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ADVANCED BIOFUELS IN THE EUROPEAN UNION

2022

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

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Contents

Abstract

This report presents an assessment of the state of the art of key technologies for advanced biofuels production. Advanced biofuels are those fuels produced using only feedstocks which have no direct or indirect land use change.

Commercial pathways exist to produce Advanced Biofuel (e.g., anaerobic digestion to biomethane, hydrogenated vegetable oil, lignocellulosic ethanol production), but with very limited installed capacity (0.43 Mt/y) and production (1.85 Mt/y). A variety of innovative technologies such as biomass gasification to Fischer–Tropsch synthetic fuels and biomethanol production have been demonstrated in an industrial environment and are ready to take-off. Also some next generation technologies are making progress.

The main challenges are currently the high capital expenditure needed and the availability of sustainable biomass feedstock. There is potential for a 25-40% cost reduction through R&I, and a 50% further reduction by large scale deployment and co-processing feedstocks in existing (fossil fuel) plants.

Private R&I biofuels funding was on average EUR 250 million per year in the period 2010-2021, dominated by the US and Canada, with an EU share of only 6% in the last five years. However, for high-value patents the EU is leading with twice as many as the US. EU based companies Neste Oy (with 39 inventions) and Novozymes (with 13 inventions) are in the first and third position of the top 10 entities for patenting globally.

Concerning the value of all biofuels to the economy, it has a EUR 2.3 billion direct contribution impact to the EU GDP, and provides 250 000 direct and indirect jobs along the value chain. 29% of innovative companies are based in the EU, behind the US and Japan.

The sector of advanced biofuels is just emerging and the number of commercial plants is still quite low. The EU is the world leader with 19 out of 24 operational, commercial plants of advanced biofuels, with Sweden and Finland having the highest number (12).

International trade concerns all biofuels and is nearly inexistent for advanced biofuels. As a whole biofuel imports to the EU have constantly increased since 2014, with EU's biofuel trade deficit above EUR 2 billion in 2021, mainly due to imports from Argentina, China and Malaysia

Foreword

This report is an output of the Clean Energy Technology Observatory (CETO). CETO's objective is to provide an evidence-based analysis feeding the policy making process and hence increasing the effectiveness of R&I policies for clean energy technologies and solutions. It monitors EU research and innovation activities on clean energy technologies needed for the delivery of the European Green Deal; and assesses the competitiveness of the EU clean energy sector and its positioning in the global energy market.

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Executive Summary

Renewable fuel technologies can contribute significantly in the short (and medium) term to the decarbonisation of transport, to ensuring security of energy supply and energy diversification. Advanced biofuels are produced from feedstocks that don't induce direct or indirect land use change (and competition with food and feed).

The Fit for 55 legislative proposals increase the targets for the shares of advanced biofuels and renewable fuels of non-biological origin (set in the revised RED II proposal) considerably. REPowerEU proposes to further increase required renewable fuel quantities. It also identifies biomethane as key to diversify the EU gas supplies by increasing its production twice above the EU 2030 target, thus putting biomethane on top of renewable energy priorities. For the aviation and maritime sector where in 2030 electrification is expected to be negligible, the REFuelEU Aviation and FuelEU Maritime proposals project that renewable fuels supply 5% and 6.5% of total EU jet and shipping fuel consumption.

Technology analysis: Commercial pathways do exist (e.g., anaerobic digestion to biomethane, hydrogenated vegetable oil, lignocellulosic ethanol production), but without significant installed capacity (currently 0.43 Mt/y) and with limited planned production (1.85 Mt/y). A variety of innovative technologies such as biomass gasification to Fischer–Tropsch synthetic fuels and biomethanol production, which have been demonstrated in industrial environment, are ready to take-off and some next generation technologies are making progress. Technologies for other renewable synthetic fuels (solar fuels, microbial fuels and micro-algae fuels) are mostly at lab-scale.

Value chain analysis: The main challenges for the market uptake of advanced biofuels are their lack of cost competitiveness with existing conventional biofuels derived from food crops and fossil fuels (estimated at 1.5 to 3 times the market price), high capital expenditures and the availability of sustainable biomass feedstock. There is a significant potential of 25-40% for cost reduction through R&I, and 50% further reduction by large scale deployment and co-processing in existing plants.

EU public funding: Concerning the European funding within Horizon 2020 (and Horizon Europe), the countries with the highest number of projects are those where biofuel production is strong: Germany, UK, Netherlands, Italy and Spain. Finland, France, Belgium, Sweden and Austria are also participating heavily in projects, due to their feedstock availability or history of biofuels production. The projects treat most of the described technologies, with a focus on gasification and fuel synthesis, but also including biogas, pyrolysis, fermentation and hydrothermal liquefaction. The 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 two projects for support (FirstBio2Shipping, and Waga 4 World) with a contribution of EUR 133 million.

Private R&I biofuels funding was on average EUR 250 million per year in the period 2010-2021, dominated by the US and Canada, with an EU share of only 6% in the last five years. However, the EU is leading with twice more high-value patents than the US. China is holding most low innovation patents and invention flows are increasing from EU to US and China. From 2009 to 2019 EU and US has kept constantly the lead in terms of high value inventions averaging both reaching more than 200 inventions each in 2012. For the triennium 2017-2019 EU had 65% share of high-value patents for a total 532 patents application, while China applied for total 3130 patents with only 2% high-value. For the triennium 2017-2019, at country level US is the leading country with 176 high-value patents, while France and Finland follow with 78 and 69 patents application. EU based companies Neste Oy with 39 inventions and Novozymes with 13 inventions are in the first and third position of top 10 world entities High Value inventions ranking for the triennium 2017-2019. The inventions granted decreased in the triennium 2017-2019 from total 558 in 2017 to 268.8 in 2019, China leads this category with share 53% in 2017 and 56 % in 2019.

Scientific publications: Worldwide, publications on advanced biofuels have increased from around 60 articles per year to around 140 articles per year in the last 10 years. The European Union took a leading place at the same time, with the U.S. decreasing their publication activity and the "rest of the world" increasing theirs sharply. The share of highly cited articles is around 20% on average over the whole period since 2010, a bit higher for the UK and China and lower for the U.S. and the "rest of the world". Within the European Union, Italy and Spain tripled their publications in that period to about 10 publications per year (moving average over 3 years to eliminate the inter-year noise), followed by Germany and Poland. The Netherlands lost their clear leading position, but are still publishing around 5 papers a year, as do the Czech Republic and Finland. The share of highly cited papers is above 30% for Sweden and the Netherlands, and around 20% for the other countries with high publication numbers.

Global market analysis: EU shares roughly 7% of the global biofuel market worth EUR 100 billion in 2020, mostly generated from first generation biodiesel. In 2018 the turnover reached a peak at EUR 14.4 billion mostly generated in France, Germany and Spain. Beyond a EUR 2.3 billion direct contribution impact to the EU GDP, 250,000 direct and indirect jobs were created along the value chain. The EU shares 29% of innovation companies, while the US and Japan have the most.

The sector of advanced biofuels is just emerging, the number of commercial plants is still quite low, and international trade is very limited. The EU is the world leader with 19 out of 24 operational, commercial plants of advanced biofuels, with Sweden and Finland having the highest number (12).

International trade concerns all biofuels and is nearly inexistent for advanced biofuels. EU biofuel imports have constantly increased since 2014, with a trade deficit above EUR 2 billion in 2021, mainly due to imports from Argentina, China and Malaysia. The Netherlands and Germany are the biggest EU and global biofuel exporters.

In conclusion, despite the fact that the installed and planned production capacity of advanced biofuels for 2030 is negligible compared to total fuel use, and the potential of advanced biofuels from sustainable feedstock in the EU is limited, they can contribute to the Fit for 55 GHG emission savings targets, covering sufficiently any transport electrification lag. In order to fully realise the potential of renewable fuels in transport, certain technical and economic risks must still be overcome. The cost of all renewable fuels and, in particular, of synthetic, are still high because they rely on renewable energy and hydrogen prices. Yet, advanced biofuels rely on local sustainable biomass resources and short supply chains creating many skilled jobs, reducing energy poverty and driving industrial competitiveness. The EU is the clear market leader in operational, commercial plants of advanced biofuels and high-value innovations, with EU companies currently among the world's top 10 but at risk of losing technological leadership due to the lack of private funding.

SWOT analysis:

Strengths	**Weaknesses**
• several technologies are available and getting close to commercialisation • only available option nowadays for the (complete) decarbonisation of hard to decarbonise sectors such as aviation, shipping and heavy road freight transport • can be produced from a wide range of feedstocks available in large amounts • 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 technical modifications in the engine • high greenhouse gas emission reduction potential	• several technologies are not yet demonstrated in commercial operation • limited feedstock resources from residues and waste • advanced fuels can only be produced at 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 diversification and energy security • contribution to decarbonisation of transport and the reduction of dependency on fossil fuel imports	• high technology 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

• synergies between fuels and chemicals production • employment and business opportunities along the supply chain • driver of agriculture, forestry and industrial development in rural areas and diversification of the rural economy • enable circular economy through use of energy in biogenic waste streams • contribution to the remediation of marginal and degraded land	• failure to reach cost competitiveness through technology improvement • lack of stable policy framework, lack of long term policy perspectives and change in policy directions • low public awareness, public perception and public acceptance • lack of adequate incentives for large scale deployment (including for biomass supply chains)

1 Introduction

This study builds on the Technology Development Report on sustainable advanced biofuels (PADELLA *et al.*, 2020) and updates it.

Advanced biofuels are those fuels produced using only specific feedstocks which have no indirect land use change iLUC. For example, used cooking oils, waste lipids, residual biomasses, wastes and their derived bio-intermediates (e.g. biocrudes produced from lignocellulosic material) can be used as feedstock to produce advanced biofuels for the EU market. According to the Renewable Energy Directive (RED II) 2018/2001 (The European Parliament, 2018), it is possible to produce such fuels if the initial feedstock is listed in the Annex IX part A/B of the directive. The list includes many types of wood- and agro- residues, animal manure, sewage sludge, and algae, as well as other biowaste-derived materials. The European Commission may adopt specific delegated acts to expand this list based on scientific advice, while it may not remove items.

Moreover, advanced biofuels targets have been recently updated by the European Commission 'Fit-for-55' package amending the former RED II and setting the new frameworks towards 2030. This revision includes large modifications such as the main 14% target for renewable energy in transport (as set by RED II) has been replaced by a new 13% GHG intensity reduction target for 2030. Moreover, the updated target for advanced biofuels sets a new target at 2.2%, which might appear to be lower than the 3.5% proposed in the RED II, but as it also excludes the use of multipliers, it results in real target that guarantees equal volumes of renewable fuels replacing fossil fuels. The only multiplier maintained is based on a figure of 1.2x for advanced biofuels and Renewable Fuel Non-Biological Origin RFNBOs in aviation and maritime sectors. Moreover, the contribution of biofuels produced from the feedstocks defined in Annex IX, part B, including used cooking oil and category 1 and 2 animal fats, is limited to 1.7%, with an option for Member States to request higher caps depending on national feedstock availability.

As regards the sustainability issues, according to the criteria set by RED II, such fuels are required to pass a Green House Gas GHG reduction threshold 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 ReFuel EU and FuelEU Maritime initiatives, which set a target of 63% of Sustainable Aviation Fuel SAFs and -75% as GHGs reduction intensity respectively, by 2050.

According to RED II (ANNEX IX Part A), fuels produced from the following feedstocks can be considered as advanced biofuels.

(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, tree tops, saw dust, cutter shavings, black liquor, brown liquor, fibre sludge, lignin and tall oil;

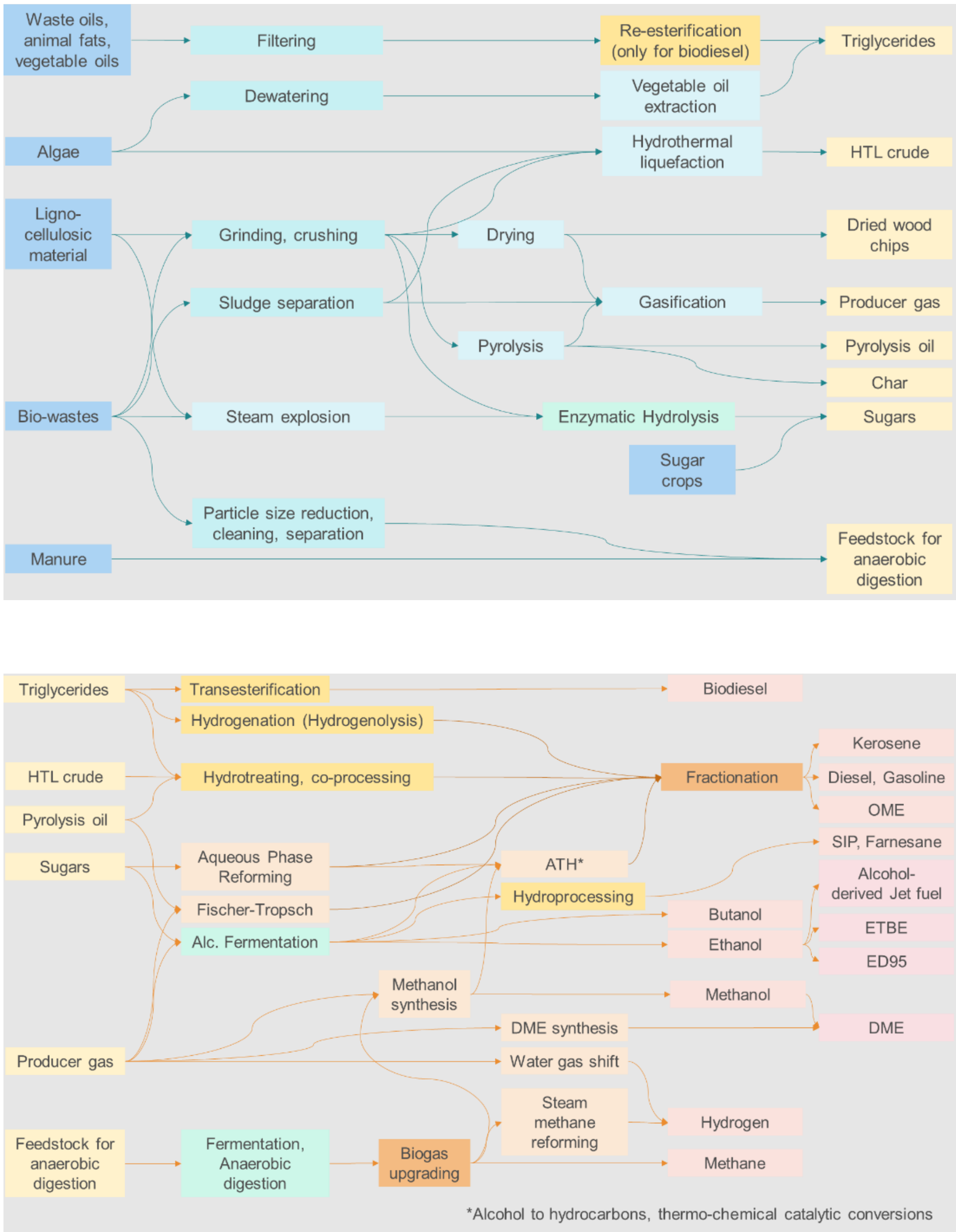
(p) Other non-food cellulosic material;

(q) Other lignocellulosic material except saw logs and veneer logs.

Advanced biofuels from biomass can be transformed 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.

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



Source: JRC analysis

Color 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

2 Technology State of the art and future developments and trends

2.1 Technology readiness level (TRL)

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 above. Below, the most promising pathways are summarized.

Recycled carbon fuels (RCFs) can be produced by the same pathways as described below, notably:

- RCF from industrial or biogas off-gases 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

TRL will be provided 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, 2022) with some exceptions.

2.1.1 Intermediate Bioenergy carriers

In this section, technologies to obtain Intermediate Bioenergy Carriers (IBC) are 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.

