climate (soil moisture, soil temperature). Some management practices can offset soil carbon loss due to residue removal, such as the use of cover crops, no-tillage, crop rotation and the application of digestate, compost or biochar into the soil. Perennial crops (perennial grasses, short rotation coppice, etc.) can reduce water consumption and wind erosion, improve soil and water quality through riparian buffers and windbreaks, and provide a substantial carbon sequestration potential for cropland when introducing annual crops grass rotation, etc. (Englund et al 2021, Englund et al 2022). In particular, the addition of biochar can promote long-term carbon sequestration in soil.
Hazardous materials	The various bioenergy technologies do not use hazardous materials for the manufacture of various reactor components.
Economic	
standards or best practices	*Not available*
Cost of energy	See 2.3 Technology Cost – Present and Potential Future Trends
Critical raw materials	Common materials include stainless steels and nickel–chromium alloys, depending on operating conditions (pressure, temperature) and working environment. Materials with higher temperature capabilities are a necessity. The choice of materials takes into account characteristics at high temperature, corrosion due to various impurities, water vapour oxidation, hydrogen embrittlement etc. Certain catalysts are needed in relatively small quantities to enhance the yield of desired product or selectivity by promoting various reactions in gas cleaning, fuel synthesis, gas shift reactions, cracking reactions, etc., depending on the process involved and operating parameters. A range of catalysts used can be grouped into naturally occurring catalyst (dolomite, olivine, zeolite), alkali and alkaline earth metals and stable metal catalysts. Natural catalysts are inexpensive and are

	readily available. Stable metal catalysts (Ni, Ru, Pd, Pt, Rh, Zn, Cu, Al, Co, Cr, Fe based catalysts etc.) show better performance but they are costly and can suffer from fouling or poisoning and catalyst deactivation in various environments (Basu, 2018).
Resource efficiency and recycling	The concept of resource efficiency emerged aims to achieve sustainable growth, and to decouple economic growth from resource and energy use. The multiple uses of biomass (food, feed, fiber, biomaterials and bioenergy) entails a combination of several biomass applications in a cascade of uses, based on the prioritization of biomass use. A number of factors could be considered in the prioritization of biomass use, such as the economic or social value of biomass products, the conversion efficiency of biomass, GHG emission reduction performances, etc. According to RED II, when developing support schemes, Member States should consider the availability of sustainable biomass and respect the principles of the circular economy and of the waste hierarchy (in line with Directive 2008/98/EC) to avoid unnecessary distortions of raw materials markets.
Industry viability and expansion potential	*Yes, see markets section*
Trade impacts	*Yes, see markets section*
Market demand	*Yes, see markets section*
Technology lock-in/innovation lock-out	There is no considerable risk of technology lock-in as the advanced biofuels will be able to use existing infrastructure, transport and distribution network and fuel stations. They offer the only available option nowadays for the decarbonisation of aviation and shipping sectors together with renewable fuels of non-biological origin.
Tech-specific permitting requirements	The rules for permitting are very complex and lengthy, representing important barriers for renewable energy deployment and include environmental and building permits. The duration, complexity and the steps for the permit-granting procedures varies largely between different renewable energy technologies and MS, from 6 weeks up to 24 months. A Commission recommendation was adopted in May 2022 for accelerating permitting for renewable energy projects to ensure that projects are approved in a simpler and faster way (max two years, for projects outside renewables go-to areas), streamlining the different steps of the permit-granting processes

	and providing a specific framework for permit-granting procedures. Bioenergy (including biofuels) is today the most regulated energy sector when it comes to environmental protection under the RED II. Economic operators must comply with additional requirements in comparison to other renewable energy installations, irrespective of the place of origin of biomass. Economic operators must provide evidence that biofuels, bioliquids and biomass fuels fulfil the sustainability and the greenhouse gas emissions saving criteria, in accordance with a scheme that has been recognised by the Commission.
Sustainability certification schemes	Voluntary schemes and national certification schemes of EU MS can ensure that biofuels, bioliquids and biomass fuels are sustainably produced by verifying that they comply with the sustainability criteria set by the renewable energy directive. Several schemes consider additional sustainability aspects, as compared to the minimum RED mandatory sustainability criteria, such as soil, water, air protection and social criteria. The EU Member States are responsible for checking compliance with the sustainability criteria, while the European Commission can recognise the compliant voluntary sustainability certification schemes. The European Commission has formally recognized 15 voluntary schemes under RED II by October 2024. The UDB Union database aims to ensure the tracing of liquid and gaseous transport fuels that are eligible for being counted towards the share of renewable energy in the transport sector in any Member State
Social	
	Not available
Health	Air pollution has now been identified as the most significant environmental risk to human health. Biofuel combustion emits nitrogen oxides (NOx), carbon monoxide (CO), particulate matter (PM), and other hazardous air pollutants. Like other combustion fuels, air pollution from burning biofuels can cause various human health impacts. The use of various waste for energy or fuels has to protect the environment, reduce methane emissions and protect human health from the harmful effects of waste in accordance with

	contribute to the objectives of the Waste Framework Directive 2008/98/EC.
Public acceptance	Public acceptance is essential for successful development and take up of biofuels. The debate around the sustainability concerns of biofuels questioned the real benefits and the synergies with agriculture, forestry and rural development and decreased social acceptance. Social acceptance and perception of bioenergy and biofuels as well as the awareness of the risks and benefits depend on knowledge. Public awareness and knowledge can contribute to social acceptance of biofuels and to the overall improvement of consumers' energy behaviour. Public acceptance also depends on environmentally consciousness and awareness. The lack of information about biofuels and their positive effects or potential negative impacts prevents citizens to use biofuels for transports. Another important aspect in shifting towards biofuels are the availability of biofuels at petrol stations and their price. However, some citizens are willing to pay more for biofuels as compared to conventional fuels.
Education opportunities and needs	Biofuel production has multiple trade-offs and synergies with agricultural production, forestry and environmental preservation as well as technological development. Biomass production for bioenergy and biofuels can contribute to improve the competitiveness of agriculture and forestry, to protect the environment and the countryside, to diversify the rural economy and to support rural development. The need for further R&D requires the availability of education programs on advanced biofuel technologies. Education opportunities concern the development of new processes, improvement of process performances, process control, process integration and optimisation, opportunities for development of new analysis and testing methods, development of new materials.
Employment and conditions	*For employment data see section 3.5*
Contribution to GDP	*see Section 3.2*
Rural development impact	Biofuel production ensures significant positive impact on sustainable rural development. Biofuel production provides job opportunities along the supply chain, including skilled labour that can be a driver of agriculture, forestry and industrial development in rural areas. Biomass production provides opportunities to promote sustainable agriculture and forestry, to improve agricultural

	practices, supply chain logistics and local infrastructure that are beneficial for food production. Positive effects of biomass production include new income-generating opportunities in rural areas, enhanced economic security of rural communities by supporting economic activities and economic growth (Scarlat and Dallemand, 2018).
Industrial transition impact	Advanced biofuels can contribute significantly in the short term to the decarbonisation of transport, energy diversification in the transport sector and energy security, while promoting innovation, growth and jobs and reducing the dependence on energy imports. They offer the big advantage of achieving very high greenhouse gas emissions reduction in the short term with the valorization of waste and residues with the use of existing infrastructure. Advanced biofuels are one of the most promising solutions for the decarbonisation of certain sectors such as aviation and shipping.
Affordable energy access (SDG7)	Sustainable energy is a key enabler for sustainable development. Energy poverty in a wide context is related to access and affordability of energy. Advanced biofuels produced from waste and residues offer great opportunities to the local communities for the use of local resources and provide access to energy (fuels) for transport. Advanced biofuels, together with renewable fuels of non-biological origin will be of utmost importance in the near- and medium-term to decarbonize aviation and shipping where other options are less suitable.
Safety and (cyber)security	*Not relevant to specific technology.*
Energy security	Advanced biofuels rely on the local biomass resources and on short supply chains, contribute to reducing the need for imported fossil fuels and diversify the energy supply for transport. Advanced biofuels avoid creating import dependencies elsewhere, improve EU energy security and resilience prospects.
Food security	The most significant concerns for the use of biofuels include the risks of increased competition with food and feed production. RED II strictly limits the use of biofuels and bioliquids, as well as of biomass fuels consumed in transport, where produced from food and feed crops, in order to reduce the impact on food availability and food security. Food security, according to FAO, has multiple dimensions: availability, accessibility, stability and utilization. The competition between

	food and non-food uses may put at risk local food supplies and food security, while bringing little benefits for local population other than additional income (Fritsche *et al.*, 2017). The use of agricultural, forestry residues and industrial waste for bioenergy, and the use of marginal, abandoned or degraded land for biomass feedstock production can minimize food-bioenergy competition. Advanced lignocellulosic biofuels might also be able to mitigate the competition between food and bioenergy, when using waste and residues (waste oil, crop residues, wood residues, etc.) or energy crops cultivated on land that is not currently used for crops (marginal, degraded land, etc.). The production of advanced biofuels could have a positive impact on the economic conditions of rural communities, providing new job opportunities, increasing accessibility and affordability of food.
Responsible material sourcing	Responsible sourcing has become a topic of interest to address sustainability risks in the global mineral supply chains. Several responsible sourcing initiatives exist for various materials, aligned with the OECD guidance for responsible supply chains of minerals from conflict-affected and high-risk areas. The OECD Guidance focuses on issues of human rights, forced and child labour, occupational health and safety, human well-being and legality of operations. EU Regulation (EU) 2017/821 established the requirements for supply chain obligations for materials originating from conflict-affected and high-risk areas. Responsible consumption and production is addressed by the Sustainable Development Goal 12 that aims to ensure responsible consumption and production patterns in the world, by ensuring the efficient and sustainable use of natural resources by 2030. Some companies have taken voluntary commitment for responsible sourcing into account, with social and environmental considerations in their supply chains and their products. Sustainability assessment, using a variety of standards and frameworks, has also become a more common practice at corporate level and plays a prominent role for responsible sourcing. For bioenergy and advanced biofuels, voluntary schemes and national certification schemes were developed to ensure that biofuels, bioliquids and biomass fuels comply with the sustainability criteria set by the renewable energy directive. Voluntary schemes generally consider additional

	soil, water, air protection and social criteria. Regulation (EU) 2017/821 has low relevance for bioenergy and advanced biofuels, which require higher grade steel and certain metal catalysts in relatively small quantities.

