BIKE

BIOFUELS PRODUCTION
AT LOW - ILUC RISK
FOR EUROPEAN SUSTAINABLE
BIOECONOMY

D 3.4
The role of low ILUC-risk biofuels in the future EU renewable energy share

Dissemination level:
PU

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Executive summary

Sustainable production of biofuels requires well-designed value chains and detailed monitoring to avoid negative impacts, including Indirect Land Use Change (ILUC). The low ILUC-risk concept was first introduced in the EU directive (EU) 2015/1513 in 2015, amending the Renewable Energy Directive 2009/28/EC. In the 2018 recast of the EU RED, low ILUC-risk fuels were better defined, and an exemption was provided from the cap on high ILUC-risk feedstock. Within the year 2030, the REDII mandates fuel suppliers to ensure that at least 14% of their supply, import or commercialisation of fuels comes from renewable sources. The overarching goal of the BIKE project is to facilitate the market uptake of European low ILUC-risk feedstocks for the production of sustainable biofuels and bioliquids. The BIKE project follows a value chain approach that covers land use, feedstock provisioning, conversion processes, and end-product outputs. This approach combines top-down modelling estimates, based on statistical data and recent research, with bottom-up analysis of actual case studies, with profiles matching the current definition of low ILUC-risk biofuels, bioliquids and biomass fuels.

The activities of BIKE are organized around two low ILUC-risk value chains that match the definition of additionality given by RED II Directive: 1) Cultivation on unused, abandoned or severely degraded lands and 2) Productivity increased through improved agricultural practices. The BIKE project identified two case studies per each value chain, i.e. four in total, where low ILUC-risk feedstocks are used for the production of three types of biofuels: cellulosic ethanol, renewable diesel (HVO), and biomethane. Two case studies refer to cultivation on unused lands and are: i) perennial grasses to advanced (lignocellulosic) ethanol, and ii) castor beans to renewable diesel (HVO). The other two case studies refer to implementation of sequential cropping systems and are: iii) brassica carinata for renewable diesel production and iv) the Biogas Done Right (BDR) model for biomethane-to-liquid fuels.

Task 3.3 of the BIKE project employed a modeling and mapping approach to investigate the potential replication of low ILUC-risk case studies across Europe. Building on the outcomes of this task, Task 3.4 aims to identify the opportunities and challenges associated with a large-scale use of low-ILUC-risk biofuels within the European transportation sector. The evaluation covers the timeframes of 2030 and 2050. Ones the boundaries established by the European regulatory framework are defined, the large-scale use of low ILUC-risk biofuels will be investigated across dimensions of technology and environmental sustainability. Specific attention will be placed on investigating the potential of low ILUC-risk biofuels in aviation and maritime sectors, given the current projections that highlight the pivotal role of biofuels in driving decarbonisation within these industries. Findings suggest that a potential exists to produce about 1.1 – 1.5 billion liters of Sustainable Aviation Fuel (SAF) by 2030. With aviation's fuel demand projected to reach 54.9 billion liters by 2030, achieving the 5.3% SAF share from advanced biofuels, as mandated by the ReFuelEU Aviation proposal , would require approximately 2.9 billion liters of SAF. Ultimately, the replication of BIKE low ILUC-risk case studies could contribute up to 52% of the SAF required to meet the proposed mandate by 2030.

1 Introduction

1.1 Contribution of the transport sector to CO_2 emissions

The transport sector is a major contributor to CO_2 emissions, both globally and in the European Union (EU). In 2021, transport sector accounted for 37% of global CO_2 emissions from end-use sector and for 25.7% of the EU's total greenhouse gas emissions[1]. Global and European CO_2 emissions from transport sector are shown in Figure 1, expressed in million tons per year.