2.1.1.1 Pretreatment and enzymatic hydrolysis to sugars

Lignocellulosic material can be converted to sugars through pretreatment and enzymatic hydrolysis. Its conversion requires: a) pretreatment, 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. Pretreatment converts biomass into a more accessible form for hydrolysis through mechanical, physical-chemical, chemical and biological methods. Several processes can be used, including physical processes (steam explosion, thermohydrolysis), chemical (acid hydrolysis, alkaline hydrolysis, organic solvolysis or biologic) and combined (catalysed steam explosion, ammonia or CO_2 explosion). Steam explosion is the most widely used pretreatment technology, involving high-pressure steam at high temperature for a short time, followed by rapidly depressurization. The next step, which is also part of the pretreatment, consists of lignin removal and hydrolysis of the hemicellulose. However, the process needs a lot of energy and leads to the creation of byproducts that inhibit downstream fermentation (IRENA, 2016). Other pretreatment options include acid or alkali treatment, or solubilisation with solvents, e.g. organic solvolysis. Overall, this 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 high 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 offer 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*

2.1.1.2 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. The characteristics of bio-oil (highly acidic, high viscosity and high-water content) make it difficult to store and process it (Karatzos et al., 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 (Bridgwater, 2012, Attia et al., 2019). 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 very limited (IRENA, 2016).

Process description	
Inputs	*Mechanical and thermally pre-treated biomass (i.e., drying, fragmentation).*
Outputs	*Pyrolysis oil, biochar and hydrogen*
Process conditions	*Heating in absence of oxygen*

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

2.1.1.3 Gasification of biomass and pyrolysis oil to syngas

Gasification is a high-temperature (700-1500 ºC) 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, fluidisedbed 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 (IEA, 2014b, Gasification Guide, 2010). Gasification process conditions can be designed to optimize the syngas quality. For the production of 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) (IEA, 2014c). 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); pyrolysis oil and other biocrudes; 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*

2.1.1.4 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 el al 2018, Reißmann et al 2018, Pasu 2018). The bio-crude has high heating value (30–37 MJ/kg), considerably 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 (Chen 2017, Matayeva 2019, Zhu 2019). Biocrude quality depends on the feedstock type and operating conditions – temperature, solvent type, 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 et al. 2018, Kumar et al 2018).

Biocrude upgrading techniques include steam reforming, sub/super-critical fluid treatment, cracking (hydrocracking, zeolite cracking, thermal cracking) and hydrotreating. Cracking is one of the major processes in oil refining, that can be used to upgrade biocrude 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 high temperature and moderate pressure to convert them into saturated hydrocarbons (Chen 2017, Attia 2020, Hao 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 (Chen, 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*

2.1.1.5 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 et al 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 from microalgae 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	

2.1.1.6 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 like 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. Pretreatment 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)

2.1.2 Fuel synthesis and upgrading

2.1.2.1 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	*9*
Plant example	*La Mede (Total)*

2.1.2.2 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 (Alemany et al 2018, Paniagua et al 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 (Alemany et al 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	*4-6*
Plant example	

2.1.2.3 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 & Khanal, 2010). Acetogenic bacteria convert CO, H_2 and CO_2 derived from biomass or waste materials into acetic acid (Drake et al 2008). Gases can originate from industrial waste off gases 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 (Philips et al 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 can 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)*

2.1.2.4 Aqueous Phase Reforming of sugars to hydrogen

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	

2.1.2.5 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	

2.1.2.6 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 & 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 & 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 biocrudes; 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*

2.1.2.7 Methanol to Gasoline synthesis

An interesting option to produce 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 produces 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 a 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	

2.1.3 Promising pathways

2.1.3.1 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 aqueous biomass (micro and macro algae) (EPA and NREL 2009). 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, under the EU funding programme NER300. The existing reactors generally show methane yields above 50%.

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. The number of biomethane plants in Europe reached 880 in 2020 with a production of 3 billion m^3 biomethane in comparison to a total biogas production of 18 billion m^3.

Process description	
Inputs	*biowastes, lignocellulosic material*
Outputs	*biomethane*
Process conditions	*mild*

Technical development	
TRL	*9*
Plant example	*commercial*

2.1.3.2 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 Austria*

2.1.3.3 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. 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 pretreatment 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 LHV 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	*6-7*
Plant example	*To-Syn-Fuel Hohenburg, Germany*

2.1.3.4 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

2.1.3.5 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 pretreatment 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 pretreatment 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

2.1.3.6 Aquatic biomass to advanced biofuels

Possible biofuel pathways from algae include their conversion to biogas, bioalcohols, bio-oils, biodiesel, renewable diesel 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 carbo-hydrates in algae make them suitable for wet conversion methods, including anaerobic digestion and fermentation to biomethane or bioalcohols. 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 the high moisture content (70-80 %) of algae, 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 et al, 2009, Murphy et al, 2015, Rocca et al. 2015).

Process description	
Inputs	*aquatic biomass (algae)*
Outputs	*ethanol*
Process conditions	*mild*

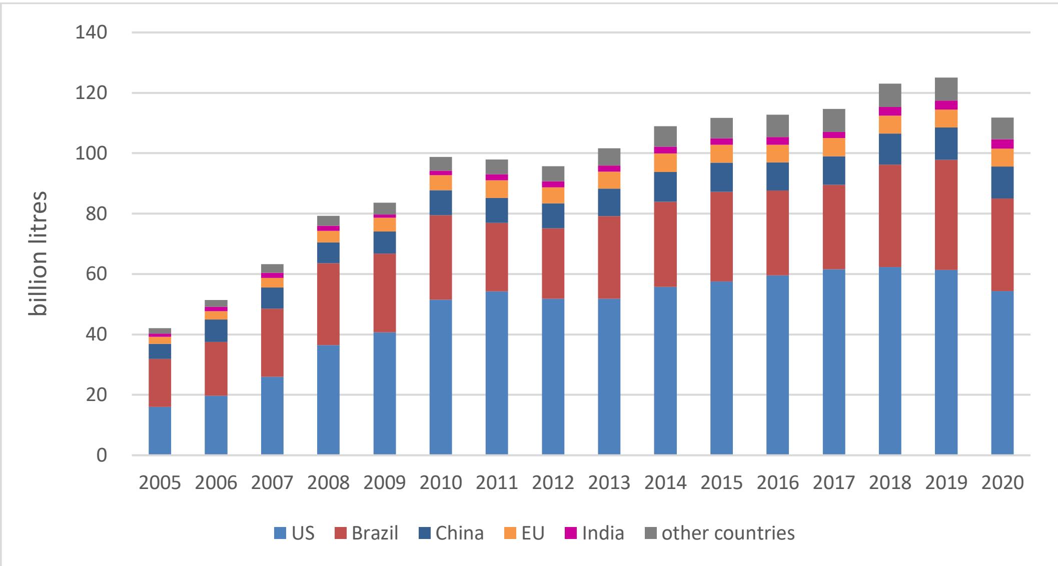
Technical development	
TRL	*3-4*
Plant example	

2.2 Installed energy Capacity, Generation/Production

2.2.1 Global biofuel production

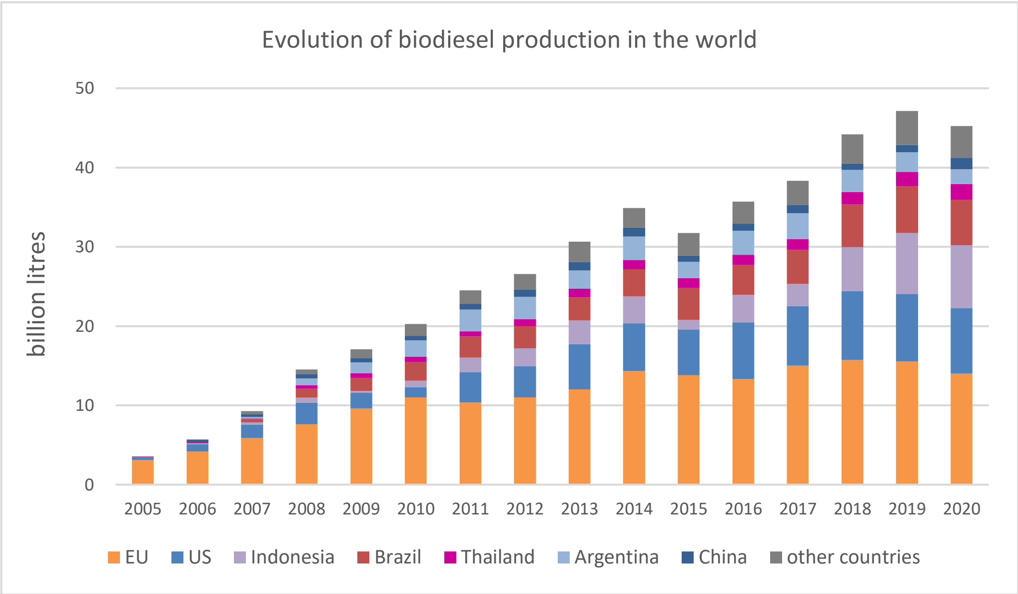
In EU, the definition of advanced biofuels is a political decision based on specific feedstock categories, while in the rest of the World, generally this classification is based on the technology deployed. Differently, the elaborations on biofuels volumes are generally divided per biofuel class, or sometimes per feedstock category. This results in a challenging classification for the EU advanced biofuels eligible for the RED II targets. Therefore, the aim of this chapter is a quick investigation on statistics on the global production of biofuels and then on the current advanced biofuels contribution to biofuel supply. It is reasonable to assume that currently the part of advanced biofuels in the overall production lies below 1%, given that the most ambitious goal for advanced biofuels is a 0.2% share in 2022 in the EU. The global biofuel production has increased from 45 to over 170 billion litres from 2005 to 2019, with a sharp increase from 2005 to 2011 (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 (see Figure 2). Biodiesel production at global level steadily increased from 2005 to 2014 from around 4 billion litres/year to 35 billion litres/year. After a fall to around 32 billion litres/year in 2015, the production started to increase again and passed the 40 billion litres/year from 2018 (see Figure 3).

Figure 2. Evolution of ethanol production in the world



Source: (OECD, 2022a)

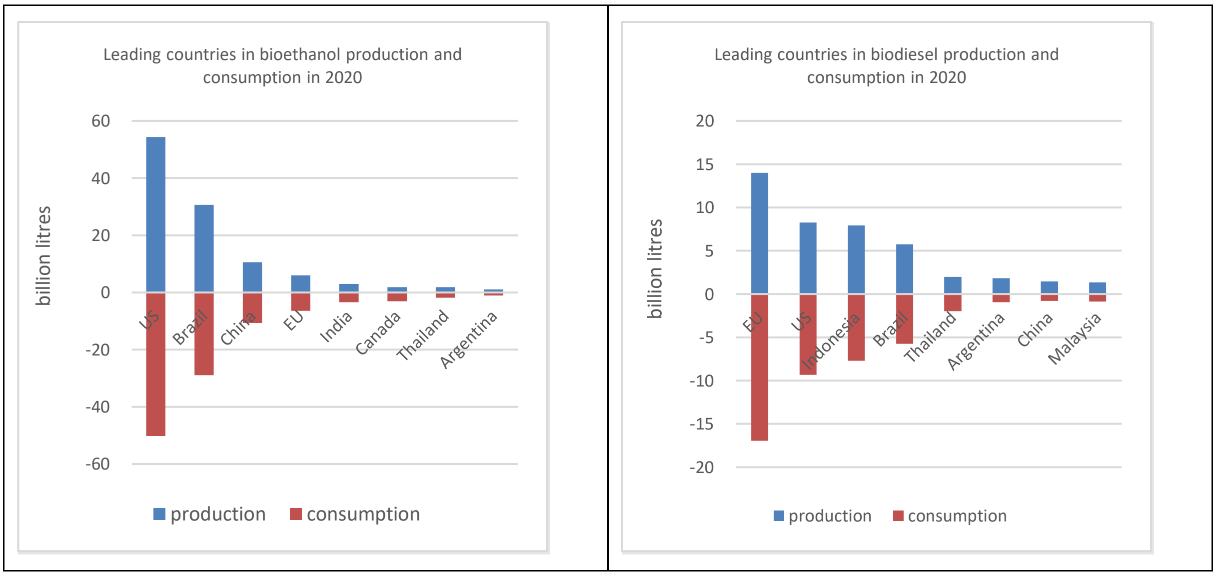
Figure 3. Evolution of biodiesel production in the world



Source: (OECD, 2022a)

For the bioethanol sector, the lead global producer and consumer countries are US and Brazil, for the Biodiesel EU is lead producer and consumer (see Figure 4).

Figure 4. Leading countries in bioethanol production and consumption in 2020

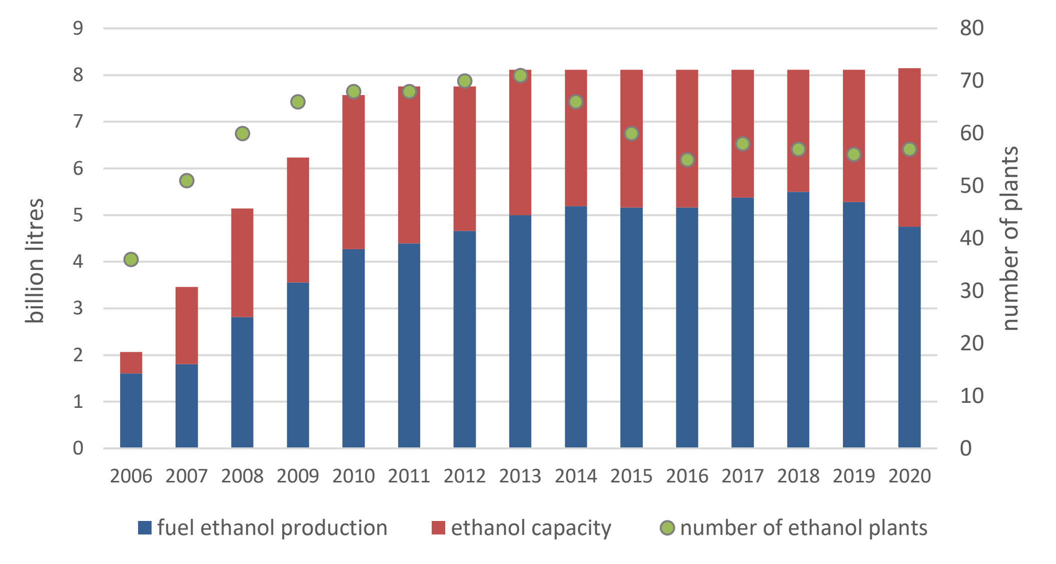


Source: (OECD, 2022b)

2.2.2 Biofuel production EU

As shown in Figure 5, the ethanol production in EU, after growing from 1.6 billion litres to 5.2 between 2006 and 2014, remained at around this level until 2020. On average the production stays below 60% of nominal capacity.

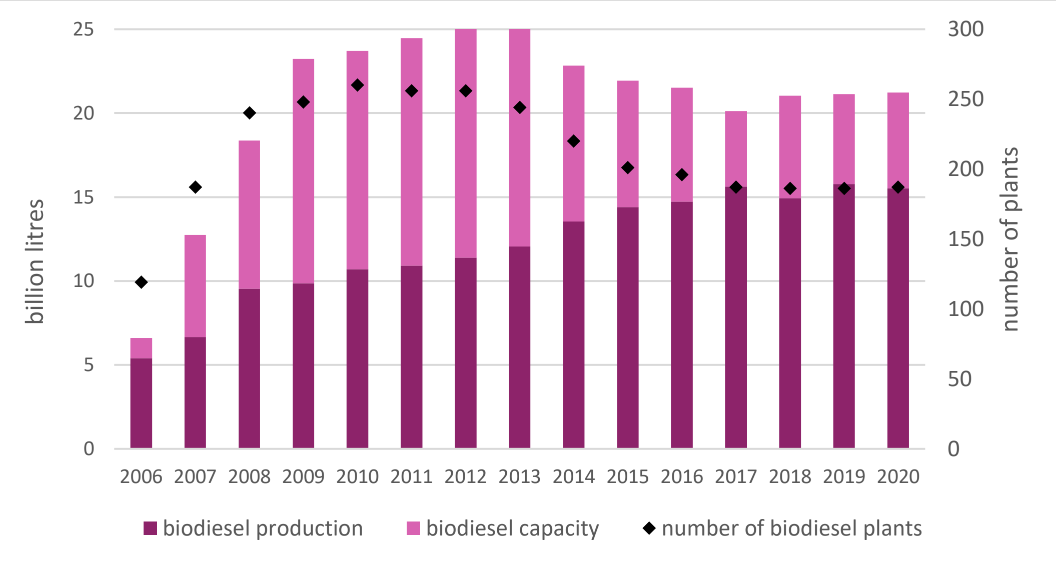
Figure 5. Evolution of ethanol production and capacity in the EU



Source: (USDA Foreign Agricultural Service et al., 2021)

Figure 6 shows the remarkable biodiesel production capacity increase in EU between 2006 and 2012, from 7 billion litres/year to 25 billion litres/year, while the actual production was around 50% of nominal capacity in 2013 and has raised to 78% in 2020.