Annex 3 Energy System Models and Scenarios: POTEnCIA and POLES-JRC

AN 3.1 POTEnCIA Model

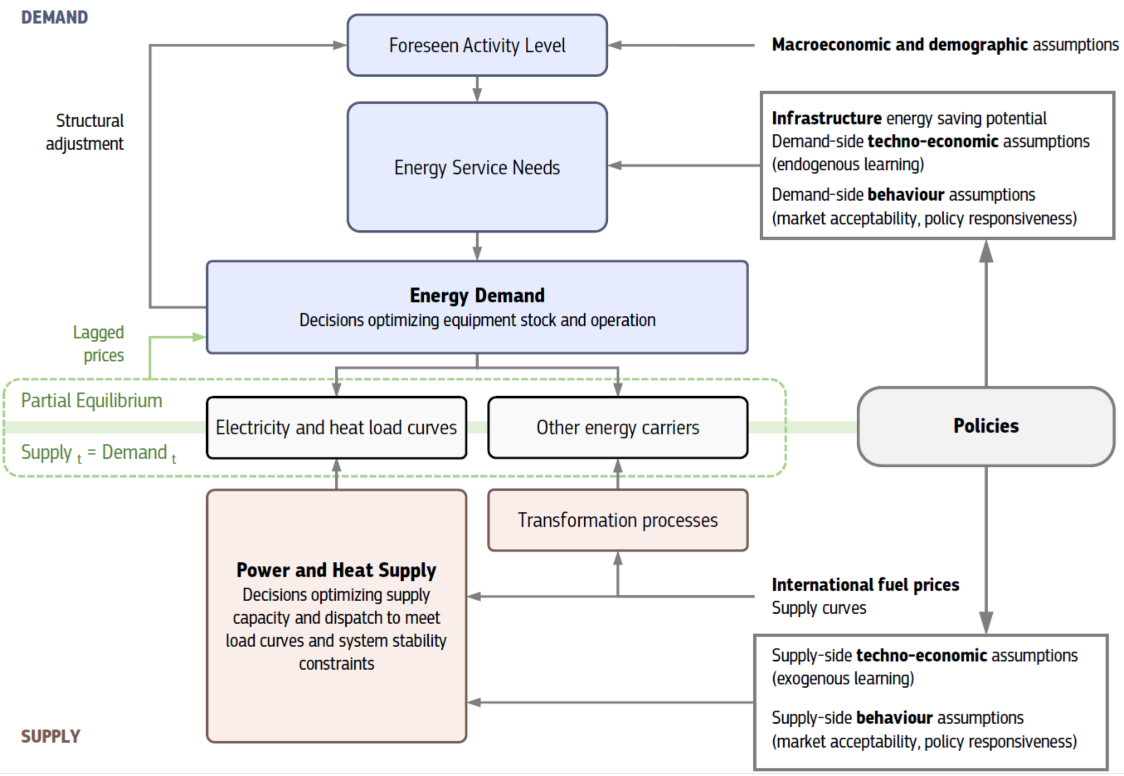
AN 3.1.1 Model Overview

The Policy Oriented Tool for Energy and Climate Change Impact Assessment (POTEnCIA) is an energy system simulation model designed to compare alternative pathways for the EU energy system, covering energy supply and all energy demand sectors (industry, buildings, transport, and agriculture). Developed in-house by the European Commission's Joint Research Centre (JRC) to support EU policy analysis, POTEnCIA allows for the joint evaluation of technology-focused policies, combined with policies addressing the decision-making of energy users. To this end:

- By simulating decision-making under imperfect foresight at a high level of techno-economic detail, POTEnCIA realistically captures the adoption and operation of new energy technologies under different policy regimes;
- By combining yearly time steps for demand-side planning and investment with hourly resolution for the power sector, POTEnCIA provides high temporal detail to suitably assess rapid structural changes in the EU's energy system;
- By tracking yearly capital stock vintages for energy supply and demand, POTEnCIA accurately represents the age and performance of installed energy equipment, and enables the assessment of path dependencies, retrofitting or retirement strategies, and stranded asset risks.

The core modelling approach of POTEnCIA (Figure 51); detailed in (Mantzos *et al.*, 2017, 2019)) focuses on the economically-driven operation of energy markets and corresponding supply-demand interactions, based on a recursive dynamic partial equilibrium method. As such, for each sector of energy supply and demand, this approach assumes a representative agent seeking to maximize its benefit or minimize its cost under constraints such as available technologies and fuels, behavioural preferences, and climate policies.

Figure 51. The POTEnCIA model at a glance



Source: JRC adapted from (Mantzos et al., 2019)

This core modelling approach is implemented individually for each EU Member State to capture differences in macroeconomic and energy system structures, technology assumptions, and resource constraints. The national model implementation is supported by spatially-explicit analyses to realistically define renewable energy potentials and infrastructure costs for hydrogen and CO_2 transport. Typical model output is provided in annual time steps over a horizon of 2000-2070; historical data (2000-2021) are calibrated to Eurostat and other official EU statistics to provide accurate initial conditions, using an updated version of the JRC Integrated Database of the European Energy System (Rózsai *et al.*, 2024).

AN 3.1.2 POTEnCIA CETO 2024 Scenario

The technology projections provided by the POTEnCIA model are obtained under a climate neutrality scenario aligned with the broad GHG reduction objectives of the European Green Deal. As such, this scenario reduces net EU GHG emissions by 55% by 2030 and 90% by 2040, both compared to 1990, and reaches net zero EU emissions by 2050. To model suitably the uptake of different technologies under this decarbonisation trajectory, the scenario includes a representation at EU level of general climate and energy policies such as emissions pricing under the Emissions Trading System, as well as key policy instruments that have a crucial impact on the uptake of specific technologies. For instance, the 2030 energy consumption and renewable energy shares reflect the targets of the EU's Renewable Energy Directive and of the Energy Efficiency Directive. Similarly, the adoption of alternative powertrains and fuels in transport is consistent with the updated CO_2 emission standards in road transport and with the targets of the ReFuelEU Aviation and FuelEU Maritime regulations. A more detailed description of the *POTEnCIA CETO 2024 Scenario* will be available in the forthcoming report (Neuwahl *et al.*, 2024).

AN 3.2 POLES-JRC model

AN 3.2.1 Model Overview

POLES-JRC (Prospective Outlook for the Long-term Energy System) is a global energy model well suited to evaluate the evolution of energy demand and supply in the main world economies with a representation of international energy markets. It is a simulation model that follows a recursive dynamic partial equilibrium method. POLES-JRC is hosted at the JRC and was designed to assess global and national climate and energy policies.

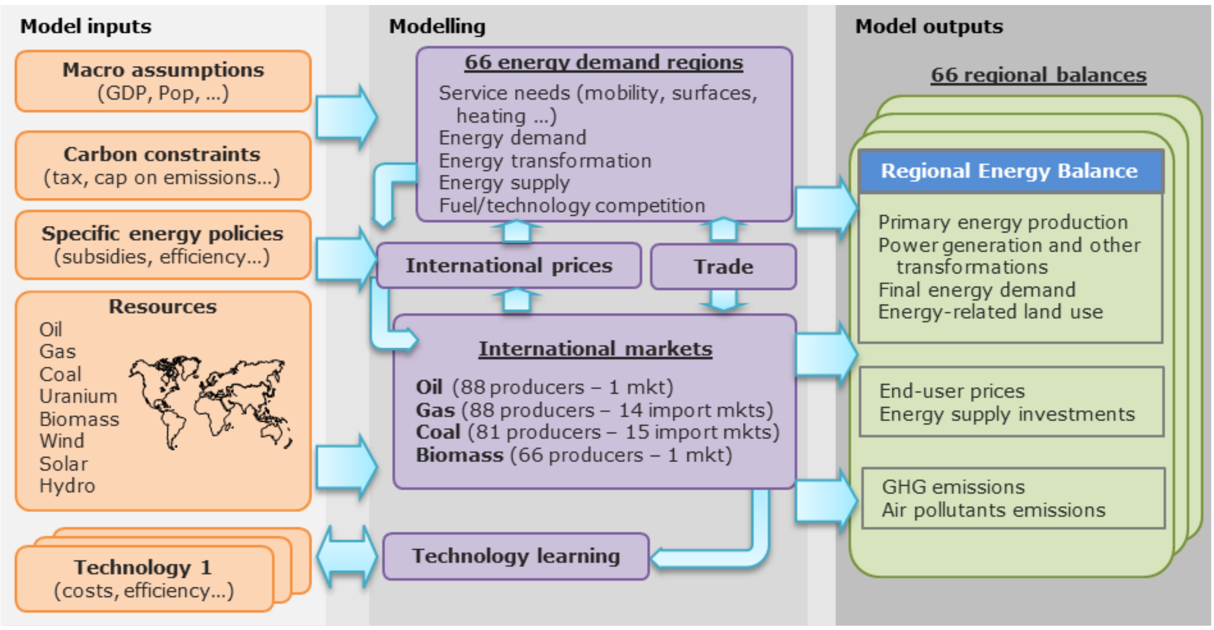
POLES-JRC covers the entire energy system, from primary supply (fossil fuels, renewables) to transformation (power, biofuels, hydrogen and hydrogen-derived fuels such as synfuels) and final sectoral demand (industry, buildings, transport). International markets and prices of energy fuels are calculated endogenously. Its high level of regional detail (66 countries & regions covering the world with full energy balances, including all detailed OECD and G20 countries) and sectoral description allows assessing a wide range of energy and climate policies in all regions within a consistent global frame: access to energy resources, taxation policy, energy efficiency, technological preferences, etc. POLES-JRC operates on a yearly basis up to 2100 and is updated yearly with recent information.

The POLES-JRC model applied for the CETO project is specifically enhanced and modified to capture learning effects of clean energy technologies.