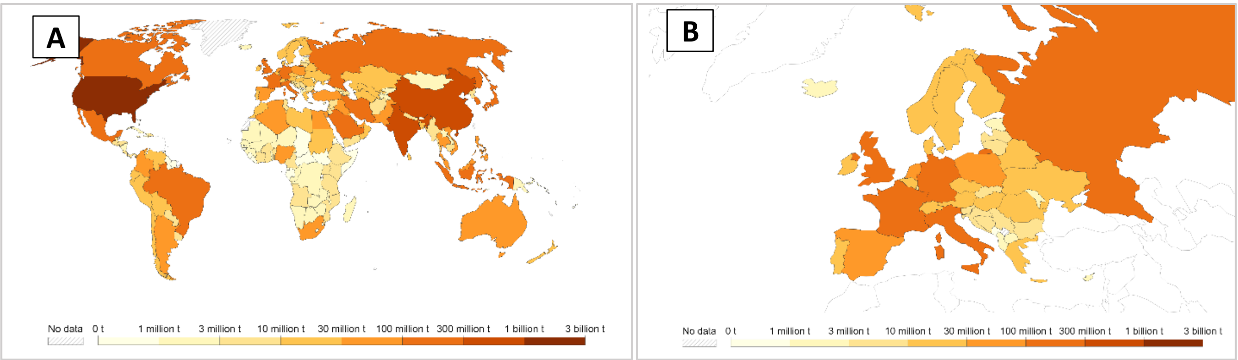

Figure 1. CO_2 emissions from transport sector (2019). A: Global emissions; B: European emissions. Source: Our World in Data.

Looking at the timeline, worldwide transportation emissions increased from 1990 to 2021 at an average 1.7% annual rate, higher than any other end-use industry. A similar pattern was found in Europe. The increase in transport emissions is primarily due to rising amounts of inland freight volumes and passenger transport. In addition to domestic transport, international aviation and navigation also contribute to the increase of the overall emissions related to transportation (Figure 2).

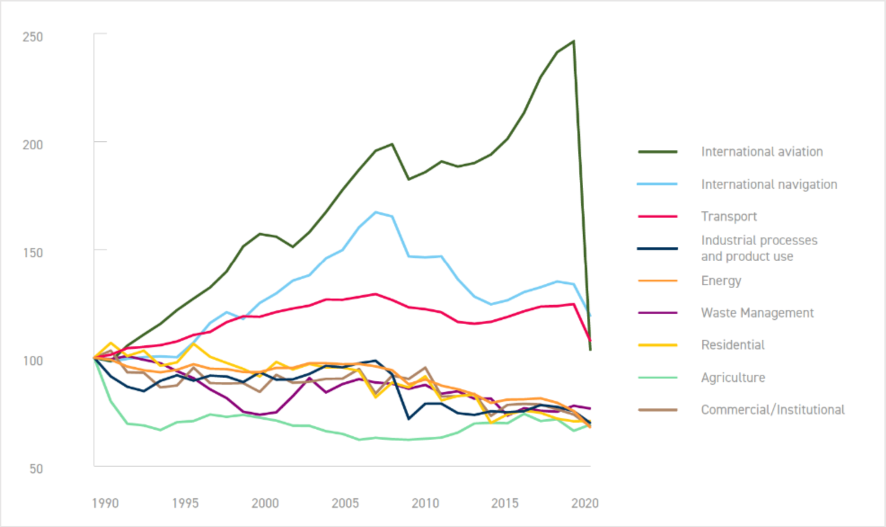

Figure 2. CO_2 emission trend by sector in the EU-27 (unit: % of 1990 level). Source: European Environmental Agency (EEA).

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[1] European Environment Agency (EEA), Greenhouse gas emissions from transport in Europe

The demand for transportation is expected to grow globally over the next several decades as the world's population and income rise, resulting in a growing number of people able to purchase cars, trains, and flights. The International Energy Agency (IEA)[2] forecasts that by 2070, demand for passenger and freight aviation would triple, vehicle ownership rates would rise by 60%, and global transport (measured in passenger-kilometers) would double. These elements working together could cause a significant rise in emissions from transport. When this is taken into account, the crucial role played by the decarbonisation of the transportation industry immediately emerges. This is especially true given that in 2021, Europe adopted the European Climate Law, which sets the goal of reaching zero net greenhouse gas emissions by the year 2050[3].