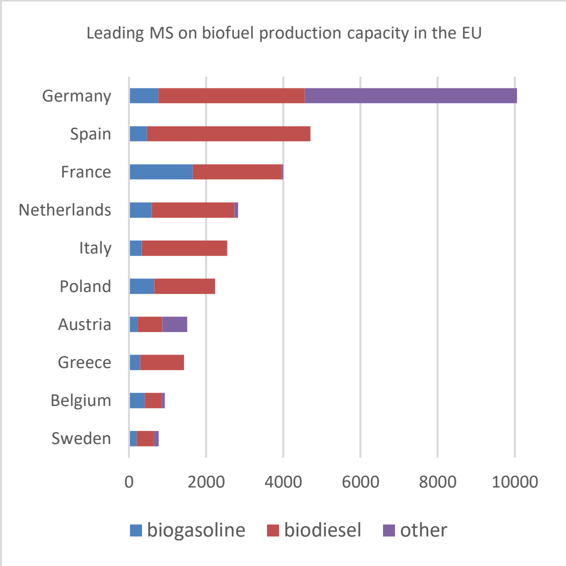
Figure 6. Evolution of biodiesel production and capacity in the EU



Source: (USDA Foreign Agricultural Service et al., 2021)

In 2020 the biofuel production in leading EU member states is resumed in Figure 7.

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



Source: (USDA Foreign Agricultural Service et al., 2021)

The following Table 1 shows projects and operational plants in EU for advanced biofuels. There are two commercial plants (TRL 9) producing pyrolysis oil and biomethanol, and several first-of-a-kind plants (TRL 8) producing pyrolysis oil, bioethanol and biomethanol and FT liquids. The combined production capacity of those plants is a bit above 1 billion litres per year (compared to the roughly 20 billion litres of bioethanol and biodiesel produced in the EU in 2020, as shown above).

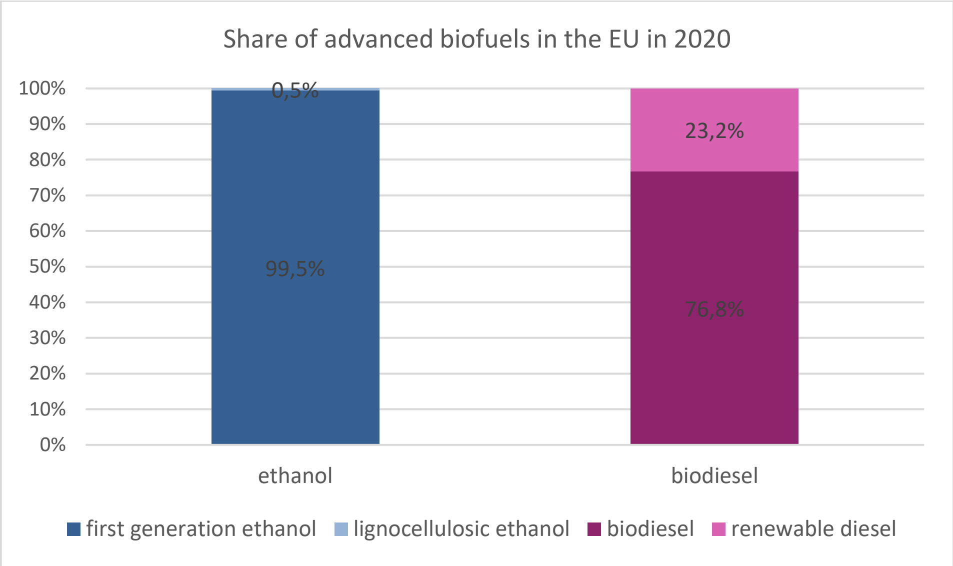
Table 1. Advanced biofuel plants in Europe operational or planned

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		6-7	Transport fuel intermediates from thermolytic processes	bio-oil (3,200 t/y)	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	Vaermland smetanol	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	

Source: (BEST GmbH, 2022)

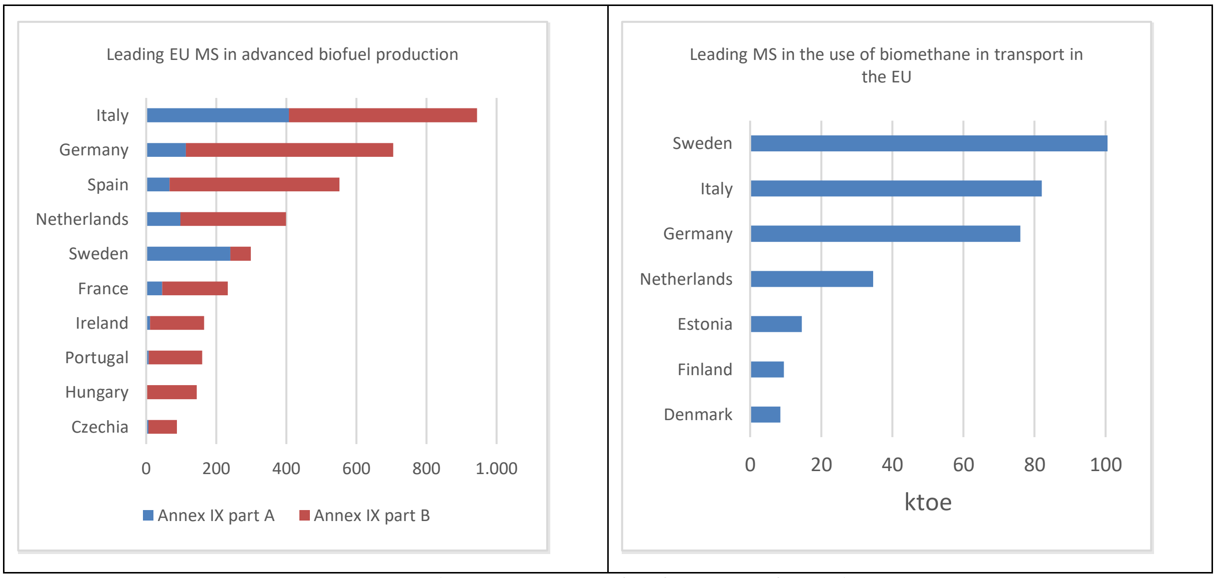
As shown in Figure 8 the share of advanced Biodiesel in the total biodiesel use in EU reached 23.2% in 2020, mainly due to the use of used cooking oil (UCO). Advanced ethanol was at only 0.5% (see Figure 8). For biofuel produced using feedstock listed in RED II Annex IX, Italy and Germany are the leaders in EU for the year 2020, Italy with 400 ktoe/year leads Annex IX part A, and Germany with 600 ktoe/year leads Annex IX part B (see Figure 9).

Figure 8. Share of advanced biofuels in biofuel use the EU in 2020



Source: (USDA Foreign Agricultural Service et al., 2021), p.4

Figure 9. Leading EU MS in advanced biofuel production 2020



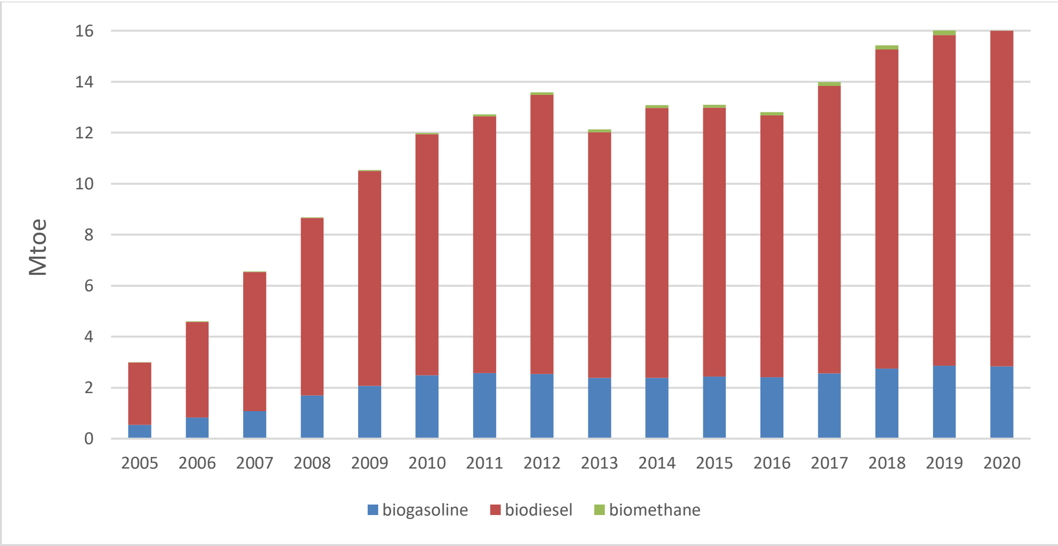
Source: (USDA Foreign Agricultural Service et al., 2021)

2.2.3 Biofuel consumption

The consumption data is given in tonnes of oil equivalent (toe). One toe corresponds to approximately 2 000 l of ethanol and 1 300 l of biodiesel. The biofuel consumption in EU transport sector was 13 Mtoe in 2015 and reached 16 Mtoe in 2019, biodiesel has around 80% of share (see Figure 10). The use of advanced biofuel has been increasing in the last years and was slightly above 4 Mtoe in 2020 at around 25% of total biofuel consumption (Figure 11). Germany was by far the main biofuel consumer in Europe in 2020, with almost 3.5

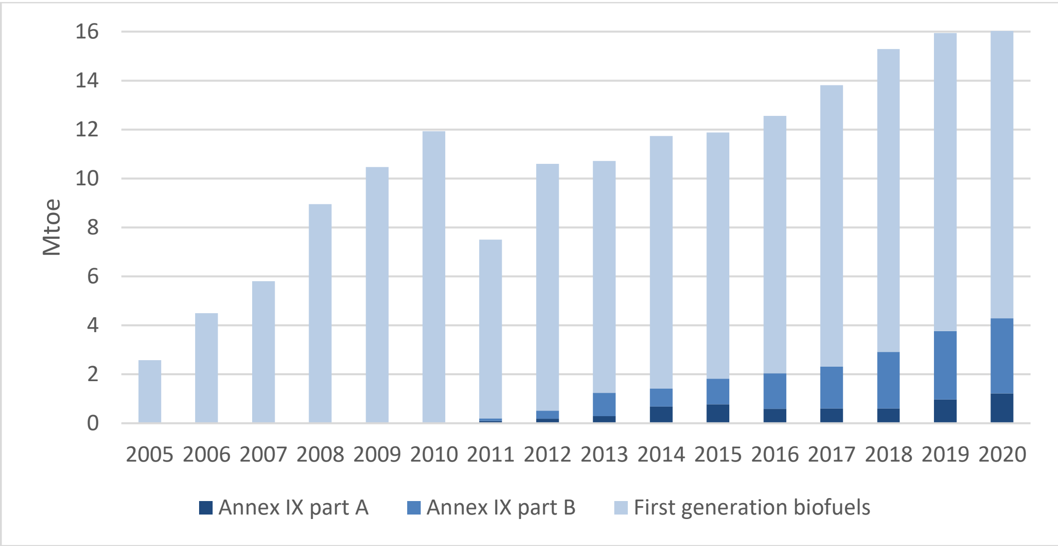
Mtoe, followed by France with more than 2.5 Mtoe consumed (Figure 12), while most of countries are still under 0.5 Mtoe.

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



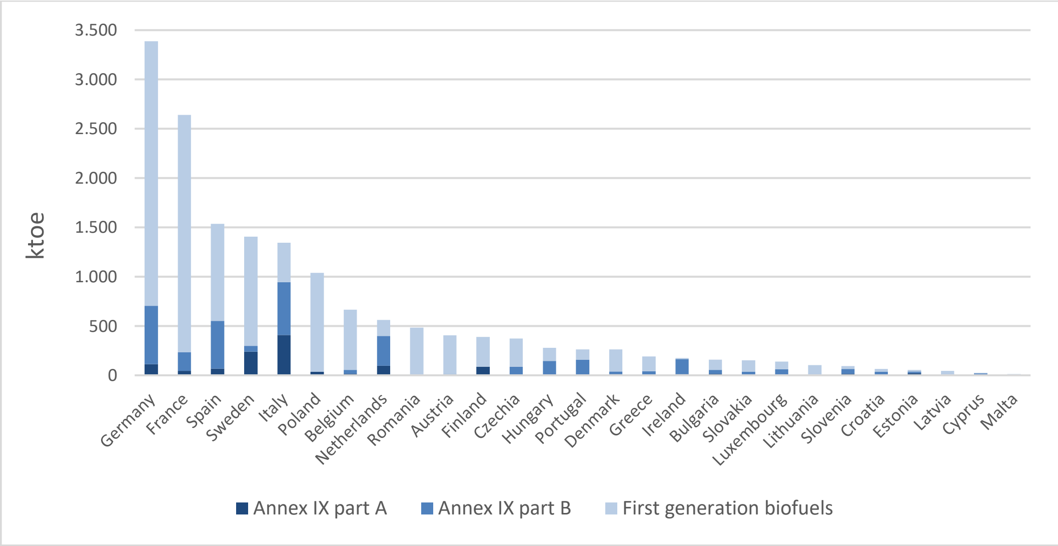
Source: (USDA Foreign Agricultural Service et al., 2021)

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



Source: (OECD, 2021)

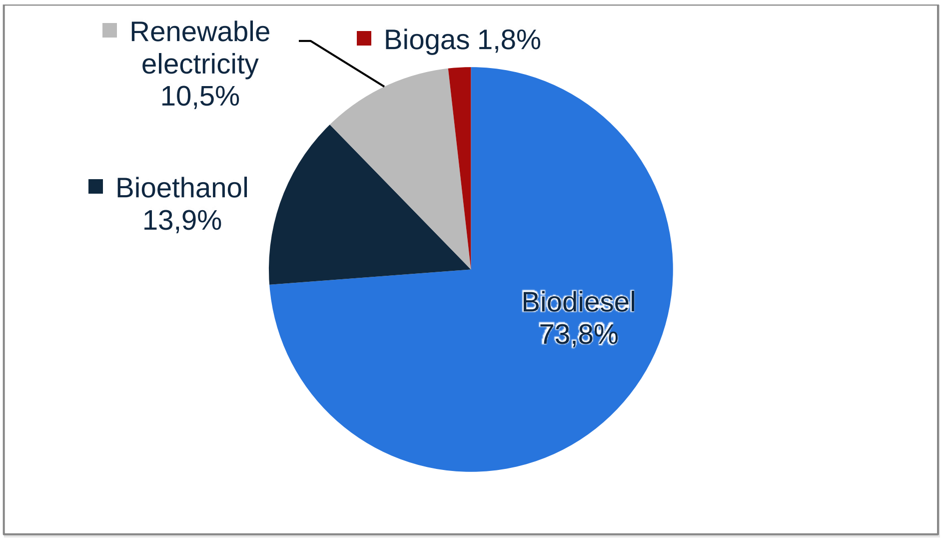
Figure 12. The use of biofuel, including advanced biofuels in MS of the EU



Source: (OECD, 2021)

When we consider also the renewable electricity share used in the transport sector in EU, biodiesel still had a share of 73.8% in 2020 (see Figure 13).