POLES-JRC results are published within the series of yearly publications "Global Climate and Energy Outlooks" – GECO. The GECO reports along with detailed country energy and GHG balances and an on-line visualisation interface can be found at: https://joint-research-centre.ec.europa.eu/scientific-activities-z/geco_en

A detailed documentation of the POLES-JRC model is provided in (Despres *et al.*, 2018).

Figure 52. Schematic representation of the POLES-JRC model architecture.



Source: POLES-JRC model

AN 3.2.2 POLES-JRC Model description

Power system

The power system considers all relevant power generating technologies including fossil, nuclear and renewable power technologies. Each technology is modelled based on its current capacities and techno-economic characteristics. The evolution of cost and efficiencies are modelled through technology learning.

With regard to the power technologies covered by CETO, the model includes solar power (utility-scale and residential PV, concentrated solar power), wind power (on-shore and off-shore), hydropower and ocean power. Moreover, clean thermal power technologies are taken into account with steam turbines fuelled by biomass, biomass gasification, CCS power technologies and geothermal power. Furthermore, electricity storage technologies such as pumped hydropower storage and batteries are also included.

For solar and wind power, variable generation is considered by representative days with hourly profiles. For all renewables, regional resource potentials are considered.

Electricity demand
Electricity demand is calculated for all sectors taking into account hourly fluctuations through the use of representative days. Clean energy technologies using electricity consist of heat pumps (heating and cooling), batteries and fuel cells in transport, and electrolysers.

Power system operation and planning
Power system operation allocates generation by technology to each hour of representative days, ensuring that supplying and storage technologies meet overall demand, including grid imports and exports. Capacity planning considers the existing power mix, the expected evolution of electricity demand as well as the techno-economic characeristics of the power technologies.

Hydrogen

POLES-JRC takes into account several hydrogen production routes: (i) low temperature electrolysers using power from dedicated solar. wind and nuclear plants as well as from the grid, (ii) steam reforming of natural gas (with and without CCS), (iii) gasification of coal and biomass (with and without CCS), (iv) pyrolysis of gas and biomass as well as (v) high temperature electrolysis using nuclear power.

Hydrogen is used as fuel in all sectors including industry, transport, power generation and as well as feedstock for the production of synfuels (gaseous and liquid synfuels) and ammonia. Moroever, hydrogen trade is modelled, considering hydrogen transport with various means (pipeline, ship, truck) and forms (pressurised, liquid, converted into ammonia).

Bioenergy

POLES-JRC receives information on land use and agriculture through a soft-coupling with the GLOBIOM-G4M model (IIASA, 2024). This approach allows to model bioenergy demand and supply of biomass adequately by taking into account biomass-for-energy potential, production cost and reactivity to carbon pricing.

Biomass is used for power generation, hydrogen production and for the production of 1st and 2nd generation of liquid biofuels.

Carbon Capture Utilization and Storage (CCUS)

POLES-JRC uses CCUS technologies in:

- Power generation: advanced coal using CCS, coal and biomass gasification with CCS, and gas combined cycle with CCS.
- Hydrogen production: Steam reforming with CCS, coal and biomass gasification with CCS, and gas and biomass pyrolysis.
- Direct air capture (DAC) where the CO_2 is either stored or used for the production of synfuels (gaseous or liquid).
- Steel and cement production in the industrial sector.
- Second generation biofuels production.

The deployment of CCS technologies considers region-specific geological storage potentials.

Endogenous technology learning

The POLES-JRC model was enhanced to capture effects of learning of clean energy technologies. To capture these effects, a one-factor learning-by-doing (LBD) approach was applied to technologies and technology sub-components, aiming at endogenising the evolution of technology costs.

POLES-JRC considers historical statistics and assumptions on the evolution of cost and capacities of energy technologies until the most recent year available (this report: 2022/2023). Based on the year and a capacities threshold, the model switches from the default time series to the endogeneous modelling with the one-factor LBD approach. Within the LBD, the learning rate represents the percentage change of the cost of energy technology based on a doubling of the capacity of the energy technology.

This generic approach is applied on a component level to capture spillover effects as well. For instance, a gasifier unit is used as component for several power generating technologies (e.g. integrated gasification combined cycle, IGCC) as well as for several hydrogen production technologies (e.g. gasification of coal and biomass). Therefore, the component-based LBD approach allows to model spillover effects not only across technologies, but also across sectors. Also, it allows to estimate costs for emerging technologies for which historical experience does not yet exist.

Moreover, for each component a floor cost is specified which marks the minimum for the component's investment cost and serves as limitation for the cost reduction by endogenous learning. Cost reductions by learning in POLES-JRC slow down when the investment cost approaches the floor cost.

The described method above applies not only for the overnight investment cost of energy technologies, but as well for operation and maintenance (OM) costs, which also decrease as technologies improve, and for efficiencies. In the model, OM costs diminish synchronously to the decrease of total investment cost of the technology. The efficiency of renewables is implicitly taken into account in the investment cost learning and the considered renewable potentials. For most technologies the efficiencies are endogenously modelled.

AN 3.2.3 Global CETO 2°C scenario 2024

The global scenario data presented in the CETO technology reports 2024 refers to a 2°C scenario modelled by the POLES-JRC model in a modified and enhanced version to address the specific issues relevant for the CETO project.

The *Global CETO 2°C scenario 2024* and its specific POLES-JRC model configuration is described in detail in the forthcoming report "*Impacts of enhanced learning for clean energy technologies on global energy system scenario*" (Schmitz *et al.*, 2024).

The *Global CETO 2°C scenario 2024* is designed to limit global temperature increase to 2°C at the end of the century. It is driven by a single global carbon price for all regions that reduces emissions sufficiently so as to limit global warming to 2°C. This scenario is therefore a stylised representation of a pathway to the temperature targets. This scenario does not consider financial transfers between countries to implement mitigation measures. This is a simplified representation of an ideal case where strong international cooperation results in concerted effort to reduce emissions globally; it is not meant to replicate the result of announced targets and pledges, which differ greatly in ambition across countries.

As a starting point, for all regions, it considers already legislated energy and climate policies (as of June 2023), but climate policy pledges and targets formulated in Nationally Determined Contributions (NDCs) and Long-Term Strategies (LTSs) are not explicitly taken into account. In particular, the EU Fit for 55 and RePowerEU packages are included in the policy setup for the EU. Announced emissions targets for 2040 and 2050 for the EU are not considered.

The *Global CETO 2°C scenario 2024* differs fundamentally from the *Global CETO 2°C scenario 2023* used in the CETO technology reports in 2023 in various aspects[2]:

- The version of the POLES-JRC model used for the *Global CETO 2°C scenario* has been further enhanced and modified to capture effects of endogenous learning of clean energy technologies and, furthermore, several technology representations were further detailed, e.g. DAC (composition of renewable technologies, batteries and DAC unit), fuel conversion technologies (for hydrogen transport) and batteries in transport.

[2] A description of the *Global CETO 2°C scenario 2023* can be found in Annex 3 of (Chatzipanagi *et al.*, 2023).

- The techno-economic parameters have been thoroughly revised and updated taking into account the expertise of the authors of the CETO technology reports.

As a result, major scenario differences occur in the *Global CETO 2°C scenario 2024* regarding DAC, synfuels, CCS power technologies, wind power and ocean power.

AN 3.3 Distinctions for the CETO 2024 Scenarios – POLES-JRC vs. POTEnCIA

The results of both models are driven by national as well as international techno-economic assumptions, fuel costs, as well as policy incentives such as carbon prices. However, on one side these two JRC energy system models differ in scope and level of detail, on the other side the definitions of the POTEnCIA and POLES-JRC scenarios presented in this document follow distinct logics, leading to different scenario results:

- The *Global CETO 2°C scenario 2024* (POLES-JRC) scenario is driven by a global carbon price trajectory to limit global warming to 2°C, where enacted climate policies are modelled, but long-term climate policy pledges and targets are not explicitly considered. Scenario results are presented for the global total until 2100.
- The *POTEnCIA CETO 2024 scenario* is a decarbonisation scenario that follows a trajectory for EU27's net GHG emissions aligned with the general objectives of the European Climate Law (ECL) taking into consideration many sector-specific pieces of legislation. Scenario results are presented for the EU27 until 2050.

Annex 4. Biofuels facilities

Advanced biofuel plants in Europe operational or planned

Project name	Project owner	Country	Production capacity	TRL	Technology	Product	Start year
Waste to Methanol	JV controlled by ENI	Italy	300 t/d	8	Fuel Synthesis	Biomethanol	2023
Clariant Romania	Clariant Romania	Romania	50 Kt/y	8	Fermentation	Bioethanol	2022
BioTfueL pilot	BioTfueL-consortium	France	60 t/y	4-5	Fuel Synthesis	FT liquids, SAF	2012
BioTfueL demo	Total	France	8,000 t/y	6-7	Fuel Synthesis	FT liquids, SAF	2021
Booster	TU Munich	Germany	0.15 MW	4-5	Torrefaction and HTC and Fuel Synthesis	SNG	
EMPYRO Hengelo Twence	BTG-Bioliquids	Nether-land	24 kt/y	9	pyrolysis	Bio-oil	2015
Silva Green Fuels (SGF)	Statkraft & Södra	Norway	5 kl/d	4-5	Hydrothermal liquefaction	Bio-oil	2021
GFN Lieksa	GFN OY	Finland	24 kt/y	8	Fast pyrolisis	Bio-oil	
Pyrocel Gavle	Pyrocell	Sweden	24 kt/y	8	fast pyrolisis	Pyrolyis oil	2021
RenFuel Backhammer	RenFuel	Sweden	3,200 t/y	6-7	Transport fuel intermediates from thermolytic processes	bio-oil	2016
To-Syn-Fuel	Fraunhofer UMSICHT	Germany	200 kl/y	4-5	Thermo-Catalytic Reforming TCR®	Bio-oil	2021
bioliquid project	Karlsruhe Institute of Technology (KIT)	Germany	608 t/y	8	Gasification and Fisher Thropsch	FT liquid	2021
BioMCN	BioMCN	Nether-land	200 Kt/y	8	Biogas steam reforming	Biomethanol	2010
Vaermlandsmetanol Hagfors	Vaermlandsmetanol	Sweden	92 Kt/y	8	HTW gasification and methanol synthesis	Biomethanol	2015
Sodra biomethanol	Sodra	Sweden	5.2 kt/y	9		Biomethanol	2020
Ecoplanta Molecular Recycling Solutions	Enerkem and Suez	Spain	220 kt/y	8	gasification	Biomethanol	2025
Cellulonix Pietarsaari	ST1	Finland	10 Ml/y	8	fermentation	Bioethanol	2017
chempolis Oulu	Chempolis Ltd	Finland			fermentation	no	
Versalis crescentino	Versalis	Italy	25 kt/y	8	fermentation	Bioethanol	2022
ethanolix Ghotenburg	st1	Sweden	5 Ml/y	4-5	fermentation	Bioethanol	2015
ArcelorMittal Ghent Steelanol	ArcelorMittal	Belgium	62 Kt/y	8	Fermentation	Bioethanol	