According to most recent data from European Environment Agency (EEA), oil-derived fuels in transport sector represent in Europe 92% of the total energy consumption, with major contribution given from road diesel (47%), road gasoline (18%), aviation kerosene (13%) and ship fuel oil (8%) [4]. The two main pathways commonly identified for decarbonisation are represented by efficiency improvement and the switch to fuels or energy carriers with lower carbon intensity. The switch to electric engines is thought to account for a sizeable portion of the decarbonisation of transportation. However, in the near future, electrification will be difficult for the majority of bigger vehicles, such as vans and trucks, and almost impractical for shipping and aviation due to a number of factors, including battery pricing, distances, weight, and performance. As a result, fuels in transportation will be required for a long time and the potential for biofuels in this regard can be extremely considerable, filling a significant share of the transport decarbonisation gap for the following decades.

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[2] International Energy Agency (IEA), Transport

[3] European Commission | Climate Action: European Climate Law

[4] European Environment Agency (EEA), Energy consumption in transport

2 EU policies shape biofuels development

The EU promotes biofuels through a number of policy instruments that have recently been introduced and that are being further elaborated. Among them stands out the Renewable Energy Directive (2009/28/EC) (now more often identified as REDI), whose updated version entered into force at the end of 2018 (2018/2001/EU) (now more often identified as RED II). The REDII and related regulations are now being revised. This is largely due to legislative proposals included in the "Fit for 55" package, that defines new initiatives like ReFuelEU Aviation and FuelEU Maritime, in addition to revising several current directives and legislations.

Before becoming a low, directive or regulation, the legislative proposals have to be approved via a "Trilogue" process, in which members of the European Council and the European Parliament examine them and have the authority to submit amendments to the original text. The "Trilogue" process is now ongoing for the various proposals of the “Fit for 55” package, with different levels of completion depending on the specific piece of legislation being discussed.

2.1 RED II Directive

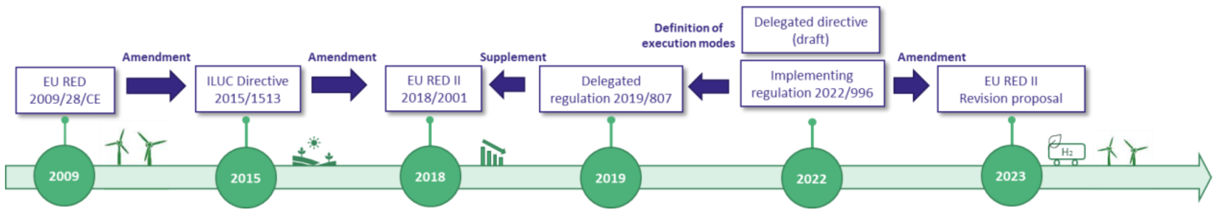

Figure 3. Renewable Energy Directive (RED) implementation timeline.

The Renewable Energy Directive (RED) was first introduced in 2009 and represents the legal framework for the development of renewable energy across all sectors of the EU economy. The Directive (2009/28/CE) was then revised, and the recast entered into force on 24/12/2018 (RED II Directive, 2018/2001)[5].

Overall Targets and Biofuels contribution to the Transport Sector Target

Article 3 of the RED II establishes two targets that must be met by 2030:

- An overall target of at least 32% renewable energy consumption, which Member States must achieve collectively;
- A sub-target for the transportation sector, which requires that a minimum share of 14% of the energy consumed in transportation comes from renewable sources in each Member State.