Figure 13. Distribution of renewable energy by fuel used in EU, 2020

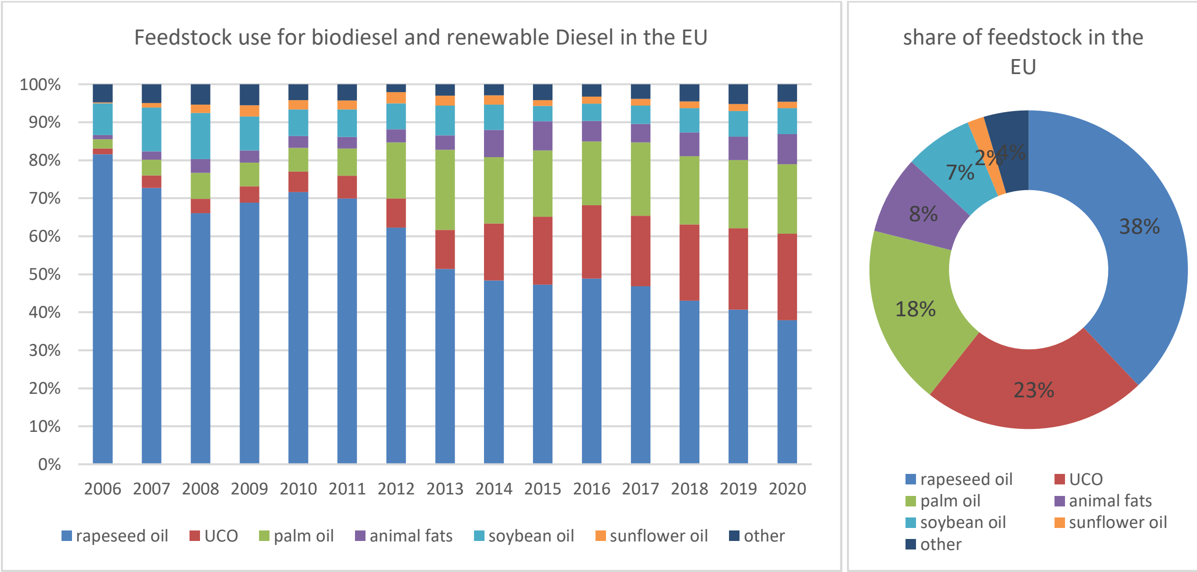


Source: (EurObserv-ER, 2021), p.17

2.2.4 Feedstock Use and Co-products Production

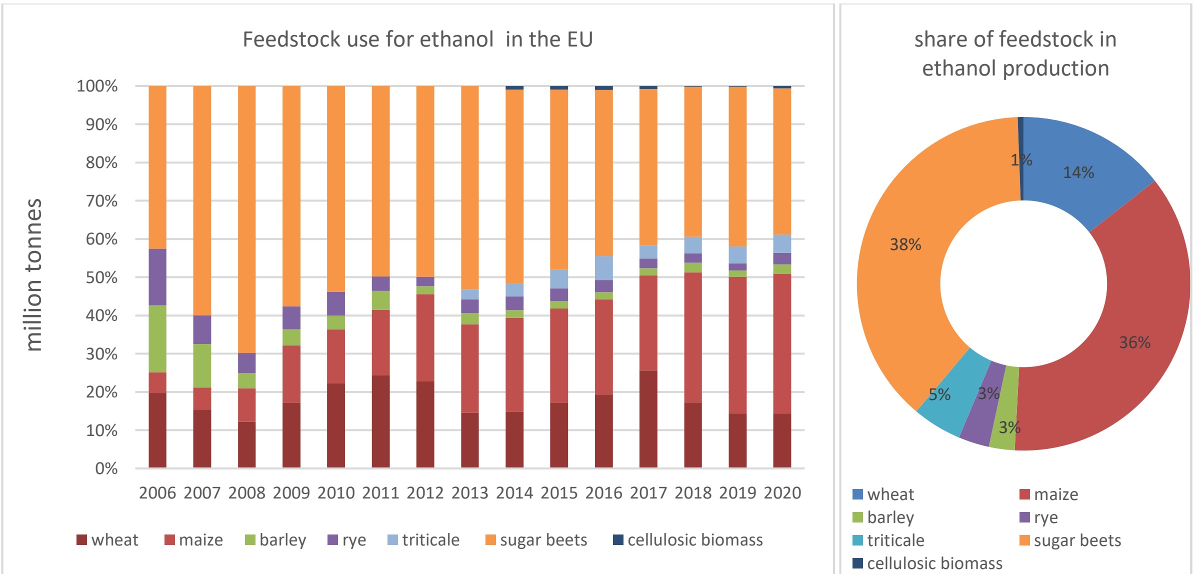
Globally, about 75% of biodiesel is based on vegetable oils (20% rapeseed oil, 25% soybean oil, and 30% palm oil) or used cooking oils (20%) (OECD, 2021). Rapeseed oil is still the dominant biodiesel feedstock in the EU, accounting for 38% of total feedstock use in 2020 (see Figure 14). The popularity 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 2020, accounting for 23% of the total feedstock. Palm oil was third in terms of feedstock source in 2020 (18%), mainly used in Spain, Italy, France, and the Netherlands, and to a much lesser extent in Belgium, Finland, Germany, and Portugal. Palm oil use will be affected by the phase-out of biofuels deriving from high-risk ILUC crops.

Figure 14. Feedstock use share, Biodiesel EU 2020



Source: (USDA Foreign Agricultural Service et al., 2021)

Figure 15. Feedstock use share, Ethanol EU 2020



Source: (USDA Foreign Agricultural Service et al., 2021)

Regarding ethanol, at world level, about 60% of ethanol is produced from maize, 25% from sugarcane, 3% from wheat, 2% from molasses and the residues from other grains, cassava or sugar beet. 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, 2021). Advanced biofuels from cellulosic feedstock (e.g. crop residues, dedicated energy crops, or wood) account for a very small share of total biofuel production. As for EU, the feedstock used for bioethanol production are mainly sugar beets and corn (see Figure 15).

2.3 Technology Cost – Present and Potential Future Trends

The fuel production costs are composed of investment (capital) costs (CAPEX), operating costs (OPEX) and feedstock costs. Even if each of those is heavily influences 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 8 000 hours/year result in in low CAPEX (from 3-15 €/MWh) compared to the OPEX (which range from 48-76 €/MWh).

Again, according to IEA, to produce cellulosic bioethanol, the capital cost of a production plant represents the main share of the overall costs. The plants installation cost range 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.

The other pathway analysed 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 Plan 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 2, which in detail sometimes differ from the costs shown above, but follow a similar trend and similar overall costs.

Table 2. Current advanced biofuel costs (CAPEX, feedstock and OPEX)

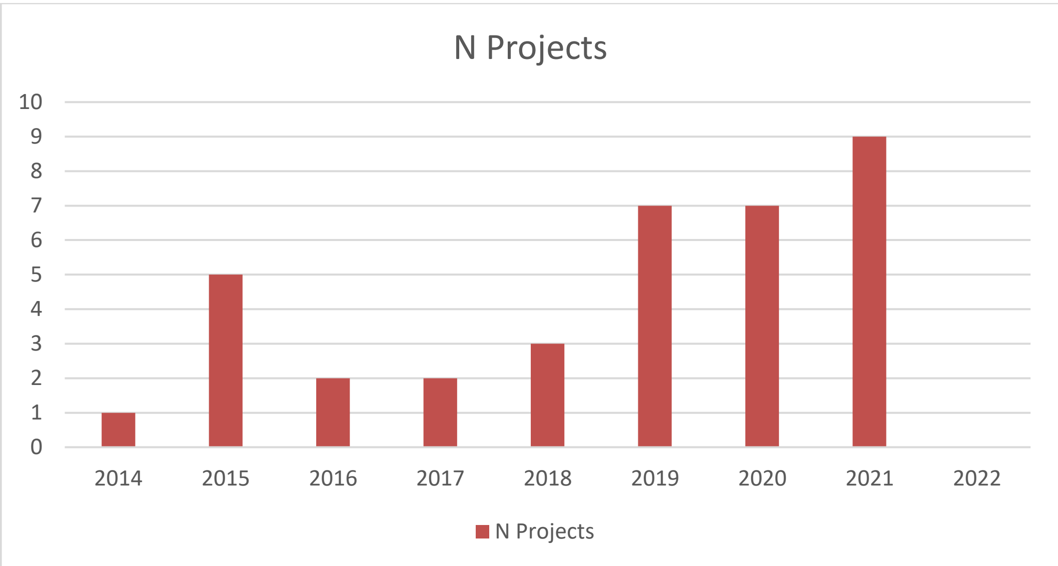
		Costs, EUR/MWh			
Process		**Capital**	**Feedstock cost**	**Operating cost**	**Total**
Cellulosic ethanol	Low	42	33	28	103
	High	60	50	48	158
Cellulosic ethanol "1/2 Gen"	Low	33	0	18	51
	High	38	0	21	59
Methanol and methane - biomass	Low	33	15	14	62
	High	49	33	30	112
Methanol and methane - wastes	Low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

2.4 Public R&I funding

European funding within Horizon 2020 (and Horizon Europe) has been quite stable over the last years. Figure 16 shows that approximately 5 projects have been funded on average each year since 2015 (with data for 2022 not available at the time of writing).

Figure 16. Number of H2020 projects on advanced biofuels

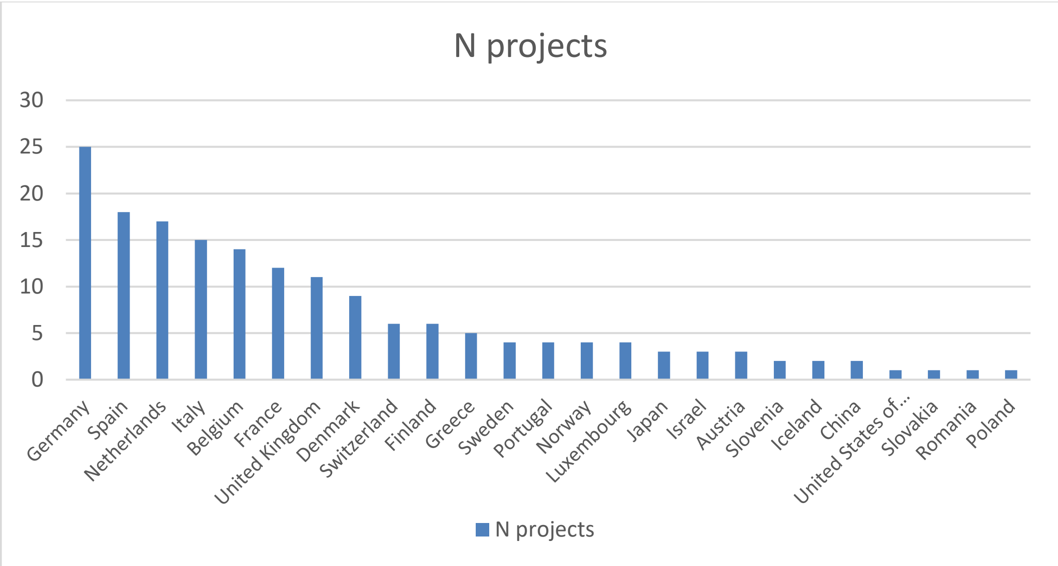


Source: JRC analysis based on JRC TIM (Cordis database)

Typically, an H2020 project is coordinated by one institution, but having inside the project consortium even more than 20 partners, could be also several partners from the same nation inside a single project. As shown in Figure 17, the countries with the highest number of projects are those where biofuel production is strong:

Germany, UK, Netherlands, Italy and Spain. But also, Finland, France, Belgium, Sweden and Austria are participating heavily in projects, also due to their feedstock availability or history of biofuels production.

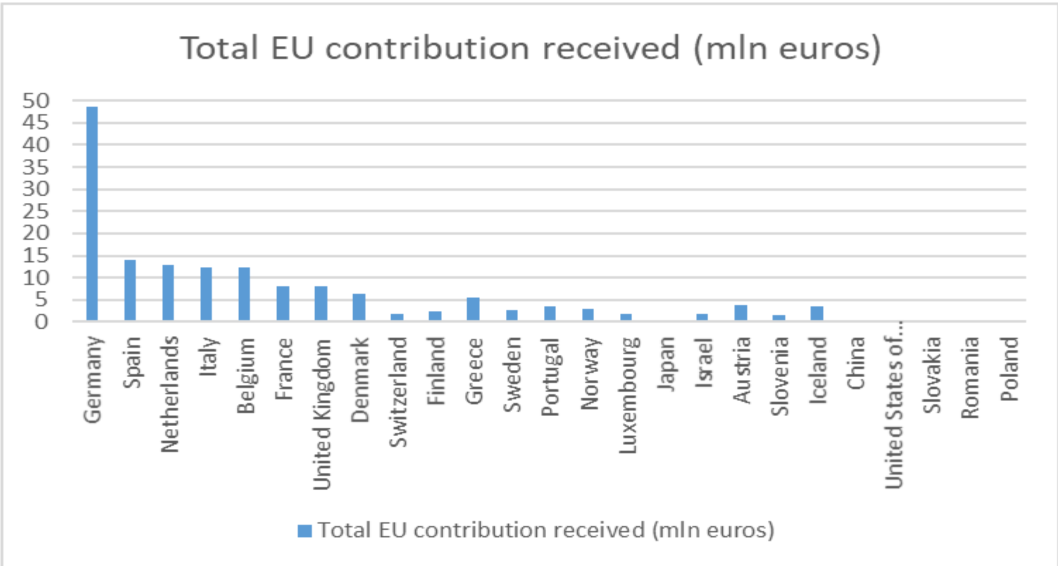
Figure 17. Number of H2020 projects on advanced biofuels per country



Source: JRC analysis based on JRC TIM (Cordis database)

The amount of funding received follows a similar pattern (see Figure 18), even if some countries like Netherlands, France, Sweden and Romania received higher funding amounts per project than the average.

Figure 18. Total EU contribution to H2020 advanced biofuels projects



Source: JRC analysis based on JRC TIM (Cordis database)

The projects cover most of the described technologies, with a focus on gasification and fuel synthesis, but also including 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 as well as 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.

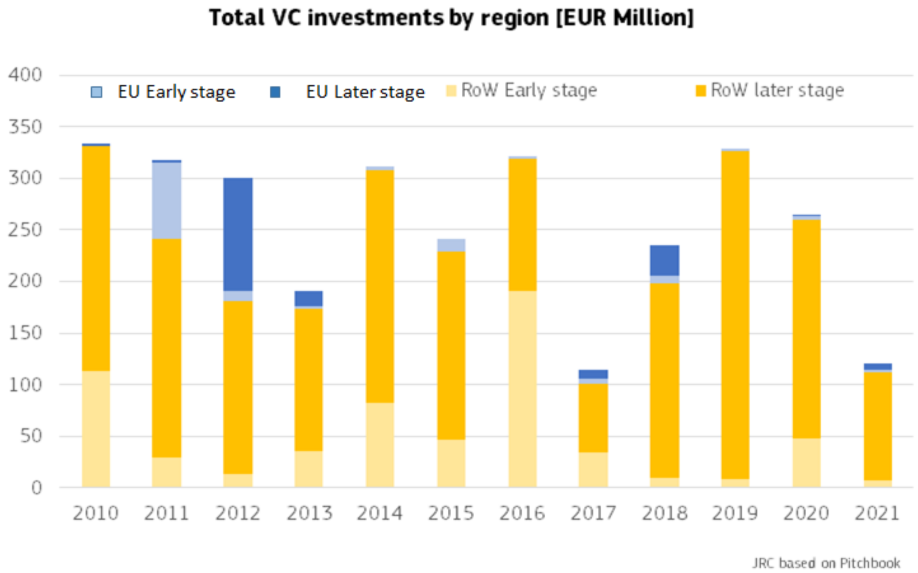
2.5 Private R&D funding

Investments considered in this analysis are early and later stages investments in Venture Capital (VC) companies over the considered period. VC companies include Pre-Venture companies and Venture Capital companies. Pre-venture companies are companies that: (1) have received Angel or Seed funding (i.e. capital from high-net-worth individuals which provide financial backing for small startups or entrepreneurs, typically in exchange for ownership equity in the company), (2) have been funded in a period less than 2 years before; (3) have not received funding before. Venture Capital companies are companies that have, at some point, been part of the portfolio of a venture capital firm. Investments reflect investments in all active companies over that period irrespectively of their current status (defunct, publicly held, privately held with no VC backing, merged or acquired, no longer actively tracked in the data source…).