Advanced oil-based biofuel plants in Europe operational or planned

Company	City	Feedstock	Capacity
Neste	Rotterdam, Netherlands	Vegetable oil, UCO and animal fat	800,000 t/y (1.26 bn L/y)
Neste	Singapore	Vegetable oil, UCO and animal fat	800,000 t/y (1.26 bn L/y)
Neste	Singapore expansion	Vegetable oil, UCO and animal fat	1,400,000 t/y
Neste	Porvoo 1, Finland	Vegetable oil, UCO and animal fat	190,000 t/y (240 m L/y)
Neste	Porvoo 2, Finland	Vegetable oil, UCO and animal fat	190,000 t/y (240 m L/y)
ENI	Venice, Italy	Vegetable oils	360,000 t/y (450 m L/y)
ENI	Gela, Italy		750,000 t/y
Diamond Green Diesel	Norco, Louisiana	Vegetable oils, animal fats and UCO	411,000 t/y (500 m L/y)
UPM	Lappeenranta, Finland	Crude tall oil	130,000 t/y (120 m L/y)
World Energy	Paramount, California	Non-edible oils and waste	130,000 t/y (150 m L/y)
World Energy	Paramount expansion		1,000,000 t/y
Renewable Energy Group	Geismar, Louisiana	High and low free fatty acid feedstocks	225,000 t/y (315 m L/y)
Emerald Biofuels	Port Arthur, Texas	Vegetable oils	417,000 t/y (330 m L/y)

TOTAL	La Mede, France	Vegetable oils and waste	500,000 t/y
TOTAL	Grandpuits, France	Vegetable oils	~350,000 t/y
Preem	Gothenburg, Sweden	Tall oil	800,000 t/y
Tidewater	Prince George, Canada	Vegetable oils	150,000 t/y
Sunpine	Pitea, Sweden	Tall oil	77,000 t/y
St1	Gothenburg, Sweden	Oils and fats	200,000 t/y
Repsol	Cartagena, Spain	Oils and fats	250,000 t/y
Phillips 66 (Rodeo renewed)	San Francisco, USA	Oils and fats	2,000,000 t/y
Imperial Oil (Strathcona project)	Edmonton, Canada	Oils and fats	1,000,000 t/y
Marathon	Dickinson, North Dakota	Oils and fats	184 million gallons per year
Marathon	Martinez, California	Oils and fats	730 million gallons per year
Covenant Energy	Saskatchewan, Canada	Oils and fats	300-325 MLPY
Come by Chance	Newfoundland, Canada	Oils and fats	14,000 bpd
Heartwell Renewables (Cargill JV)	Hastings, Nebraska	Oils and fats	80 MGPY
Shell	Rotterdam, Netherlands	Oils and fats	820,000 t/y
Go Sunshine	New Orleans	Oils and fats	29 (110)

Facilities based on drop-in biofuel technologies under construction or announced

Company	**Technology pathway**	**Vol MGPY (MLY)**	**Status - Start-up date**
Gevo (Silsbee)	Isobutanol-to-jet	Demo	2020
Gevo (Luverne)	Isobutanol-to-jet	19 (72)	2023
Fulcrum Bioenergy (Sierra)	Gasification/FT	7 (26)	2021
Red Rock Biofuels (Lakeview)	Gasification/FT	6 (23)	2021
Fulcrum #2 (Indiana)	Gasification/FT	21 (80)	2023
Velocys (Altalto, UK)	Gasification/FT	16 (60)	2025
Velocys (Bayou Fuels)	Gasification/FT	35 (132)	
Lanzajet (Freedom Pines)	Ethanol-to-jet	10 (38)	2022
Lanzajet	Ethanol-to-jet	90 (340)	2024
Readifuels	Catalytic hydrothermolysis	24 (91)	2023

Existing commercial and pre-commercial operating bio-crude facilities in the world

Company	**City**	**Stage**	**Barrels Bio-crude per year**	**Product**	**Feedstock**
Ensyn	Ontario, Canada	Pre-commercial	70	Heat	Sawmill residues
Ensyn	Cote du Nord, Quebec, Canada	Commercial	36,000	Gasoline-type products	Sawmill residues
Twence/ Empyro	Hengelo, the Netherlands	Commercial	20,000	BTG-BTL technology	Broken and dust wood pellets
Green Fuel Nordic	Lieksa, Finland	Commercial (2020)	~20,000	BTG-BTL technology Heating oil	Sawdust
Pyrocell (Setra/Preem)	Gavle, Sweden	Commercial (2021)	~20,000	BTG-BTL technology coprocessing	Sawdust
Altaca Energy	Gonen, Turkey	Demonstration	20,000	HTL (CatLiq®, SCF Technologies)	Biomass/coal
Licella Bio-crude	Somersby, Australia	Demonstration	350	Cat -HTR	biomass
Arbios	Prince George, Canada	announced	50,000	Cat –HTR	
Silva Green Fuel (JV Statkraft, Sodra)	Tofte, Norway	Demonstration (2021)	1400	Steeper Technology	Forest residues Bio-crude

Source: (BEST GmbH, 2024; ETIP Bioenergy, 2024)

Annex 5 Technology Pathways

TRL could be different for the various processing steps along the biofuel pathways. TRLs are taken from various sources, including (A Brown *et al.*, 2020). Example plants are taken from the IEA task 39 database (BEST GmbH, 2024) with some exceptions.

Intermediate Bioenergy carriers

In this section, technologies to obtain Intermediate Bioenergy Carriers (IBC) are briefly described. As several of the technologies are identical to the ones described in the Bioenergy, RFNBO and hydrogen CETO reports, please refer to those reports for details.

Pre-treatment and enzymatic hydrolysis to sugars

Pre-treatment converts biomass into a more accessible form for hydrolysis through mechanical, physical-chemical, chemical and biological methods. Its conversion requires: a) pre-treatment, usually thermal or thermochemical, to disrupt the cellular structure and facilitate access to enzymes; b) enzymatic hydrolysis, to break the large carbohydrates (cellulose and hemicellulose) down into monomeric C5-C6 sugars; and c) fermentation of the sugars to alcohol using yeasts, other species of fungi or bacteria. . Several processes can be used, including physical processes (steam explosion, thermos hydrolysis), chemical (acid hydrolysis, alkaline hydrolysis, organic solvolysis or biologic) and combined (catalysed steam explosion, ammonia or CO_2 explosion). Steam explosion is widely used pre-treatment technology, involving high-pressure steam at high temperature for a short time, followed by rapidly depressurization. The process needs a lot of energy and leads to the creation of by-products that inhibit downstream fermentation (IRENA, 2016). Other pre-treatment options include acid or alkali treatment, or solubilisation with solvents, e.g. organic solvolysis., but makes the use of special steels. Hydrolysis process converts cellulose into fermentable sugars, through acid or enzymatic routes. Enzymatic hydrolysis with enzymes is the most common route, although the inflated cost of enzymes currently represents a major contribution to the production costs (IRENA, 2016). Hydrolysis can also take place using strong acid processes or a combination of dilute acid followed by enzymatic treatment. Enzymatic process occurs in mild conditions of pH (4.8) and temperature (45-50ºC) and allows higher yields (75-85%) and simultaneous saccharification and fermentation. Hydrolysis with diluted acid has limitations in terms of yield (50-70%) while hydrolysis with concentrated acid offers higher yields (75-85%). These conversion processes need acid resistant steel reactors, Teflon or ceramics-coated materials (JRC, 2011). Acid hydrolysis leads to the creation of inhibitors with a negative impact on the fermentation process (IRENA, 2016).

Process description	
Inputs	*Lignocellulosic material, biowastes*
Outputs	*Sugars*
Process conditions	*Mild*
Technical development	
TRL	*8-9*
Plant example	*ChemCell Ethanol, Alpena Biorefinery*

Pyrolysis of biomass to pyrolysis oil

Pyrolysis is the thermochemical conversion of biomass into bio-oil, gases and a solid product (biochar) in the absence of oxygen at lower than combustion temperatures, between 450–600 ºC (typically 500 ºC). Fast pyrolysis is an option to produce Fast Pyrolysis Bio-Oil (FPBO) (40-60%), along with biochar (10-15%) and gases (15-35%), such as hydrogen, methane, carbon monoxide and carbon dioxide (Buffi *et al.*, 2024). The characteristics of bio-oil (highly acidic, high viscosity and high-water content) make it difficult to store and process it (Karatzos, Mcmillan and Saddler, 2014). Catalytic Fast Pyrolysis (CFP) employs various catalysts that promote cracking, dehydration, deoxygenation reactions to produce a bio-oil with lower oxygen levels, increased higher heating value and higher hydrocarbon content (mostly aromatics and olefins). Catalysts may be deactivated via coking and condensation of poly-aromatics.

Bio-oil upgrading is challenging due to the high oxygen and water content. Various upgrading techniques have been developed, through physical, chemical, and catalytic pathways. Physical upgrading includes solvent extraction to reduce its viscosity and improve homogeneity and energy density, or emulsion to enhance its ignition properties. The most important upgrading processes involve chemical pathways through hydrocracking, hydrotreatment and hydrodeoxygenation. A series of reactions occur, including decarbonylation, decarboxylation, hydrodeoxygenation, hydrogenation, deoxygenation, cracking, and hydrocracking. Hydrocracking involves cracking the heavy molecules at high temperature of 300–500 ºC and pressure of 10–20 MPa and hydrogenation reaction of the cracked molecules.