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[5] Renewable Energy Directive 2018/2001/EU

Within the REDII RES-T (Renewable Energy in Transport) objective of 14%, there is a gradually increasing sub-target for biofuels generated from advanced feedstocks (i.e., feedstocks classified in Part A of Annex IX). According to article 25, a minimum contribution of 0.2% of energy for transportation is expected by 2022, 1% by 2025, and at least 3.5% by 2030. Part B of Annex IX further includes a list of different feedstocks for the generation of biofuels and biogas for transportation (i.e., used cooking oil and animal fat), which are instead limited to a contribution of 1.7% within 2030. Moreover, article 27 provides the rules for Member States to calculate the share of renewable energy in the transportation sector. In particular:

- Advanced biofuels can be double - counted for both the 3.5% objective (which becomes 1.75% in real quantities) and the 14% target;
- Biofuels delivered to the marine and aviation industries – with the exception of fuels derived from food and feed crops – can be counted 1.2 times.

Finally, the REDII also defines a set of sustainability and GHG reduction criteria that biofuels used in transportation must achieve in order to be counted toward the overall 14% target and be eligible for funding from public authorities. Sustainability and GHG reduction criteria are listed in ANNEX V (liquid biofuels) and ANNEX VI (solid and gaseous biomass for power and heat generation).

Figure 4 shows the evolution of the use of biofuels in Europe, including advanced biofuels, from 2005 to 2020.

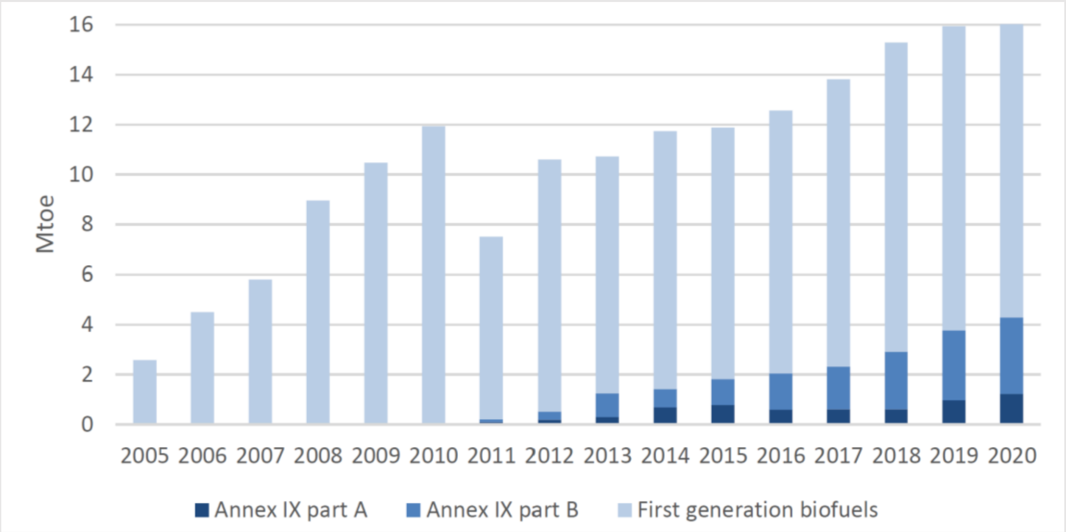

Figure 4. The evolution of the use of biofuels in Europe, including advanced biofuels. Source: OECD, 2021

<u>RED II support for low-ILUC risk biomass and biofuels</u>

RED II defines low Indirect Land Use Change (ILUC)-risk biofuels, bioliquids, and biomass fuels as those biofuels produced in a way that prevents the displacement of food and feed crops. The certification standards for identifying such low ILUC-risk biofuels, bioliquids, and biomass fuels were established by the Commission Delegated Regulation (EU) 2019/807 supplementing RED II

Directive. According to the Regulation, biofuels can be certified as low ILUC-risk if they adhere to the sustainability criteria outlined in Article 29 of the Directive and if they have been produced from additional feedstock obtained through *additionality measures.* Additional feedstock can be produced through adoption of two main pathways:

1) Cultivation of food and feed crops on abandoned land or severely degraded land;
2) Cultivation of additional feedstock on a cultivated land through adoption of improved agricultural practices (e.g., cover cropping, catch cropping, etc.)