Early stages investments include Grants, Angel & Seed (i.e. Pre-Seed, accelerator / Incubator, Angel and Seed) and Early-stage VC. Later stages investments include Late-Stage VC (and undisclosed series), Small M&A and Growth Private Equity. 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 list of VC companies includes all the identified companies, irrespectively of their founding year, the fact that have received investments over the period or their current status.

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. Concerning the period under consideration the Advanced fuel sector gained higher VC investment for the years 2010, 2011, 2014, 2016 and 2019 with amounts invested at above 300 EUR Million annually (see Figure 19).

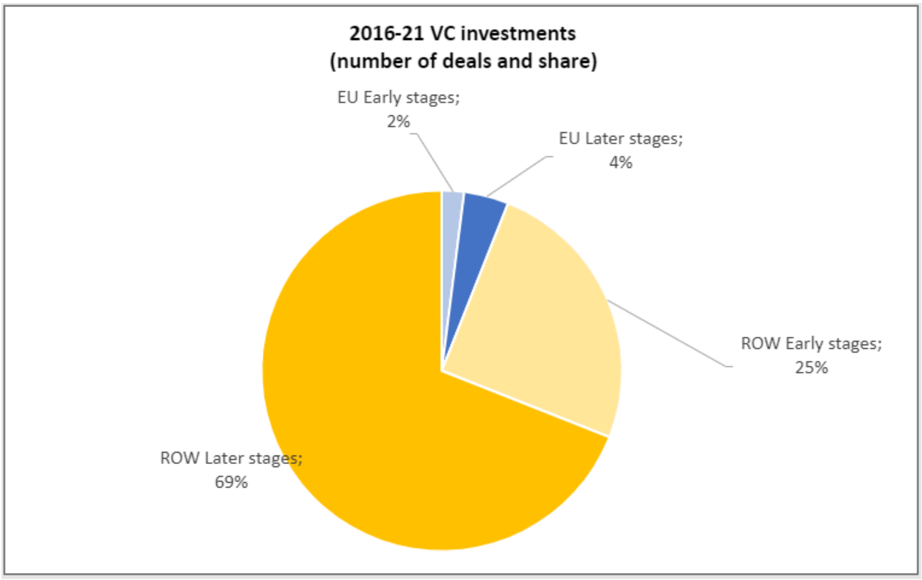
Figure 19. Total VC investments by region



Source: JRC analysis based on Pitchbook

According to the Figure 20, between 2016 and 2021 the VC number of deals in EU compared to the Rest of World (RoW) amounted to 6%, so the deals are smaller on average than in the RoW.

Figure 20. Number of VC investments by region

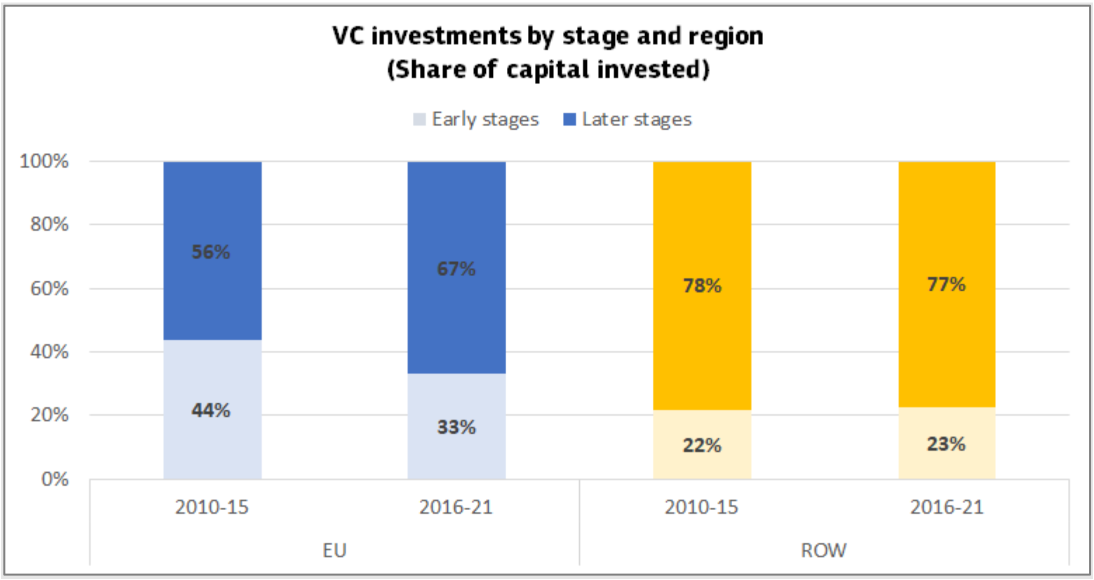


Source: JRC analysis based on Pitchbook

The early-stage investment peaked in 2016 when it reached almost 200 M€, due to two big investments into Enerkem in Canada. Later stage investments reached a peak of more than 300 M€ in 2019, again due to Enerkem raising over 280 M€. 57% of the investment since 2010 was invested in the U.S., 28% in Canada, while only 10% was invested in the whole EU. This share went down to 5% in the 2016-2021 period compared to nearly 14% in the 2010-2015 period.

As shown in Figure 21, the later-stage investments share is higher in RoW compared to EU, from 2016 to 2021 early-stage investment in EU were 33%.

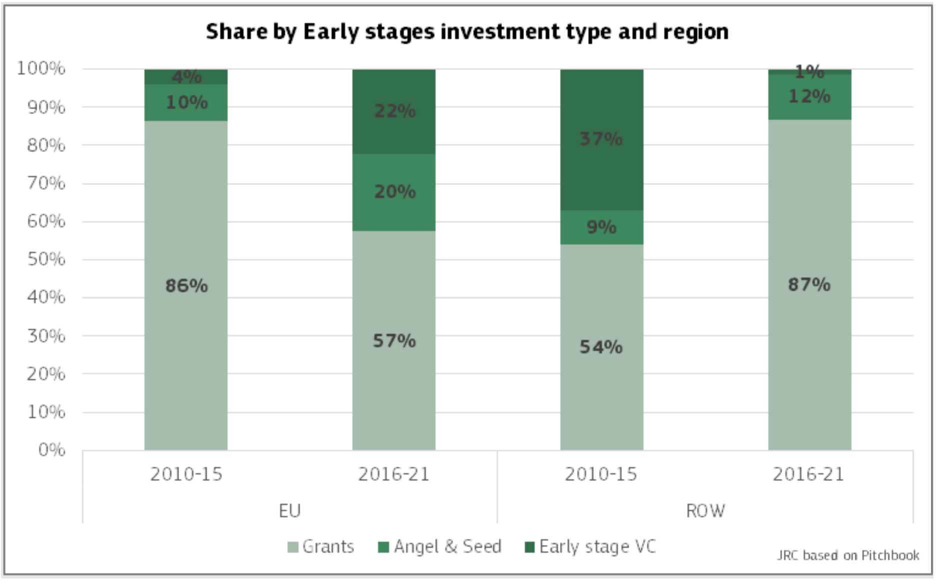
Figure 21. Share of VC capital investments by region and stage



Source: JRC analysis based on Pitchbook

As shown in Figure 22, in EU, grants represented 86% of early-stage investments during 2010-2015, grants dropped to 57% investment share during 2016-2021, while in RoW the exact opposite happened: grants grew from 54% to 87%.

Figure 22. Share of early-stage VC capital investments by region and type



Source: JRC analysis 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 2017 and 2019 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.

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

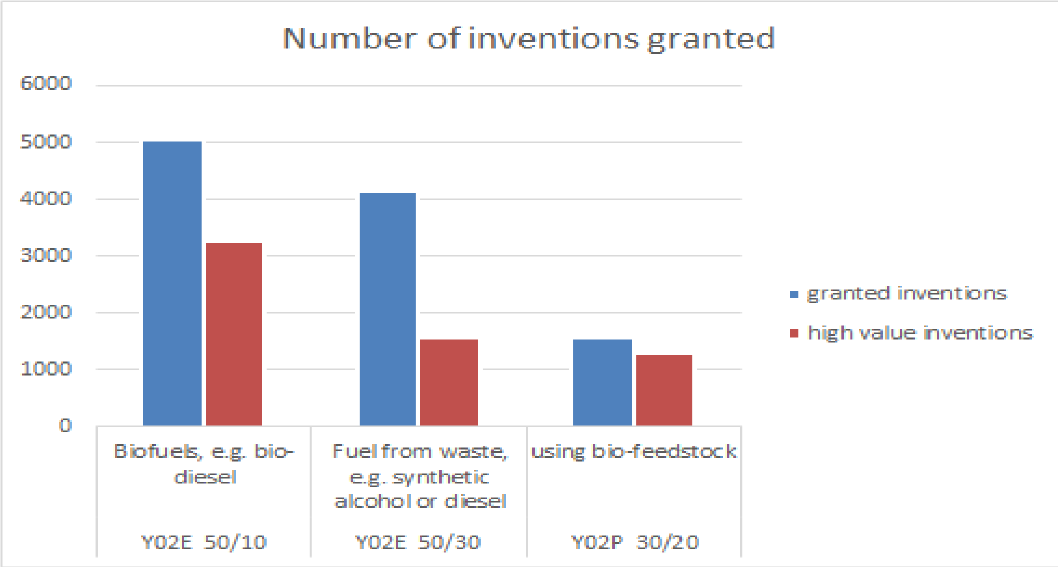
- CPC: Y02E 50/10 Biofuels, e.g. bio-diesel
- CPC: Y02E 50/30 'Fuel from waste, e.g. synthetic alcohol or diesel'
- CPC: Y02P 30/20 'production or processing of goods using bio-feedstock

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 23, most granted patents are in the "Biofuels" class, followed by "fuels from wastes".

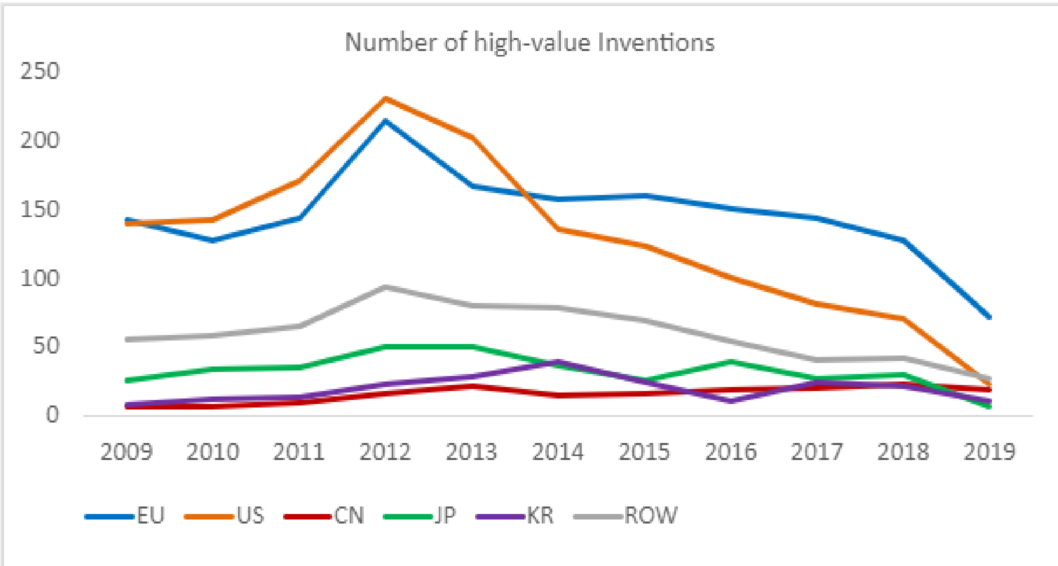
Figure 23. Number of patents granted



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

From 2009 to 2019 EU and US have kept constantly the lead in terms of high value inventions averaging, both reaching more than 200 inventions each in 2012 (see Figure 24).

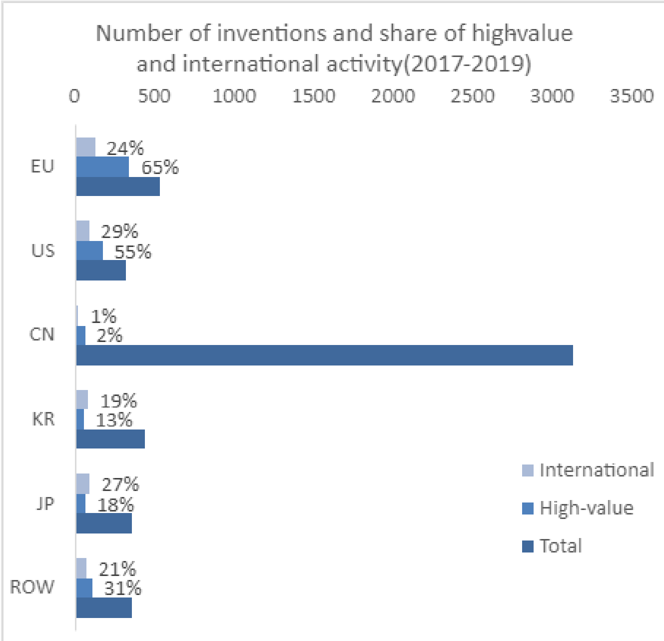
Figure 24. Number of high value inventions advanced fuel



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

Figure 25 shows that for the triennium 2017-2019 EU had 65% share of high-value patents out of a total 532 patent applications, while for example China received a total of 3130 patents with only 2% high-value.

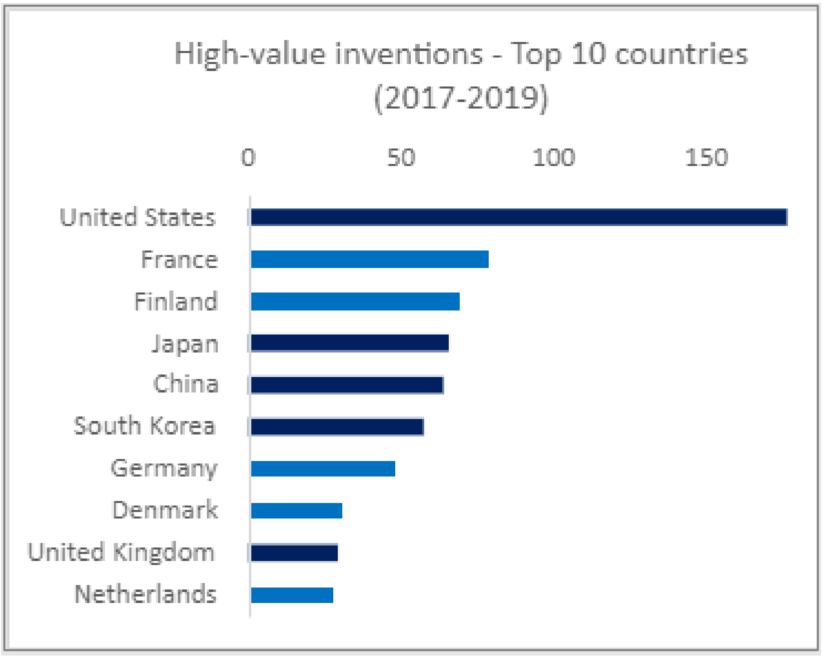
Figure 25. Number of inventions and share of high value and international activities



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

Figure 26 shows the situation for the same triennium 2017-2019 but at country level. US is the leading country with 176 high-value patents, while France and Finland follow with 78 and 69 patents application.