Hydrotreatment is employed and is a well-established process in oil refineries, carried out at temperatures of 300–450 ºC and high pressure up to 20 MPa. Hydrodeoxygenation (HDO) involves a combination of different reactions such as hydrogenation, hydrogenolysis, decarbonylation, and dehydration, during which oxygen is removed. HDO involves removing oxygen from a hydrocarbon through different catalytic reactions at temperature up to 400 ºC and pressure up to 20 MPa (Attia, Farag and Chaouki, 2020). The yield and properties of upgraded bio-oil depend on the temperature, residence time, pressure, solvent, catalyst type, and reactor configuration. Biomass pyrolysis has been demonstrated at small-scale and several large pilot plants or demo projects (up to 200 ton/day biomass) are in operation although current production capacity is limited (IRENA, 2016).

Process description	
Inputs	*Mechanically and thermally pre-treated biomass (i.e., drying, fragmentation).*
Outputs	*Pyrolysis oil, biochar and hydrogen, methane, carbon monoxide and carbon dioxide, ie gases*
Process conditions	*Heating in absence of oxygen*

Technical development	
TRL	*8-9*
Plant example	*BTG, Netherlands, Pyrocel Gavle, GFN Lieksa, Ensyn plants in North America*

Gasification of biomass

Gasification is a high-temperature (700-1500 °C) partial oxidation process through which biomass and a gasifying agent (air, oxygen or steam) is converted into synthesis gas, or syngas, principally CO and H_2. The pyrolysis oil can also be converted through gasification into a synthesis gas. Gasifiers can be classified by operating temperature, pressure, heat source (internal or external), and technology type (fixed-bed, fluidised-bed type etc.).

Most medium to larger scale biomass gasifiers are fluidized-bed type, while small-scale biomass gasifiers are fixed-bed downdraft type due to the low amount of tar they produce (Bioenergy, Gasification and Workshop, 2014). Gasification process conditions can be designed to optimize the syngas quality. To produce synthesis fuels, pressurized, oxygen-blown gasifiers are usually used. The use of air as a gasification agent is not favourable due to the resulting high N_2 content in the syngas (ETIP Bioenergy, 2018).

Along with CO and H_2, gasification gas contains CH_4, CO_2 and a range of higher condensable hydrocarbons (tars) & other pollutants, such as H_2S, particulate matter and nitrogen species. The raw syngas must be cleaned and conditioned before catalytic conversion. The main processes needed in raw syngas cleaning are: tar removal/cracking, particulate matter removal, and sulphur, nitrogen, and chlorine species removal. Methods of syngas clean-up can be categorised into primary and secondary.

Primary methods include modifying gasifier design, adjusting operating conditions (p, T, gasifying agent, residence time amongst others) and the use of in-bed catalysts and additives. Secondary methods concern physical processes (i.e. using cyclones, filters, electrostatic precipitators, scrubbers), and thermal-catalytic processes (thermal cracking, partial oxidation, catalytic reforming, plasma processes) (Karatzos, Mcmillan and Saddler, 2014).

Catalytic cracking of tar can be achieved partially in-situ via choice of bed materials, but a specific additional reactor is needed to achieve the concentration limits required by downstream catalysts. Following syngas cleaning, the gas is conditioned to optimise its quality for catalytic synthesis. These steps may include the water-gas shift (WGS) reaction to ensure the desired H_2/CO ratio, steam reforming to convert hydrocarbons (such as methane) to additional syngas, and possibly CO_2 removal if necessary.

Process description	
Inputs	*Physically and thermally pre-treated biomass (i.e., drying and fragmentation); dry wastes.*
Outputs	*Producer gas (mixture of CO, H2, CO2, light HCs, water and tars) further upgraded to syngas (e.g. for FT-synthesis for drop-in fuels production).*
Process conditions	*Depending on reactor type, T over 700 °C*

Technical development	
TRL	*7-8*
Plant example	*Enerkem plant in Edmonton, Canada, IFPEN technology, Vaskiluodon Voima Oy plant*

Hydrothermal liquefaction to bio-crude

HydroThermal Liquefaction (HTL), also called hydrous pyrolysis, is direct thermochemical conversion of wet biomass into a bio-oil (bio-crude) at relatively high temperature (300–350 °C) and pressure (10-25 MPa). The process converts biomass into a liquid (bio-oil or bio-crude), solid (hydrochar), or a gas (e.g., hydrogen, methane), depending on the process parameters. Water serves as both reactant and catalyst (Kumar, Olajire Oyedun and Kumar, 2018; Reißmann, Thrän and Bezama, 2018).

The bio-crude has heating value (30–37 MJ/kg), higher than pyrolysis oil. The bio-crude oil contains primarily C16-C18 hydrocarbons, aromatics such as phenols, benzenes and naphthalene, other heavy components, 10-20% oxygen, 3-7% nitrogen, and up to 20% water content (Wan-Ting, 2017; Matayeva *et al.*, 2019; Zhu *et al.*, 2019). Bio-crude quality depends on the feedstock type and operating conditions – temperature, solvent type, and catalyst and residence time. The use of catalysts in HTL can reduce the required reaction temperature, enhance reaction kinetics, increase the yield of liquid products, and reduce char and tar formation (Dimitriadis and Bezergianni, 2017; Gollakota, Kishore and Gu, 2018; Kumar, Olajire Oyedun and Kumar, 2018).

Bio-crude upgrading techniques include steam reforming, sub/super-critical fluid treatment, cracking (hydrocracking, zeolite cracking, and thermal cracking) and hydrotreating. Cracking is one of the major processes in oil refining, that can be used to upgrade bio-crude at high temperature (above 350°C) and high pressure with catalysts. Hydrotreating is also a well-established process in oil refineries, involving several reactions such as hydrodeoxygenation, hydrodenitrogenation, and hydrodesulfurization.

During hydrotreating, aromatics, fatty acids and other compounds react with hydrogen in the presence of a catalyst at elevated temperature and moderate pressure to convert them into saturated hydrocarbons (Wan-Ting, 2017; Attia, Farag and Chaouki, 2020; Hao *et al.*, 2021). Steam reforming is a well-established technique producing a synthesis gas at high temperature (700-1000°C) with catalysts. Sub-/ Super-critical fluid treatment involves the use of water or organic solvents. Less severe upgrading includes solvent addition that improves the viscosity and acidity of bio-oil through esterification and transesterification, chemical extraction and emulsification (Wan-Ting, 2017).

Production of renewable hydrocarbons via HTL is progressing currently at laboratory (TRL of 4) or pilot stage (TRL of 5-6), while some projects appear to be closer to commercialisation.

Process description	
Inputs	*Wet biomass and wet wastes*
Outputs	*Bio-crude*
Process conditions	*High temperature and pressure*

Technical development	
TRL	*5-6*
Plant example	*Pilot plants*

Hydrothermal gasification

In a similar way, wet biomass can also be gasified with sub- or supercritical water under pressure and high temperatures. Even if the theoretical energy and carbon efficiency of the process is very high, the need to heat large amounts of water remains a challenge. The product gas can be either methane or hydrogen.

Process description	
Inputs	*Wet biomass and wet wastes*
Outputs	*Methane or hydrogen*
Process conditions	*High temperature and pressure*

Technical development	
TRL	*3-8*
Plant example	*20 MW demonstration plant of SCW Systems in Alkmaar, Netherlands, TreaTech SARL, Switzerland*

Oil extraction from algae to triglycerides

Microalgae, due to several advantages such as high growth rate, high yield, high oil content, up to 50%–70%, are a potential source for biofuels. However, the production of microalgal biofuels faces a number of technical challenges related to algae culture and growth, harvesting, lipid extraction and biofuels production. Lipid extraction is done by physical methods and chemical methods, or a combination of them (Pragya, Pandey and Sahoo, 2013).

Oil extracting methods from microalgae include mechanical pressing, solvent extraction, supercritical fluid extraction, enzymatic extractions, ultrasonic-assisted extraction and osmotic shock (Mercer and Armenta, 2011; Rawat *et al.*, 2011). Mechanical cell disruption includes pressing, bead milling and homogenization, subjecting the microalgal biomass to high-pressure, which ruptures cell walls and releases the oil.

Solvent extraction method entails the use of solvents (hexane, benzene, methanol and ether), or ionic liquids, depending on the species of microalgae chosen to extract oil, by repeated washing or percolation with an organic solvent. Supercritical fluid extraction involves the use of compressed CO_2 in a supercritical state that extracts lipid from the microalgae through decompression. High infrastructure and operational cost associated with this process are the main disadvantages.

The use of enzymes alone, or in combination with a physical disruption method such as sonication, has the potential to facilitate the hydrolysis of cell walls to release oil with higher yields(Mercer and Armenta, 2011). Extracting and purifying oil from algae continues to be a significant challenge in producing microalgae biofuels, being relatively energy-intensive and costly. Some processes are commercial, but not applied to biofuels.

Process description	
Inputs	*Oil rich algae*
Outputs	*Triglycerides*
Process conditions	*Mild*

Technical development	
TRL	*4-6*
Plant example	*ellana's Kona Demonstration Facility on the Big Island of Hawaii, fuelgae EU project*

Dark / light fermentation to hydrogen

Biological pathways for hydrogen production involves photolytic pathways (direct water splitting with green microalgae or cyanobacteria), photo fermentation and dark fermentation. Hydrogen production through fermentation is the conversion of organic substrates to hydrogen by bacteria. Dark fermentation to hydrogen is an anaerobic process similar to anaerobic digestion involving different bacteria to convert organic substrates to hydrogen, in the absence of light, for further synthesis. This process produces relatively low hydrogen. Light fermentation, often called photo fermentation is a fermentative conversion of organic matter to hydrogen in presence of light by purple bacteria at temperatures between 30–35°C and pH value of about 7.0. However, the conversion efficiency of photo fermentation is very low around 1%–5%. The performance of light fermentation for hydrogen production depends on several factors such as temperature, pH and inoculum. In order to increase hydrogen productivity, a combination of dark and photo fermentation is an option. Pre-treatment may increase the final H_2 yield converting a lignocellulosic biomass from its native form into a more accessible form.