Figure 26. High value inventions, top 10 countries



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

Concerning the situation at individual company level, EU based companies Neste Oy, with 39 inventions, and Novozymes, with 13 inventions, are in the first and third position of the top 10 world entities with high value inventions ranking for the triennium 2017-2019 (see table 3).

Table 3. Top 10 companies for high-value inventions

High-value inventions - Global Top 10 entities (2017-2019)	
Company name (country)	High-value
Neste Oy (FI)	39
Danisco Us Inc (US)	19
Novozymes As (DK)	13
Exxonmobil Research And Engineering Company (US)	12
Dsm Ip Assets Bv (NL)	12
Valmet Oy (FI)	11
Lallemand Hungary Liquidity Management Llc (HU)	10
Poet Research Inc (US)	8
Iogen Corporation (CA)	8
Sekisui Chemical Co Ltd (JP)	8

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

The inventions granted decreased in the triennium 2017-2019 from a total of 558 in 2017 to 268.8 in 2019. China leads this category with 53% share in 2017 and 56 % in 2019 (table 4).

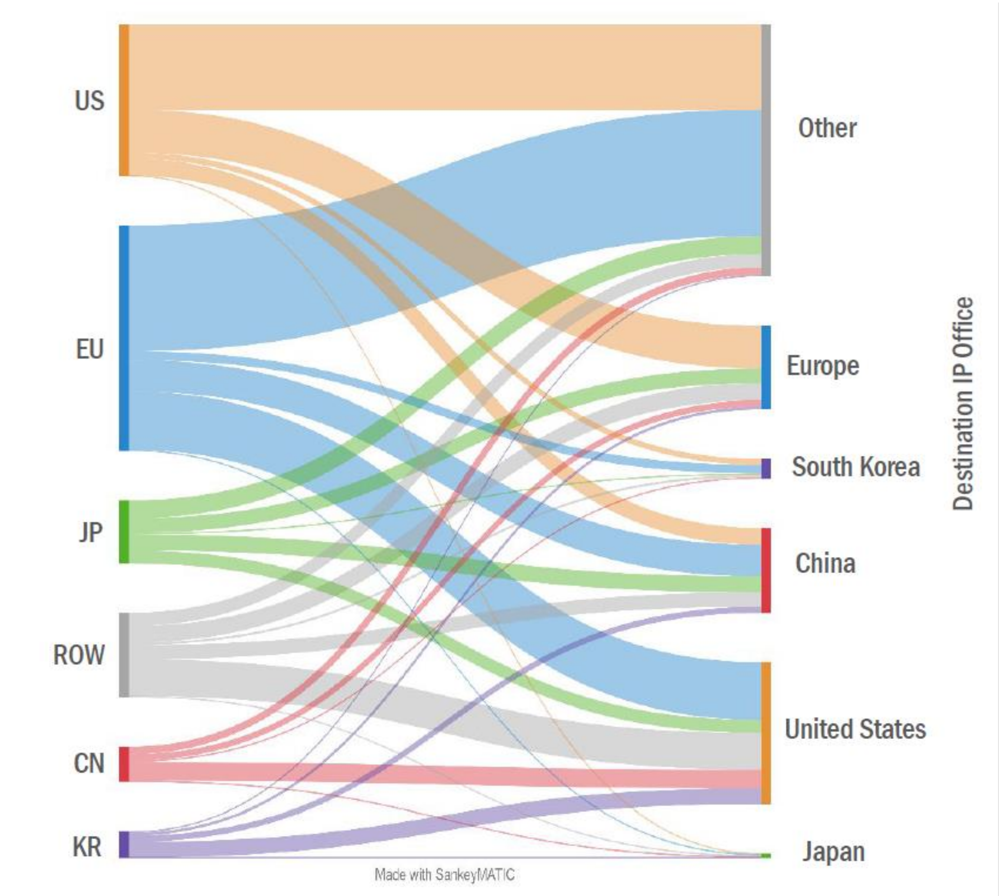
Table 4. Invention granted 2017-2019

World_player	**2017**	**2018**	**2019**
EU	46.6	38.9	13.1
CN	297.8	209.5	150.7
JP	38.0	22.2	6.3
KR	104.5	109.5	59.7
US	31.9	15.3	6.7
ROW	39.9	42.1	32.3
	558.7	**437.5**	**268.8**

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

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 2010 to 2019. Almost 50% of inventions from EU flows to US and China. The overall picture about invention flow is presented in the Figure 27.

Figure 27. Total Invention stream from 2000-2019



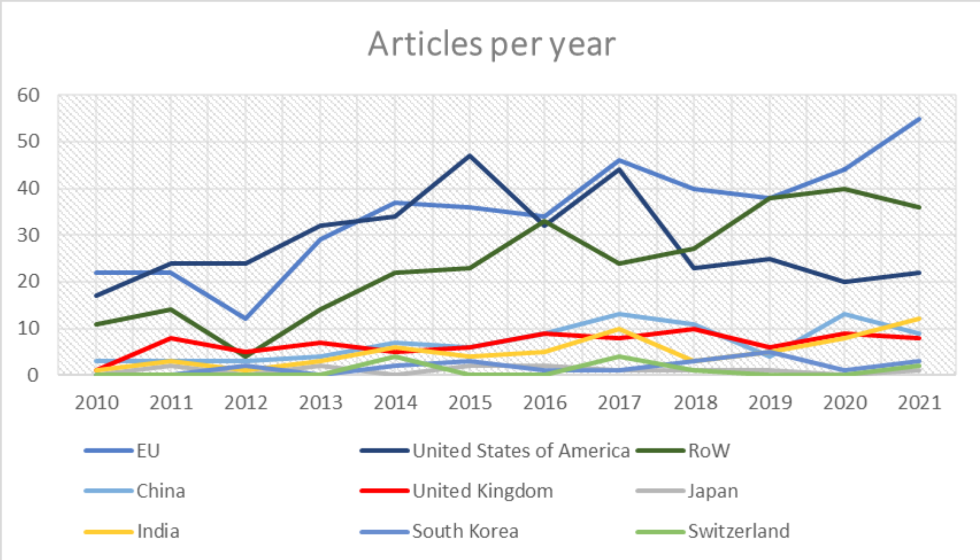
Source: JRC analysis based on data from the European Patent Office (EPO), PATSTAT database 2021

2.7 Bibliometric trends/Level of scientific publications

Articles have been extracted from the JRC database "TIM" with the search terms based on feedstocks, fuel types and processes for advanced biofuels attached in **Annex A**. This search query might include some false positive results and miss some publications on advanced biofuels, as it is nearly impossible to define a sharp query on all processes for advanced biofuels. It should however be a good approximation on publishing in the field.

Worldwide, publications on advanced biofuels have increased from around 60 articles per year to around 140 articles per year in the last 10 years. The European Union took a leading place in the same time, with the U.S. decreasing their publication activity and the "rest of the world" increasing consistently. This is shown in Figure 28.

Figure 28. Peer-reviewed articles on advanced biofuels per region and year

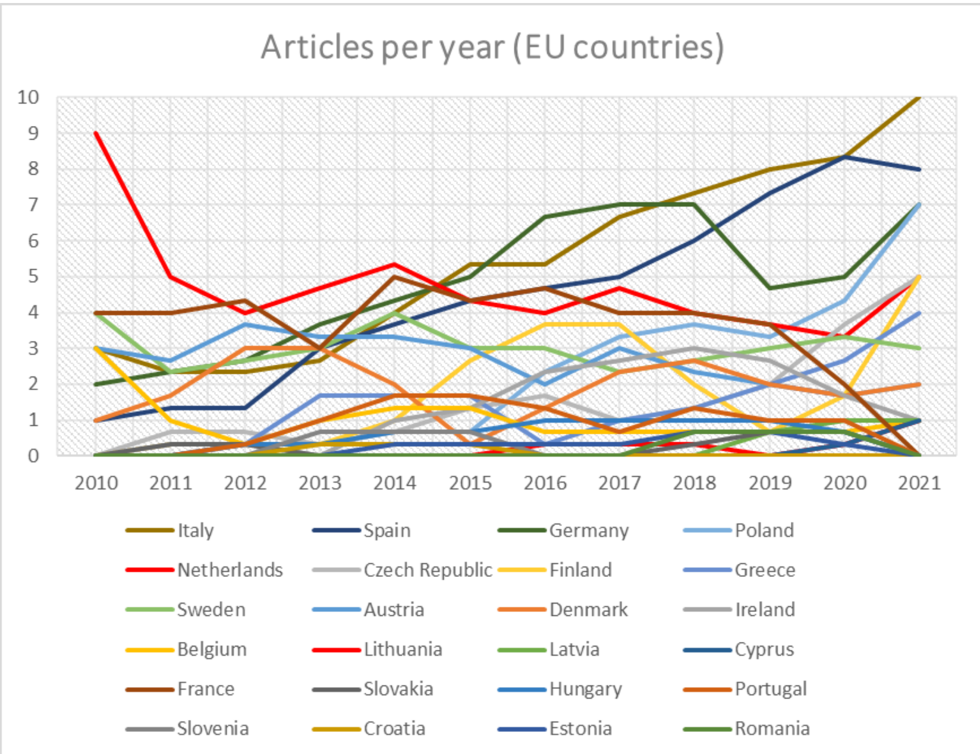


Source: JRC analysis based on JRC TIM (Scopus database)

The share of highly cited articles is around 20% on average over the whole time since 2010, a bit higher for the UK and China and lower for the U.S. and the "rest of the world". The H-index, representing the productivity and citation impact, is highest for the U.S. and EU, followed by the "rest of the world".

Figure 29 presents the situation within the European Union, where Italy and Spain tripled their publications in that period to about 10 publications per year (moving average over 3 years to eliminate the inter-year noise), followed by Germany and Poland. The Netherlands lost their clear leading position, but are still publishing around 5 papers a year, as do the Czech Republic and Finland.

Figure 29. Peer-reviewed articles on advanced biofuels per region and year, 3 years moving average



Source: JRC analysis based on JRC TIM (Scopus database)

The share of highly cited papers is above 30% for Sweden and the Netherlands, and around 20% for the other countries with high publication numbers.

This trend is in line with the nr. of EU-funded projects that have been carried out by each Member State. Thus, countries with more projects produced more peer-reviewed papers on the topic of interest. This result highlights that the scientific output is correlated with the funding availability from EC and less dependent on national initiatives.

2.8 Impact and Trends of EU-supported Research and Innovation (alternate years only)

EU-supported research on advanced biofuels increased over the years, following amongst others the legislation to decrease first generation biofuels and increase overall biofuels share. While biomethane kept an important role in the EU-funded research, technologies for second- and third-generation biofuels increased over the years. This comprises technologies to make non-ILUC feedstock available, like growing crops on degraded, contaminated or marginal land, pre-treatments to create break up feedstocks like lignin and processes like gasification, hydrothermal liquefaction, pyrolysis or fermentation that can use unconventional feedstocks.

Several projects produced pilot or demonstration plants showing the viability of those technologies. Table 5 shows the number of plants under operation, construction or in planning in 2020.

Table 5. Advanced biofuels plants in the EU

Type of plant	Operational	Under construction	Planned
gasification	1	2	7
pyrolysis oil	3	2	2
HTL		1	
Lignin to bio-oil	1		1
Cellulosic ethanol	8	2	9
Hydrocarbons from sugars and alcohols	2		1
Other (advanced biofuels and recycled carbon fuels)	7	2	1

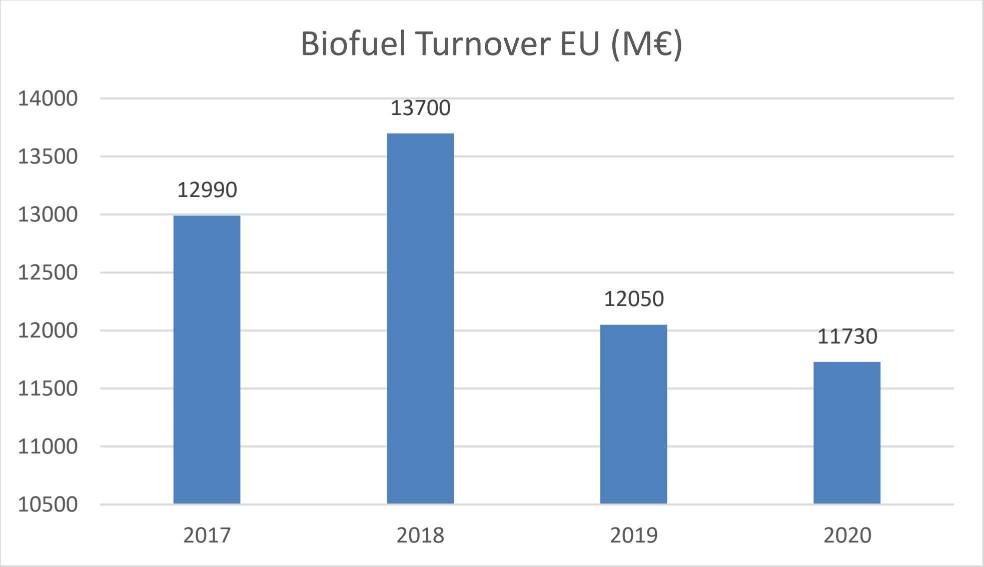
Source: (ETIP Bioenergy, 2020)

3 Value change Analysis

3.1 Turnover

As shown in Figure 30, the turnover in EU concerning the Biofuel industry peaked in 2018 reaching 13 700 M€ in 2018 then decreasing to 11 730 M€ in 2020.

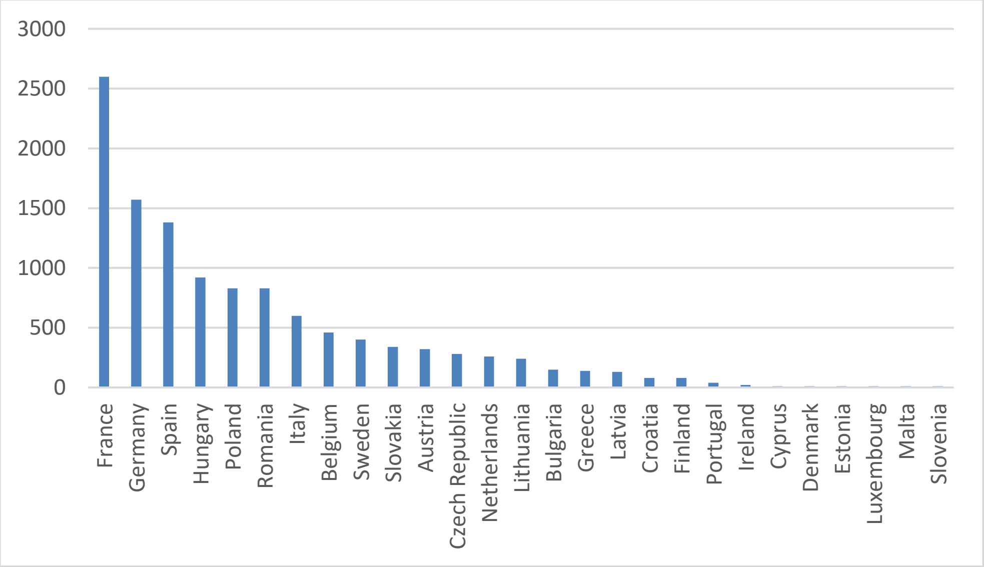
Figure 30. Biofuel industry turnover in EU



Source: (EurObserv-ER, 2022)

Figure 31 presents the situation at MS level. In 2020 France had the highest turnover for the Biofuel industry in EU, with a bit more 2 500 M€, followed by Germany with around 1 500 M€ turnover.

Figure 31. Biofuel turnover in EU in 2020



Source: (EurObserv-ER, 2022)

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 2 304 M€ and indirect at 6 621 M€ with a total 8 925 M€ (see Figure 32).

Figure 32. Biofuel impact on GDP in EU 2020

Source: (Deloitte, 2022)

According to Deloitte, the sectorial breakdown on GDP direct impact of biofuel in EU is mainly on operation and maintenance with 1 530 M€ as shown in Table 6.