Process description	
Inputs	*Carbohydrates or cellulosic biomass*
Outputs	*Hydrogen*
Process conditions	*Mild*

Technical development	
TRL	*4-5*
Plant example	*Hy-Time demo reactor (HYTIME, 2015), HYIELD hydrogen from waste project*

Fuel synthesis and upgrading

Hydroprocessing of oils, fats and bioliquid intermediates

Hydroprocessing (also called hydrotreating) can be applied to oils and fats to produce HVO (Hydrotreated Vegetable Oil) also called HEFA (Hydroprocessed Esters and Fatty Acids) drop-in biofuels. Hydroprocessing consists in a range of catalytic processes including hydrotreating and hydrocracking for the removal of sulphur, oxygen and nitrogen (Vásquez, Silva and Castillo, 2017). Saturating the double bonds present in a lipid molecule through catalytic addition of hydrogen is generally known as hydrogenation. Hydrogen addition in a catalytic reactor is also used to remove the carbonyl group after hydrogenation and, simultaneously, to break the glycerol compound, forming propane and chains of free fatty acids. The fatty acids are deoxygenated through three reactions:

- hydrodeoxygenation (HDO), where oxygen is removed as H_2O, in which the fatty acid reacts with hydrogen to produce a hydrocarbon with the same number of carbon atoms as the fatty acid chain and two molecules of water;
- decarboxylation, where oxygen is removed as CO_2, which yields a hydrocarbon with one carbon atom less than the fatty acid chain and a molecule of CO_2;
- and decarbonylation, where oxygen is removed as CO and H_2O, which also produces a hydrocarbon with one carbon atom less, as well as a molecule of CO and water.

Alternatively, non-hydrogen processes can be used. In these alternative routes, a significant amount of carbon of the feedstock has to be oxidized, to produce the required hydrogen, making them less attractive as they can consume a significant amount of the feedstock. Other downstream processes are required to improve biofuel properties and meet the specification for the various sectors (e.g. aviation, etc.): isomerization, cracking or cyclization (Al-Sabawi and Chen, 2012). The relative amounts of the various compounds are influenced by the operating conditions, including amongst others the catalyst, the reaction temperature and pressure along with the feedstock type. As regards biojet production, decarboxylation and decarbonylation reactions are recognised to be advantageous, as they can be performed at higher temperatures with a moderate acidic catalyst. Europe is a world leader in HVO/HEFA production, with several commercial-size plants currently in production.

Process description	
Inputs	Triglycerides from waste oils, animal fats, vegetable oils or algae, HTL crude, pyrolysis oil, hydrogen
Outputs	*Kerosene, gasoline, diesel, oxymethylene ether (OME)*
Process conditions	*Moderate to high temperature, medium to high pressure with catalysts*

Technical development	
TRL	*5-9*
Plant example	*La Mede (Total)*

Fermentation of syngas to biomethane

Treatment of the product gas (syngas) from biomass gasification to produce biomethane through biological routes (biomethanation) has emerged as a promising alternative. The biological method converts syngas to methane through the metabolism of methanogenic microorganisms in bioreactors operated at a low temperature and atmospheric pressure. Biological syngas methanation can convert CO/CO_2 and H_2 into CH_4 using different biological routes (Grimalt-Alemany, Skiadas and Gavala, 2018; Paniagua, Lebrero and Munoz, 2022). The two main carbon sources of syngas are CO and CO_2, which are used by methanogenic microorganisms to produce CH_4.

The biomethanation of syngas is an anaerobic process that can be carried out at both mesophilic and thermophilic conditions. Synthesis gas is converted into methane both directly and stepwise through intermediary products by a number of microbial groups such as methanogenic archaea, acetogenic bacteria and hydrogenogenic bacteria among others. The biomethanation of syngas comprises a complex network of biochemical reactions mainly based on the water-gas shift reaction, acetogenesis, hydrogenotrophic methanation, carboxydotrophic methanation and acetoclastic methanation (Grimalt-Alemany, Skiadas and Gavala, 2018).

Biological methanation, where CO_2 is used as the feedstock for microorganisms is suitable for small plants as waste heat can be used to supply the process. This biological process presents several advantages over catalytic methanation, such as the use of inexpensive biocatalysts, milder operation conditions, higher tolerance to the impurities of syngas and higher product selectivity. Therefore, the gas cleaning process can be simplified. As opposed to the catalytic methanation process, the biological process is not sensitive to the ratio of C/H. However, there are still several challenges to be addressed in order to reach a commercial stage.

One of the main shortcomings of biological processes is the limited mass transfer rate of H_2 and CO due to the low solubility of these gases in the liquid medium. The low cell growth rate of anaerobic microorganisms is another limiting factor since the low cell productivities of continuous processes result in low volumetric productivities of CH_4 (Alemany et al 2018). Biological methanation remains in the laboratory and demonstration stage.

Process description	
Inputs	Producer gas (syngas) from biomass gasification
Outputs	*Biomethane*
Process conditions	*Mild*

Technical development	
TRL	*6-7*
Plant example	*6 MW CORTUS demonstration site, Höganäs, Sweden*

Gas fermentation through microorganisms to alcohols

A range of microorganisms can produce intermediates such as ethanol, butanol and acetic acid from CO and H_2-rich gases (syngas) or CO-rich gases via fermentation (Munasinghe and Khanal, 2010). Acetogenic bacteria convert CO, H_2 and CO_2 derived from biomass or waste materials into acetic acid (Drake, Großner and Daniel, 2008). Gases can originate from industrial waste off gases (in which case the resulting fuel would be an RCF) or syngas from biomass gasification. Syngas fermentation is a hybrid thermochemical/biochemical pathway that combines the gasification process and the fermentation in syngas fermentation process (Phillips, Huhnke and Atiyeh, 2017). The pathways for gas fermentation through microorganisms to alcohols can be used to produce other products and alcohols such as butanol that are better suited than ethanol as drop-in biofuel intermediates.

Syngas fermentation has several advantages compared to sugar fermentation and thermochemical conversion processes. This bioconversion process to alcohols occurs under mild conditions of temperature and pressure and is able to utilise lignin in addition to carbohydrate fractions of biomass. LanzaTech developed a gas fermentation process to produce ethanol (and other chemicals) mainly from industrial waste gases (from coal-based steel mills or refineries). This technology has been scaled up to a commercial level this year for a refinery in India. Although ethanol is not a drop-in biofuel, it could be an intermediate for drop-in fuel production. The alcohols obtained from fermentation can be further refined for producing fuels, such as alternative aviation fuels, through dehydration, oligomerization and hydrogenation. In the Torero EU-funded project, biomass residues are torrefied to provide the renewable energy in the blast furnace and the resulting ethanol from the fermentation of the CO in the flue gas is renewable. Research focus is on reactor design, process kinetics, mass transfer, yield, catalysts, etc.

Process description	
Inputs	*Industrial gases with energy content (e.g. containing CO, HCs,), .enzymes, bacteria.*
Outputs	*Ethanol*
Process conditions	*Mild*

Technical development	
TRL	*8-9*
Plant example	*Indian Oil Corporation 3G ethanol Commercial plant (LanzaTech), Steelanol Belgium*

Aqueous Phase Reforming of sugars to hydrogen and biofuels

The Aqueous Phase Reforming (APR) is a process that produces hydrogen from biomass-derived oxygenated compounds such as glycerol, sugars, and sugar alcohols in aqueous phase in a single-step reactor process. The APR approach has the potential to be used to produce hydrocarbons from a diversity of water-soluble organic carbon compounds at much faster reaction rates than are possible using biochemical routes.

Compared to traditional reforming, APR needs less severe process conditions and can convert sugars and alcohols to mostly hydrogen (depending on the feedstock and process conditions, CO and alkanes can also be produced). The process occurs at temperatures (200-270 ºC) and pressures (15–50 bar) where the water–gas shift reaction is favourable, making it possible to generate hydrogen with low amounts of CO in a single reactor. The reactor and catalysts can be altered to allow generation of hydrocarbons (alkanes).

The production of alkanes by aqueous-phase reforming involves first the formation of hydrogen and CO_2 and the dehydration of sugar alcohols, followed by hydrogenation of the dehydrated reaction intermediates. The hydrogen produced in the first step is used for the hydrogenation of the dehydrated reaction intermediates, which leads to the overall conversion of sugars to alkanes, CO_2 and water. Platinum (Pt) and nickel (Ni)-based catalysts are used to improve the performance of hydrogen production. However, the APR process faces catalyst coking and deactivation challenges. The APR reactions are less selective than fermentation processes and produce a complex mixture of organic molecules. The selectivity of the reforming process depends on various factors, such as nature of the catalytically active metal, support, solution pH, feed, and process conditions.

Process description	
Inputs	*Sugars, alcohols*
Outputs	*H_2, CO and alkanes (hydrocarbons)*
Process conditions	*Medium temperature (200-270°C), medium pressure (15-50 bar) under presence of water and catalysts*

Technical development	
TRL	*5*
Plant example	

Transesterification of triglycerides

The most prevalent biofuel in the EU is Fatty Acid Methyl Ester (FAME), historically referred to as biodiesel. It was principally made from vegetable oils in the past such as rapeseed, palm oil etc., but now there is growing focus on using waste or used cooking oils and animal fats. FAME conversion takes place by a chemical process known as transesterification. In transesterification, one ester (a triglyceride) is converted into another (a methyl-ester) in the presence of a base catalyst. The state of the art of the process typically involves filtering/pre-treating the feedstock to remove water and contaminants, and then mixing with an alcohol (usually methanol) and the catalyst (typically sodium or potassium hydroxides). This causes the oil molecules (triglycerides) to break apart and reform into methyl esters (biodiesel) and glycerol, which are then separated from each other and purified. The process also produces glycerine, which can be used as animal feed, a chemical feedstock and many other small-scale uses.

In addition to transesterification, free fatty acids which are not attached to a glycerol molecule, and which can be prevalent in waste oil and fat feedstocks, can be directly esterified to methyl ester using an acid catalyst and methanol in a process known as esterification. Methyl esters can be blended with conventional diesel or used as pure biodiesel. The use of bioethanol instead of (typically fossil) methanol to produce Fatty Acid Ethyl Ester (FAEE) has been investigated and could in theory reduce the GHG emissions of the fuel (Joanneum Research, 2016). FAEE is not commercially successful due mainly to the higher price of ethanol compared to methanol, and to additional technical difficulties compared to FAME production (G., Van Gerpen and Krahl, 2005). Unlike FAME, FAEE production does not have a European Standard (i.e. EN14214) which stops it being blended into standard fossil diesel (EN590) and is a considerable impediment to its large-scale use or trading as a stand-alone fuel.

Process description	
Inputs	*Triglycerides from waste oils, animal fats, vegetable oils or algae*
Outputs	*Biodiesel*
Process conditions	*Ambient temperature and pressure with catalyst*

Technical development	
TRL	*9*
Plant example	

Biomethanol synthesis

An alternative to FT synthesis of syngas from gasification for producing liquid fuel is related to the production of methanol. Today methanol is produced at industrial scale from synthesis gas, typically generated from natural gas, in a steam reformer using heterogeneous catalysts (copper, nickel, palladium, and platinum). Methanol is also of importance in the fuel synthesis of transport fuels, such as methyl ethers (e.g. Dimethyl ether - DME) or as marine fuel. Current research focusses on the development of processes based on direct hydrogenation of CO_2, without requiring prior reaction to generate CO. The direct conversion of CO_2 poses several technical challenges, particularly with respect to required pressures (higher than 30 MPa) (Schmidt *et al.*, 2018).

The raw syngas leaving the gasification step needs to be cleaned and conditioned to meet the quality level required by the methanol synthesis step. Syngas cleaning involves the removal of certain impurities, tar removal/cracking, particulate matter removal, and sulphur, nitrogen and chlorine species removal. The syngas is subsequently conditioned through several steps to reach the optimal composition for methanol synthesis, for example by removing CO_2 or adding hydrogen. Raw syngas can contain small amounts of methane and other hydrocarbons that are reformed to CO and H_2 by high temperature catalytic steam reforming or by autothermal reforming (ATR) (Hamelinck and Faaij, 2006).

The initial hydrogen concentration in the syngas is usually too low for optimal methanol synthesis. Syngas conditioning also includes adjustment of the H_2/CO ratio to around 2 to 1 for optimal methanol synthesis in the Water Gas Shift reactor. To reduce the share of CO and increase the share of H_2, WGS can be used, which converts CO and H_2O into CO_2 and H_2. CO_2 removal could be needed to obtain an optimized syngas using chemical absorption by amines or other processes. Hydrogen can be produced separately, by steam reforming of methane or electrolysis of water and added to the syngas. Electrolysis can provide oxygen for gasification and hydrogen production to meet the optimal stoichiometry in the syngas. After conditioning, the syngas is converted into methanol by a catalytic process based on copper oxide, zinc oxide, or chromium oxide catalysts (Hamelinck and Faaij, 2006). Distillation is used to remove the water generated during methanol synthesis.

Process description	
Inputs	*Physically and thermally pre-treated biomass (i.e., drying and fragmentation); pyrolysis oil and other bio-crudes; dry wastes.*
Outputs	*Methanol*
Process conditions	*High temperature and pressure*

Technical development	
TRL	*8*
Plant example	*Enerkem Edmonton, Canada, BioMCM Netherlands, Tarragona, Spain (planned), Sodra biomethanol*

Biomethanol to Gasoline synthesis

An interesting option for the production of advanced biofuels is the possibility to convert methanol into liquid hydrocarbons. The Methanol to Gasoline (MtG) process is currently deployed in several commercial plants. The route has also demonstrated the conversion of methanol into middle distillate (diesel and kerosene) (Schmidt *et al.*, 2018). The first step in this process involves the conversion of the syngas to methanol, which is a commercial technology. An alternative to methanol synthesis from syngas is the production of methanol via CO_2 hydrogenation on Cu/ZnO-based catalysts.

The core reaction of the Methanol to Gasoline pathway is the reaction of one molecule of carbon monoxide with two molecules of hydrogen to form one molecule of methanol. The conversion takes place in the presence of relatively inexpensive catalysts at temperatures between 220-275 °C and pressures of 5-10 MPa. Methanol synthesis requires syngas cleaning and conditioning. To adjust the ratio of hydrogen to carbon monoxide for methanol synthesis, WGS can be used, which converts carbon monoxide and water into carbon dioxide and hydrogen.

Methanol is a liquid fuel but not a drop-in transportation fuel. However, it can be converted into a drop-in gasoline (C4-C12) using the Methanol-To-Gasoline process (MTG) in fixed beds and fluidized beds of proprietary catalysts. Methanol-to-gasoline process was developed and patented by ExxonMobil in the 1970s. The process entails two steps. In the first step, methanol is dehydrated over an alumina catalyst at 300 °C and 27 bar, to form a mixture of dimethyl-ether (DME), methanol and water. In the second stage, this mixture reacts over a zeolite catalyst (359°C and 20 bar) and is converted to light olefins in the C2–C4 range and then to paraffins, aromatics, polycyclic aromatics and higher olefins (>C4) (IEA T39 Drop in Fuels).

Catalyst deactivation by coke is a main problem in this process. MTG gasoline meets the requirements for conventional gasoline, is fully compatible with refinery gasoline and meets the ASTM D4814 specification. An additional catalytic step can be added in which the heavy fraction gasoline is isomerized to produce a high-octane gasoline fraction. DME can be also produced instead of gasoline, by limiting the process to the first step where DME is produced through methanol dehydrocondensation, to be used as a blend with LPG or as an alternative to diesel fuel, due to its high cetane number.

Process description	
Inputs	*Methanol*
Outputs	*Gasoline, DME*
Process conditions	*Medium temperature and high pressure with catalyst*

Technical development	
TRL	*8*
Plant example	

Other pathways

Biomethane from biogas upgrading

Anaerobic Digestion (AD) involves feedstock conversion by microorganisms under anaerobic conditions, through a series of biological processes: hydrolysis, acidogenesis, acetogenesis and methanogenesis. The biogas produced contains methane (50 - 70%), carbon dioxide (30 - 40%) and other gases, such as hydrogen, nitrogen, hydrogen sulphide, ammonia, and trace amounts of carbohydrates and organic silicon compounds (e.g. siloxanes). Anaerobic digestion processes differ depending on operating temperature: thermophilic digestion that occurs at 50–60 ° C and mesophilic that develops at 25–40 ° C.

The AD process may operate as a wet (<15% dry matter) or a dry process (15–40% dry matter), depending on the water content of the substrate. AD can use a variety of substrates including wet biomass and organic waste, such as agricultural, organic residues and wastes, sewage sludge, animal fats and slaughtering residues, sewage sludge from wastewater treatment and also aqueous biomass (micro and macro algae).

Co-digestion of various feedstocks (e.g. energy crops, organic solid waste, or animal manure) is a common practice that allows to maintain the optimum C/N ratio of the substrate and to maximize the biogas yield. Anaerobic digestion is also possible by using lignocellulosic residues and wastes. This might, however, require additional pre-treatment to achieve higher gas yields (Thamizhakaran Stanley *et al.*, 2022). As an example, VERBIO's technology started to produce biomethane from 100% straw at its production site in Schwedt/Oder

The biogas upgrading to biomethane entails the removal of carbon dioxide to increase the energy density as well as the removal of water, hydrogen sulphide and other contaminants: Pressurised Water Scrubbing (PWS), Pressure Swing Adsorption (PSA), physical absorption, chemical absorption, membrane separation or cryogenic separation. Several upgrading technologies operate commercially, including membrane separation, water/chemical scrubbing and PSA. Anaerobic digestion and biogas upgrading to biomethane has been successfully demonstrated.

Process description	
Inputs	*Biowastes, lignocellulosic material*
Outputs	*Biomethane*
Process conditions	*Mild*

Technical development	
TRL	*9*
Plant example	*Commercial*

Catalytic methanation of syngas for SNG production

Methanation of syngas can be a short-term solution for Synthetic Natural Gas (SNG) production. Although methanation of gas from coal gasification has been demonstrated at large scale, biomass syngas methanation is challenging. In order to produce SNG in a reliable manner, gasification process conditions can be designed to optimize the syngas quality. The use of air as a gasification agent is not favourable due to the resulting high N_2 content in the syngas and thus, pressurized oxygen or indirect gasification are usually used. In the methanation reaction, carbon monoxide and hydrogen are catalytically converted to methane and water. The catalytic methanation is an exothermic conversion to methane and water using hydrogen and carbon oxides from syngas. This process operates at temperatures above 250°C and high pressures, using metallic catalysts. The catalysts used in methanation are very sensitive to impurities such as tars, ammonia, chlorine, sulphur compounds and particles, that cause poisoning and deactivation. Therefore, the catalytic methanation requires an intensive gas cleaning process of the raw syngas. The use of biocatalysts in syngas biomethanation is investigated as they show a higher tolerance to the impurities of syngas and operate at mild temperatures.

The molar ratio between hydrogen and carbon is adjusted using a WGS reaction before the first step of methanation. This reduces the overall efficiency of the process while increasing the complexity and the cost of operation. Carbon dioxide is another possible source of methane from the product gas and can be converted through the reaction between CO_2 and H_2 with Ni-based catalysts. Thus, complete conversion of the carbon stock in the product gas (CO and CO_2) can be achieved in case enough hydrogen can be supplied. The gas produced by methanation is a mixture of methane, carbon dioxide and water, with remaining traces of nitrogen, hydrogen and carbon monoxide. The remaining CO_2 in the gas is removed. ECN developed a pilot technology for producing SNG from biomass gasification that uses the conversion of hydrocarbons from the producer gas. The GoBiGas is a first-of-its-kind plant with production of SNG from woody biomass.