Table 6. GDP impact of biofuel in EU

Biofuel EU			
Impact on GDP (M€)	**Direct**	**Indirect**	**total**
Equipment Manufacturing	142	6621	**8925**
Construction	144		
Supply of feedstock	488		
Operation and maintenance	1530		
Total	**2304**		

Source: (Deloitte, 2022)

3.3 Environmental and Socio-economic Sustainability

In the following table, the different dimensions of sustainability of advanced biofuels are described. This format is harmonized throughout the different CETO reports.

Parameter / Indicator	***Input***
Environmental	
LCA standards, PEFCR or 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 and 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, 2019). **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 CO2eq/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 are 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 - 0.82 MJ/MJ final fuel • Syndiesel from wood chips from SRF via HTL: 0.89 - 0.89 MJ/MJ final fuel • Syndiesel from waste wood via black liquor: 0.11 - 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, 2019). 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 agri, industrial and wood residues include 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 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 as 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.
Soil health	The use of agri 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. 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 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	
LCC 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 to develop a resource-efficient, 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-	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

in/innovation lock-out	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 operator 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 13 voluntary schemes under RED II by June 2022.
Social	
S-LCA standard or best practice	*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 must 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 need for 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, 2019).
Industrial transition impact	Advanced biofuels can contribute significantly in the short term to the decarbonization of transport, eenergy 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 the only or best available solution for the decarbonization of certain sectors such as aviation and shipping and heavy road transport.
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 for 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, shipping and long-distance heavy road transport, 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 industry 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 the 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 requiring higher grade steel and certain metal catalysts in relatively small quantities.

3.4 Role of EU Companies

A number of EU companies are operating or planning to operate production facilities for advanced biofuels. Below is a short description of the most relevant companies and projects.

Neste opened in 2011 a renewable diesel plant with an annual capacity of 910 million litres in Rotterdam. In addition to drop-in biofuels, the Neste plants produce renewable naphtha, propane, and alkanes. Current annual production capacity at the plant in Rotterdam is a maximum of 1.28 billion litres. Neste is planning to build another plant in the port of Rotterdam with a capacity of 2 billion litres.

UPM opened in 2015 a renewable diesel plant in Lappeenranta, with a capacity of 115 million litres of advanced biofuels per year, and the plant is using tall oil, a residue of pulp production, as a feedstock. UPM plans to build a new-generation biofuel refinery in Rotterdam with an annual capacity of 500,000 tonnes of high-quality renewable fuels, including aviation fuel.

A subsidiary of **Green Fuel Nordic Oy** (GFN Lieksa) partnered with the Dutch company BTG, to produce 24 000 tonnes of bio-oil of pyrolysis oil from sawmill by-products in Lieksa. The plant started operation in December 2020.

Nordfuel planned to open in 2021, a biorefinery in Finnish town Haapavesi, to produce bioethanol and biofuel from soft wood residues (EUR 150 million investment) using Celluapp SEKAB Technology from softwood residue. Nordfuel will be a full-scale biorefinery, producing bioethanol and biogas for the transport sector, lignin to fuel the power plant in Haapavesi.

BioEnergo plans to build a similar biorefinery for advanced biofuels in Pori using the SEKAB's CelluAPP® technology based on enzymatic hydrolysis (EUR 200 million investment). The plant will use the by-products of the sawmill industry, which processes 60,000 cubic meters of advanced bioethanol into passenger cars and 130,000 MWh of advanced liquefied biogas as fuel for heavy transport.

Fintoil Oy plans to invest around EUR 100 million in the construction of a new crude tall oil biorefinery in HaminaKotka, Finland with a capacity of 200,000 tonnes. The biorefinery will refine 50 % of the crude tall oil for the production of renewable fuels, while the rest will be used for other sustainable products.

Eni bio-refinery in Venice produces Hydrogenated Vegetable Oil (HVO) with EcofiningTM technology. In 2020, with a capacity of 400,000 tonnes/year, it processed around 220,000 tonnes of raw materials, of which more than 25% consisted of used cooking oils, animal fats and other waste vegetable oils. Production is forecast to increase from 2024, a further upgrading of the plant will increase the processing capacity up to 560,000 tonnes per year with a total production of biodiesel of 420,000 tonnes per year.

Eni converted its Gela refinery in Sicily into a renewable diesel production facility with capacity of up to 750,000 tonnes per year. The reconversion started in April 2016 and the facility opened in 2019. The plant will be able to treat used vegetable and frying oil, animal fats, algae and waste/advanced by-products to produce high-quality biofuels. In 2020, the plant produced about 585 million liters. Eni Biojet will be produced from 2024 in the Gela biorefinery from renewable feedstock.

Preem produces in Gothenburg, nearly 160 million liters of renewable diesel per year from tall oil. The company recently expanded its production capacity to 220 million liters following an upgrade of the hydrotreater plant using HydroFlex™ technology. Preem sources a variety of raw materials, including raw tall oil diesel from SunPine, and food waste including UCO. This allows Preem to achieve 85 percent coprocessing of renewable feedstock.

Energy company **St1** decided to construct a new biorefinery in Gothenburg with total capacity of 200,000 tonnes of liquid biofuels (investment cost of SEK 2.5 billion ≈ EUR 265 million). It allows to process a wide range of feedstocks to produce renewable fuels such as renewable HVO diesel and biojet fuel and to use tall oil-based feedstock. The biorefinery was expected to start production in 2023.

BioTFuel project, a cooperation of Total and five partners that aims to produce 230 million litres of advanced biodiesel and bio-jet fuel per year at Total's former Flandres refinery in Dunkerque. The plant will convert lignocellulosic biomass (straw, forest waste, dedicated energy crops) into high-quality biodiesel and biojet fuel via thermochemical conversion (gasification).

Galp operates Enerfuel facility unit in Sines producing Fatty Acid Methyl Ester (FAME) biodiesel. This product is 100% made from the processing of residual animal fats and used cooking oils. Enerfuel in 2020 produced approximately 26,000 tonnes. Galp also produces HVO in a hydrogenation unit at the Sines refinery. This biofuel results from the co-processing of vegetable oil with diesel. In 2020, production reached approximately 25,000 tonnes.

Versalis, Eni's chemical company, has begun the production of advanced bioethanol from lignocellulosic biomass using Proesa technology at Crescentino (Vercelli). The plant is capable of processing 200,000 tonnes of biomass per year, with a maximum production capacity of 25,000 tonnes of bioethanol per year. Energy supply is self-sustaining due to the production of renewable electricity and steam from the power plant, which is fed with biomass and the lignin co-produced by the process. A water treatment plant also enables the production of biogas, which in turn is used to produce steam.

Clariant started the operation in 2022 of a new commercial scale plant in in Podari, Romania for the production of cellulosic ethanol from agricultural residues using the sunliquid® technology. The plant will process approx. 250,000 tons of straw to produce 50,000 tons of sunliquid® cellulosic ethanol on an annual basis.

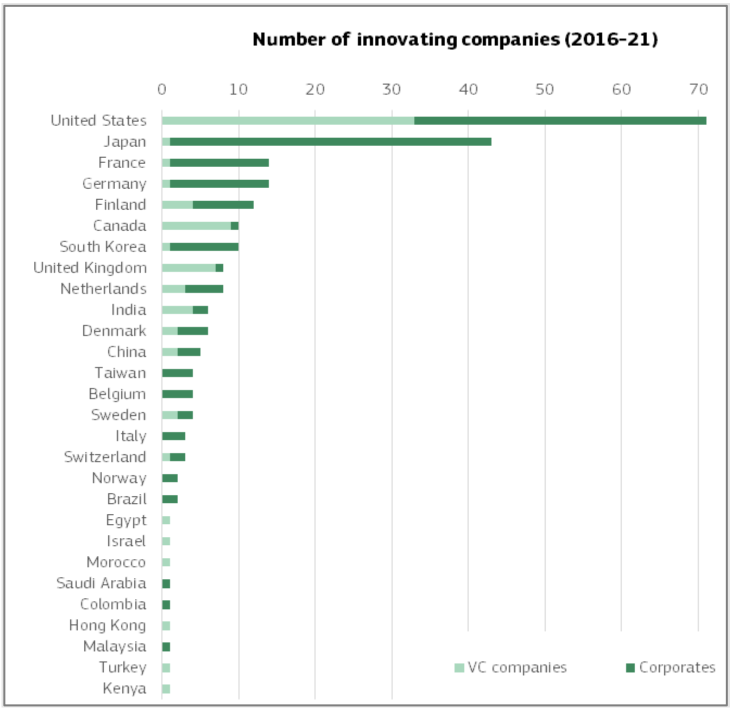
With a production capacity of 250 million litres, **BioMCN** plant produces bio-methanol from crude glycerine, a sustainable biomass which is a residue from industrial processing of vegetable oils and animal fats. BioMCN produces two types of methanol: bio-methanol and grey methanol. Bio-methanol is produced from biogas sourced from waste digestion plants.

Södra has built a commercial plant to produce biomethanol from forest biomass using Andritz technology, at Södra's pulp mill in Mönsterås (investment over SEK 100 million ≈ EUR 10.56 million). Biomethanol is produced from the crude methanol recovered from the manufacturing process from the pulping process.

Verbio is producing biomethane from straw at its plant at the Schwedt/Oder site. The plant has a capacity of 16.5 MW, meaning it can produce approximately 140 GWh of biomethane per year - produced from approx. 40,000 tonnes of straw. The biomethane is destined for use in the transport sector.

As advanced biofuels are still a young sector, it's interesting to look at innovating companies instead of market leaders. Figure 33 shows that U.S. and Japan have the highest number of innovating companies, while the EU has a total share of 29% (23% corporates and 6% VC companies).

Figure 33. Number of innovating companies per country (global*)*

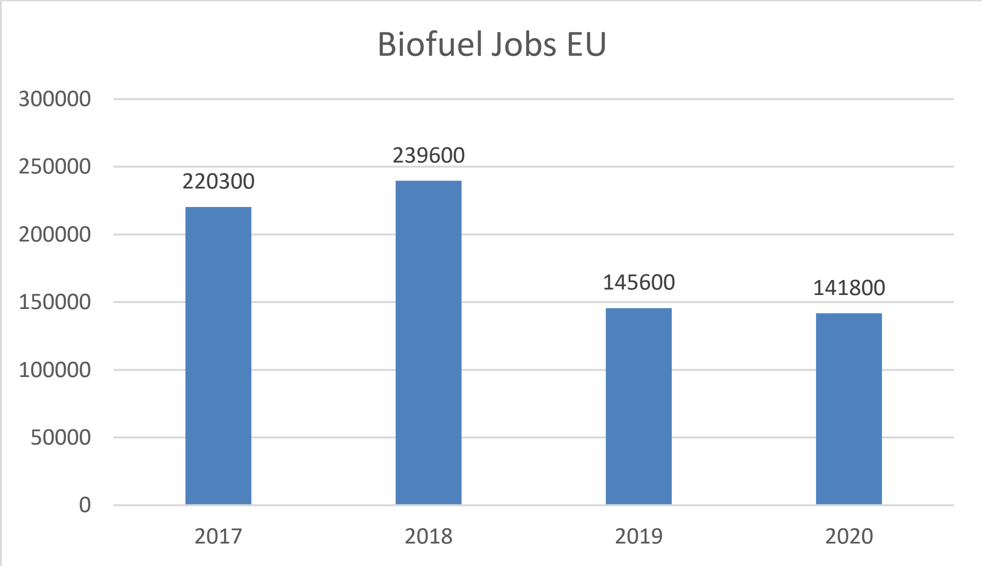


Source: JRC analysis based on EU Industrial R&D investment Scoreboard and other sources

Employment in value chain incl. R&I employment

According to EurObserv-ER (EurObserv-ER, 2022) the number of direct and indirect jobs generated for the biofuels sector in EU was 239600 in 2018 then dropped to 141800 in 2020 (Figure 34).

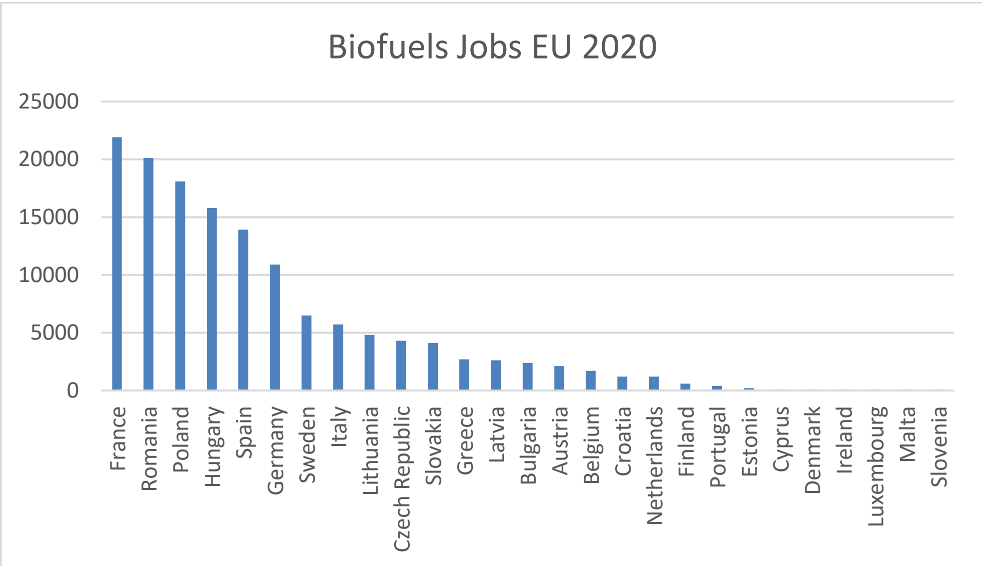
Figure 34. Number of direct and indirect jobs in the biofuels sector in EU, 2020



Source: (EurObserv-ER, 2022)

As shown in Figure 35 at EU country level, France with more than 20 000 jobs is the country with the highest job impact for the Biofuel sector in 2020.

Figure 35. Number of direct and indirect jobs in EU countries, 2020



Source: (EurObserv-ER, 2022)

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 219 651 in 2019, of which 57 216 direct jobs (see table 7).

Table 7. Impact of biofuels sector on jobs in the EU, 2019

Biofuel EU			
Impact on Jobs	**Direct**	**Indirect**	**total**
Equipment Manufacturing	3403	162434	**219651**
Construction	1678		
Supply of feedstock	35313		
Operation and maintenance	16821		
Total	**57216**		

Source: (Deloitte, 2022)

3.5 Energy intensity / labour productivity

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). So if not considering 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 15 763 ktoe in 2020 while the impact on GDP of the Biofuel sector (Deloitte, 2022) was 8 925 M€, the Energy intensity is estimated at 1.77 ktoe/M€.

Labour productivity can be defined in several ways (Borychowski, 2018). If combining the total direct employment of 57 216 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 7 billion € (see chapter 4.2), so the labour productivity is roughly 122 k€ per FTE and year. Using the turnover at 12 billion € and job data at 57 216 FTE, the turnover per job was at 211 k€/Job and year. On energy basis the biofuel production was 15 763 ktoe, putting the energy production per job at 275 toe/Job and year.

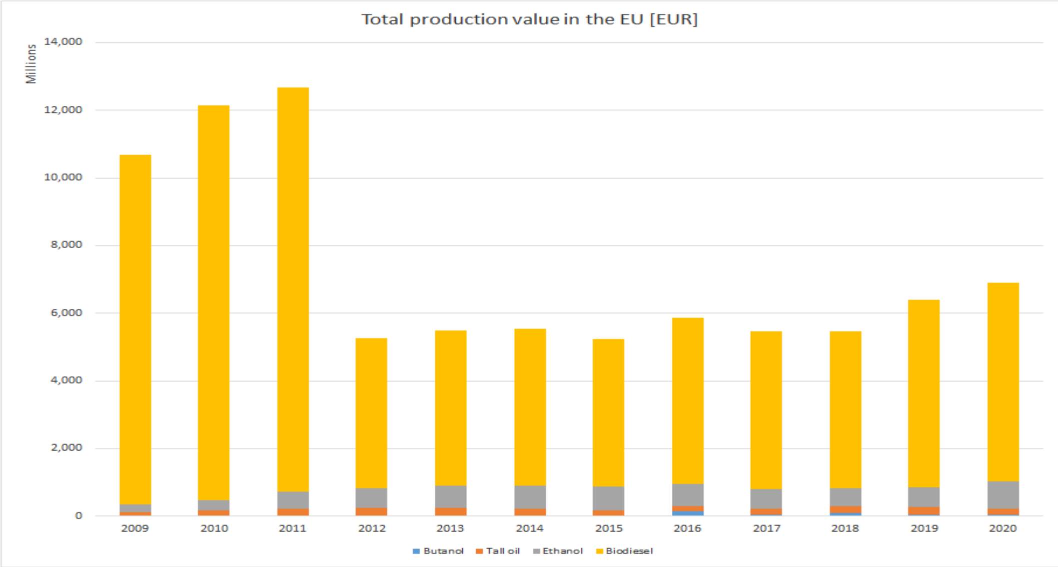
3.6 EU production Data (Annual production values)

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)

Figure 36. EU Production value biofuel

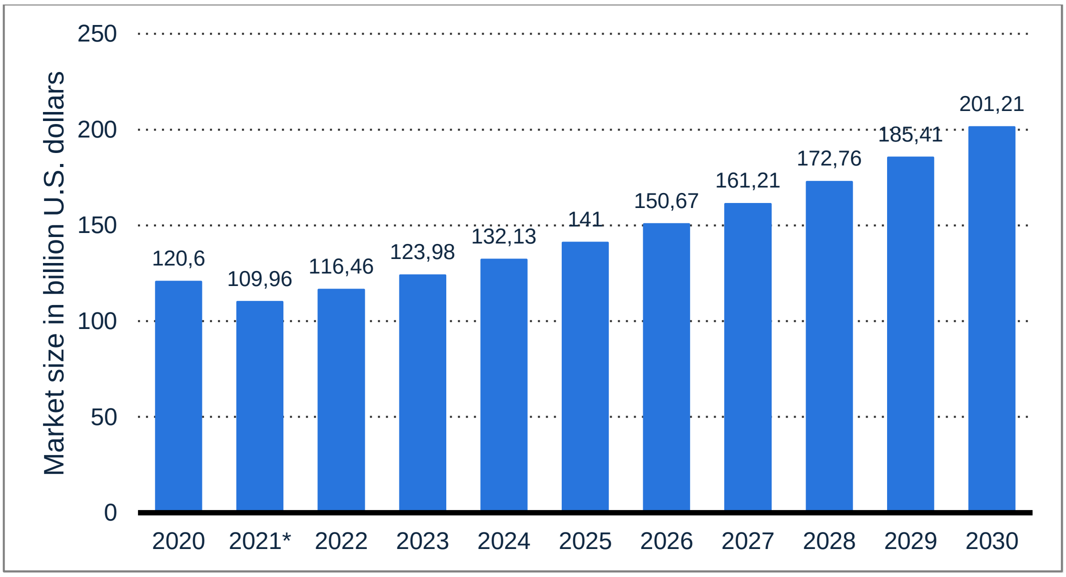


Source: JRC analysis on Prodcom

The sharp decrease of the biofuel production visible in Figure 36 in 2012 is due to the change of PRODCOM code of biodiesel that excluded "other chemical products" from that category.

According with STATISTA (Figure 37) the global biofuel market size in 2020 was at 120 Billion US $, so the EU part of that market was roughly 7%.

Figure 37. Global biofuel market size



Source: (Sönnichsen, 2022)

As described in section 2.2.2 the share of advanced biodiesel in EU reached 23.2% in 2020, while for advanced ethanol it was at only 0.5%. If assuming the same price for conventional and advanced biofuels, then advanced biodiesel had a production value of 1.4 billion € and advanced bioethanol of 4 M€.

4 EU position and Global competitiveness

4.1 Global & EU market leaders (Market share)

The sector of advanced biofuels is just emerging and the number of commercial plants is still quite low, while international trade is very limited. The list of operational, commercial plants for advanced biofuels is dominated by the EU, the clear market leader. As shown in table 7, inside the EU, Sweden and Finland have the highest number of plants.

Table 8. Global list of operational 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 for co-processing	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, 2022)

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.

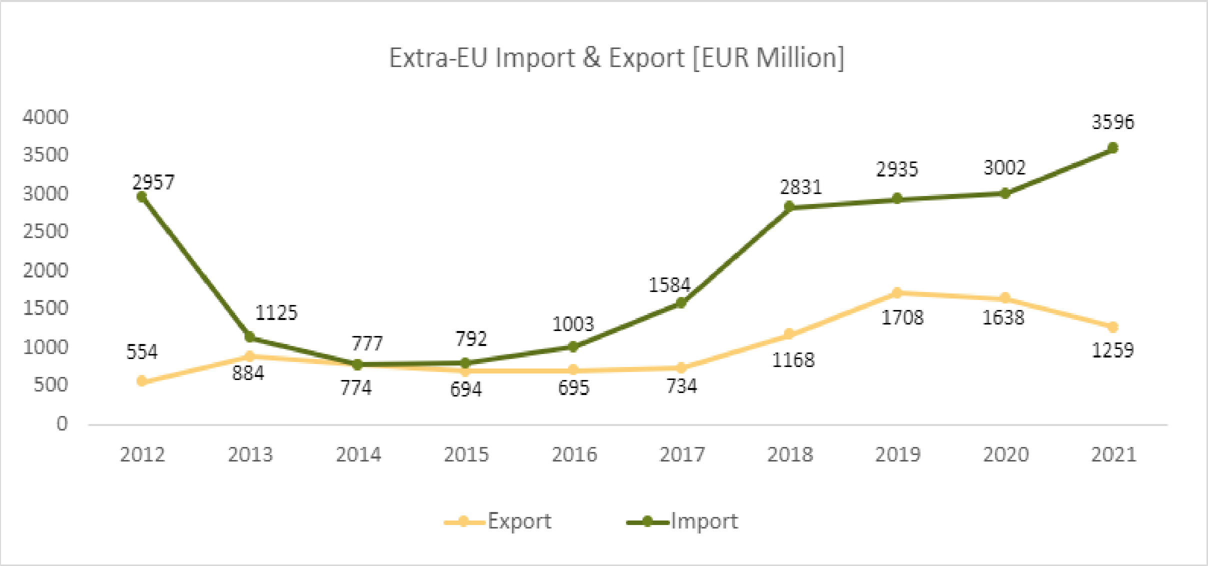
Statistics on trade have been performed by using the COMEXT Eurostat's reference database for detailed statistics on international trade in goods. It provides access on recent and historical data of the EU and its individual Member States, but also covers a significant number of non-EU countries.

International trade of advanced biofuels is nearly inexistent and if existing at all, then the trade codes generally do not permit a differentiation between biofuels and advanced biofuels. The following trade codes for COMEXT and COMTRADE were used:

220720	Denatured ethyl alcohol and other spirits of any strength
382600	Biodiesel and mixtures thereof, not containing or containing < 70 % by weight of petroleum oils
382600	n-butyl alcohol
380300	Tall oil, whether or not refined

When considering the trade concerning the aggregated goods listed above, with their total value grouped for all the EU 27 member states, the value of imports from Extra-EU countries more than tripled from 1 billion EUR in 2016 to 3.6 billion EUR in 2021, while the export from EU to extra-EU was 0.7 billion EUR in 2016 and peaked at 1.7 billion EUR in 2019 (Figure 38). So, the negative trade balance of the EU increased from -3 million € in 2014 to -2 billion € in 2021.

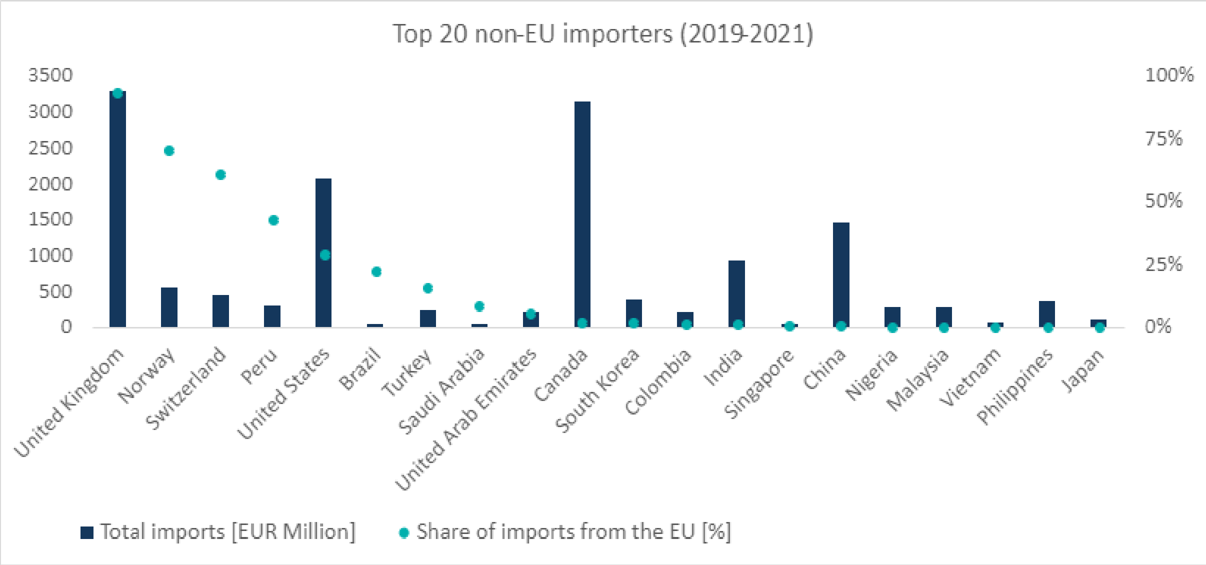
Figure 38. Extra-EU imports and exports value



Source: JRC based on COMEXT data

On a country level, the biggest EU exporters are the Netherlands and Germany (both also globally the biggest biofuel exporters), as reported in Figure 39, the biggest importers of EU biofuels are the U.K. and far behind the U.S.. Germany, the Netherlands and Spain have a positive trade balance, while France, Italy and Sweden have the biggest negative trade balance. Considering also the EU internal market, for the triennium 2019-2021 the EU countries exported a biofuel value from 10 to 16 billion € annually, while the global export increased from 15 to 22 billion € from 2019 to 2021. Argentina is the biggest biofuel exporter to the EU, followed by China and Malaysia.

Figure 39. Top 20 non-EU biofuel importers



Source: JRC analysis based on UN Comtrade data

The U.K. gets most of its imports from the EU, as well as Norway and Switzerland, while big biofuels importers like the U.S. or Canada import more from non-EU countries.

4.3 Resources efficiency and dependence in relation to EU competitiveness

The dependence on critical materials is very low (see also section 3.3). 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 can 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

Advanced biofuels will have an important role for ensuring security of energy supply and the decarbonisation of transport in sectors that are difficult to electrify, mostly aviation, maritime and heavy road transport. In the short term, advanced biofuels can also play a similar role for the decarbonisation of light road transport. They are also highly relevant to ensuring the security of energy supply in the long term, because they can be used as energy carriers in fuel cells as well as fuels for internal combustion engines.

Biomethane (or bio syngas) can contribute to reduce the dependency on natural gas imports, having a large potential for the use in transport (as gas or liquefied fuel) and for injection into the gas grid for power and heat generation.

Because biofuels rely on local biomass resources and on short supply chains, they offer great opportunities to reduce energy poverty (through local value generation and more stable prices), increase the security of supply and resilience of the EU energy system.

Not all fuels are drop-in (e.g., alcohols), thus presenting some blending limits due to engine characteristics or fuel properties (self-ignition, burning characteristics), but in many cases those limits can be revised upwards if combustion engines are adapted to the new fuel mix.

Technologies to produce advanced biofuels exist and some are at commercial level, while others still need research. Public funding in the EU is helping to bring technologies to scale, while private funding is lagging behind U.S. and Canada (as in most sectors).

Costs are currently higher than for first generation biofuels due to higher processing complexity. Costs are also high in relation to conventional fossil fuels, and reflect the delay in de-risking of the technologies and slow rate of investments, due also to the unstable long-term regulatory framework and volatile market conditions. Higher energy prices will make advanced biofuels more competitive and help them to achieve commercial production and cost effectiveness.

Environmental impacts of advanced biofuels are low, as only wastes and residues are used as feedstock. Nevertheless, attention must be paid to not create ILUC effects by diverting residues from existing uses and to not extracting too many residues from agricultural systems and forests.

In other sustainable development goals areas, substantial benefits can be expected from advanced biofuels if done right: important job creation in rural areas, co-benefits on human health, food production, soil and water quality and less dependence on energy imports (also from unstable countries).

One of the biggest challenges is the availability of sustainable biomass and competition for biomass resources, in particular for waste and residues for fuels, energy and materials. Energy crops used as rotational crops or intermediate crops in agriculture (to restore the soil in terms of nitrogen, phosphorous, carbon and other nutrients) can offer a solution. In synergies with agroforestry, advanced biofuels can assist in restoration of marginal land and maintaining biodiversity. New and promising biomass feedstocks not yet addressed by legislation could increase substantially the advanced biofuel generation capacity.

In 2022, the focus on advanced biofuels has increased even more through the painful visibility of EU energy dependence on Russia, the high environmental impact of natural gas alternatives like LNG from shale gas and high fossil energy prices. This might catalyse the increased production of advanced biofuels. Even if imports from Ukraine into the EU are small, any increase of agricultural production in the EU can lead to higher availability of agricultural residues for advanced biofuels.

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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
SET Plan	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 Captial
WGS	Water Gas Shift
WTT	Well To Tank

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Annexes

Annex A. Search query for bibliometrics

((topic:(("advanced biofuel"~2 OR "advanced bio fuel"~3 OR "second generation biofuel") AND ("non food feedstock" OR "non food feed-stock" OR "second generation feedstock" OR "waste feedstock"~3 OR biomass OR lignocellulosic OR "ligno cellulosic" OR "energy crops" OR "herbaceous crops" OR sugars OR "low ILUC" OR "vegetable oils" OR "used cooking oil" OR "waste oils" OR "animal fats" OR "lipid wastes" OR "organic wastes" OR "wood wastes" OR "agricultural residues" OR "agricultural waste" OR manure OR "bio waste" OR biowaste OR straw OR "sewage sludge" OR "palm oil effluent" OR "palm fruit bunch" OR "tall oil" OR "crude glycerine" OR bagasse OR "grape marc" OR "wine lee" OR "nut shell" OR husk OR "cleaned corn cob"~2 OR "forestry waste"~3 OR "non food cellulosic")))
OR (topic:(("advanced biofuel"~2 OR "advanced bio fuel"~3 OR "second generation biofuel") AND ("drop-in" OR "alcohol" OR "diesel" OR "gasoline" OR "methane" OR "natural gas" OR "bio hydrogen" OR biohydrogen OR "renewable jet fuel"~3 OR SAF OR SPK OR SKA OR HEFA OR HRJ OR HVO OR ETBE OR DME OR dimethylether OR dmf OR dimethylfuran OR biodme OR butanol OR methanol OR ethanol OR bioethanol OR biomethanol OR biodiesel OR propanol OR biomethane OR bioSNG OR biogas OR "biopropane" OR SIP OR "pyrolysis oil" OR "bio oil")))
OR (topic:(("advanced biofuel"~2 OR "advanced bio fuel"~3 OR "second generation biofuel")AND (transesterification OR hydroprocessing OR gasification OR "fischer tropsch" OR methanation OR reforming OR "gas shift" OR pyrolysis OR "hydrothermal liquefaction" OR fermentation OR "anaerobic digestion" OR "gas upgrading" OR "biorefinery" OR torrefaction OR "hydrotreating" OR "FCC biofuel"))))
AND class:article

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