Process description	
Inputs	*Produced gas (syngas)*
Outputs	*Biomethane*
Process conditions	*Medium temperatures and high pressure with catalysts*

Technical development	
TRL	*7-8*
Plant example	*GoBiGas plant in Sweden*

Fast Pyrolysis & Thermo-Catalytic Reforming to drop-in fuels

Thermo-Catalytic Reforming (TCR) is a technology developed by Fraunhofer UMSICHT that combines intermediate pyrolysis with post catalytic reforming of the pyrolysis products in the absence of oxygen with the char produced acting as a catalyst. The TCR produces hydrogen-rich syngas, bio-oil with improved physical and chemical properties and bio-char. The catalytic reforming of pyrolysis products is the key difference from other existing technologies. The TCR technology consists of a two-stage reactor system. Intermediate pyrolysis takes place in the first reactor stage, the Auger reactor, at a temperature around 400°C, and it converts the feed to char and vapour (Hornung *et al.*, 2022). Catalytic reforming process takes place at high temperatures (600–750 °C) in the second stage reactor, which is the post-reformer, where char acts as a catalyst. Bio-oil production is thus possible without the need of extensive pre-treatment steps or expensive metals catalysts or zeolites (Ouadi *et al.*, 2017).

Because of the catalytic reforming at high temperatures, the bio-oil produced has higher quality compared to fast pyrolysis bio-oil. The TCR bio-oil has a higher energy content (35 MJ/kg), low oxygen content, low viscosity, and lower total acid number. These characteristics make the TCR bio-oil well suited for further downstream synthesis into liquid fuels (Ouadi *et al.*, 2017; Gill *et al.*, 2021). Hydrogen can be separated from the produced syngas and used together with bio-oil in the hydrotreatment (HDO) step to produce a hydrotreated bio-oil.

The hydrotreatment process is carried out at a temperature of around 260-400°C and up to 200 bar pressure where the TCR-oil is upgraded using the hydrogen from the plant process through the removal of sulphur, nitrogen and oxygen. The hydrotreated TCR bio-oil has a lower heating value of 42 MJ/kg and can be separated by distillation to produce gasoline and diesel fractions. The To-Syn-Fuel EU funded project aims to demonstrate at Hohenburg (Germany) the thermo-catalytic reforming (TCR®) combined with hydrogen separation through PSA, and HDO, to produce green hydrogen, renewable gasoline and diesel. By this, the TCR®/PSA/HDO technology will be validated at TRL-7.

Process description	
Inputs	*Lignocellulosic biomass to bio-oil*
Outputs	Renewable gasoline and diesel
Process conditions	*Medium temperatures and high pressure with catalysts*

Technical development	
TRL	*7*
Plant example	*To-Syn-Fuel Hohenburg, Germany*

Lignocellulosic biomass to FT fuels

Fischer-Tropsch (FT) synthesis can use syngas derived from biomass gasification, in which CO and H_2 gases react in the presence of a catalysts. FT can produce a variety of hydrocarbons, including gasoline and diesel. This requires a proper H_2/CO ratio and an adequate syngas treatment and conditioning. The FT reaction takes place over specialized catalysts and is essentially a highly exothermic dehydration reaction (Swanson *et al.*, 2010). The pressures used during the FT process range from 10 to 40 bar and the nature of the hydrocarbons produced is influenced by the temperatures and catalysts used. Higher temperatures (300–350 °C) and iron catalysts produce gasoline, while lower temperatures (200-240 °C) and cobalt catalysts produce diesel.

The ratio of H_2/CO also influences the product distribution with high ratios favouring the formation of lighter hydrocarbons. Iron catalysts favour the WGS reaction such that the H_2/CO ratio is increasing. After the production of FT liquids, further upgrading is required to produce finished fuels, most likely through hydrotreating, hydrocracking, isomerisation and fractionation. As FT liquids consist of a range of hydrocarbons, fractionation through distillation might also be carried out. Fischer-Tropsch is an established technology, and many components of the system are already proven and operational for decades in coal-to-liquid or gas-to-liquid plants. But the Biomass to Liquid BtL process remains unproven at a commercial scale due to several technical barriers which still need to be overcome (Sims *et al.*, 2010). Large plants are required to benefit from economies of scale both for the gasifier as well as the catalytic equipment, but this is often problematic for biomass installations due to biomass supply logistics. Further, efficient biomass pressurized gasification is still being investigated as well as hot syngas cleaning, specifically for efficient tar cracking and particulate removal at high temperatures.

Process description	
Inputs	*Lignocellulosic biomass*
Outputs	Renewable gasoline, diesel, jet fuel
Process conditions	*Medium temperatures and high pressure with catalysts*

Technical development	
TRL	*6-7*
Plant example	BioTfueL TOTAL

Lignocellulosic biomass to ethanol

Sugars obtained from sugar crops, starch crops and lignocellulose can be fermented into alcohols. Ethanol production from sugar and starch crops through fermentation is a well-established technology. Ethanol production from cellulosic material is considered the most promising option for future fuel ethanol production. Lignocellulose consists of cellulose (C6 sugar polymers), hemicellulose (C5 sugar polymers) and lignin (aromatic alcohol-polymers).

A pre-treatment is first applied on the raw material before saccharification to separate the different elements. Once the cellulose and the hemi-cellulose are separated from the lignin, saccharification of these polysaccharides can take place, through enzymatic hydrolysis (cellulases and hemi cellulases).

The C6 sugars can be fermented by common yeasts while C5 sugars need specific microorganisms. Lignin is usually separated and dried to be used as a fuel for the process or for power generation. The fermentation of C5 sugars (pentose) is not as developed as the process for C6 sugars. For the fermentation of C5 sugars, genetically modified yeasts have been developed in the recent years. The typical alcohols produced are ethanol, n- or i-butanol. Some bacteria naturally produce butanol and yeast can be engineered to produce butanol instead of ethanol. The development of effective pre-treatment methods, more efficient enzymes and the effective conversion of pentose sugars remain considerable challenges.

Currently, the process of ethanol production from lignocellulosic materials is not yet fully commercial, although there are demo plants which are at commercial scale. Recovery/extraction of solvents is accomplished by the following methods: gas stripping, liquid-liquid extraction, evaporation, adsorption or membrane separation technology (JRC, 2011). Globally, there are several first-of-a-kind commercial scale lignocellulosic ethanol plants, some of which are in the process of commissioning or ramping up to full scale operation. However, some of the plants are currently idle or on hold.

Process description	
Inputs	*Lignocellulosic material*
Outputs	*Ethanol*
Process conditions	*Mild*

Technical development	
TRL	*7-8*
Plant example	*Clariant Podari, Romania,* Versalis Crescentino

Aquatic biomass to advanced biofuels

Possible advanced liquid biofuel or biomethane pathways from algae include their conversion to biogas (and then to biomethane), bio-alcohols, bio-oils, biodiesel, renewable diesel and gasoline and bio-hydrogen. These include various processes such as oil extraction, biochemical (AD, fermentation, etc.) and thermo-chemical conversion (pyrolysis, hydrothermal liquefaction) technologies.

The high content of moisture and carbohydrates in algae make them suitable for biological processes (i.e. wet conversion pathways), including anaerobic digestion and fermentation to biomethane or bio-alcohols. The extraction of oil from algae can be performed through chemical solvent extraction (dry biomass, 60 - 98 %) and supercritical fluid extraction (wet biomass 10 - 25 %). Further processing options include either transesterification to produce biodiesel or hydrotreating the oils to produce renewable diesel.

Algae can be used for bio-oil or bio-crude production through thermochemical conversion pathways that include HTL of algae or pyrolysis of dry algae. A major limitation for thermochemical processing of algae (in particular pyrolysis) is their high moisture content (70-80 %), requiring significant energy for drying. Hydrothermal liquefaction is better suited for algae due to the very low algae concentration. The partial dewatering of algae solutions to the level of 10-20% dry solids, adequate for HTL, is less energy intensive than pyrolysis that requires drying to >90% dry solids. The bio-oil and bio-crude require significant upgrading and additional processing into final fuel through catalytic hydrotreatment and catalytic cracking.

Algae can be used for bio-hydrogen production via photo fermentation or dark fermentation by means of a pure or mixed culture of hydrogen-producing bacteria or via a combination of dark, photo fermentation and AD in three stage processes. The integration of algae production with wastewater treatment is a feasible pathway for the large-scale production of algae, providing opportunities for the treatment of waste streams and the use of organic substrate such as nutrients (N, P) from wastewater (Redwood, Paterson-Beedle and Macaskie, 2009; Rocca *et al.*, 2015).

Process description	
Inputs	*Aquatic biomass (algae)*
Outputs	*Ethanol*
Process conditions	*Mild*

Technical development	
TRL	*3-4*
Plant example	

Getting in touch with the EU

In person

All over the European Union there are hundreds of Europe Direct centres. You can find the address of the centre nearest you online (european-union.europa.eu/contact-eu/meet-us_en).

On the phone or in writing

Europe Direct is a service that answers your questions about the European Union. You can contact this service:

— by freephone: 00 800 6 7 8 9 10 11 (certain operators may charge for these calls),

— at the following standard number: +32 22999696,

— via the following form: european-union.europa.eu/contact-eu/write-us_en.

Finding information about the EU

Online

Information about the European Union in all the official languages of the EU is available on the Europa website (european-union.europa.eu).

EU publications

You can view or order EU publications at op.europa.eu/en/publications. Multiple copies of free publications can be obtained by contacting Europe Direct or your local documentation centre (european-union.europa.eu/contact-eu/meet-us_en).

EU law and related documents

For access to legal information from the EU, including all EU law since 1951 in all the official language versions, go to EUR-Lex (eur-lex.europa.eu).

EU open data

The portal data.europa.eu provides access to open datasets from the EU institutions, bodies and agencies. These can be downloaded and reused for free, for both commercial and non-commercial purposes. The portal also provides access to a wealth of datasets from European countries.

Science for policy

The Joint Research Centre (JRC) provides independent, evidence-based knowledge and science, supporting EU policies to positively impact society

EU Science Hub
Joint-research-centre.ec.europa.eu

Publications Office
of the European Union