Biofuels produced from certified low ILUC-risk crops are considered eligible for contributing to the 14% target; on the contrary, a progressive phase-out for high ILUC-risk biofuels is established, starting in 2023 and reaching 0% by 2030.

At present, none of the entries in Annex IX are based on low-ILUC risk certification; however, Article 28 of the Directive allows for the addition of new entries to the list if the feedstock is converted into biofuels using advanced (Part A) or mature (Part B) technologies. As a result, production systems that meet the "additionality" requirements might be credited twice towards the specified goals, encouraging the adoption of innovative and sustainable biofuel production routes.

2.2 Fit for 55 package

2.2.1 Amendment to the Renewable Energy Directive (RED) II

The proposed amendment aims to strengthen the renewable energy targets previously set, aiming to achieve by 2030:

1) An overall target of 42.5% share of energy from renewable sources, which Member State must achieve together;
2) A specific target for the transportation sector, for which each Member State is required to attain either a minimum share of 29% renewable energy in their final energy consumption, or a greenhouse gas intensity reduction of at least 14.5 %, compared to the baseline set out in Article 27.

For the first target (1), which is considered as essential to align with the goal of reducing total greenhouse gas emissions by 55% compared to the 1990 baseline, there is a suggested supplementary objective of an extra 2.5%, which Member States are encouraged to pursue, thus potentially leading to a Union Renewable Energy target of up to 45%.

The proposal also raises the target for the advanced biofuels to 5.5% in 2030, introducing a sub-target for renewable fuels of non-biological origin (RFNBO), which must account for at least 1% of the total.

2.2.2 REFuelEU aviation

The newly introduced ReFuel EU aviation legislative proposal outlines a progressive set of mandates aimed at promoting the adoption of Sustainable Aviation Fuels (SAF) in the aviation sector. These fuels have the potential to significantly reduce aircraft emissions; however, their current usage remains minimal, accounting for only 0.05% of total jet fuel consumption[6].

In the context of ReFuelEU aviation, SAF include biofuels which fall into three categories:

- Advanced biofuels (produced from feedstock listed in REDII, Annex IX Part A).
- Biofuels produced from feedstock listed in REDII, Annex IX Part B.
- Liquid and gaseous fuels that are produced from waste processing gas and exhaust gas of non-renewable origin, which are in turn produced as an unavoidable and unintentional consequence of the production process in industrial installations (so-called Recycled Carbon Fuels[7]), complying with the 70 % greenhouse gas emissions savings threshold.

Until December 2034, SAF may also include non-advanced biofuels that meet REDII's sustainability and GHG emissions criteria, except for biofuels derived from 'food and feed crops, palm fatty acid distillate, all palm and soy-derived materials, as well as soap stock and its derivatives'.

The mandates set by the proposal are calculated on a volume basis rather on an energy basis, as in RED II, and there are no restrictions on use of waste oils and animal fats, as in RED II. Mandates (volume shares) are reported in ANNEX I of the proposal and summarised in Table 1.

Table 1. Minimum shares of SAF and synthetic aviation fuels as proposed in the compromised text of ReFuelEU Aviation resulting from interinstitutional negotiations.

Year	**2025**	**2030**	**2032**	**2034**	**2035**	**2040**	**2045**	**2050**
Total SAF share	2%	6%	6%	6%	20%	34%	42%	70%
Of which synthetic aviation fuels		*0.7%*	*1.2%*	*2%*	*5%*	*10%*	*15%*	*35%*

As can be seen in the previous table, a sub-target is set for synthetic aviation fuels, which include renewable hydrogen (produced from renewable electricity or from renewable liquid or gaseous fuels of non-biological origin), renewable electricity, renewable fuels of non-biological origin (RFNBO).

After its initial release, the proposal received suggested amendments from both the Council of the European Union and the European Parliament. Subsequent interinstitutional negotiations resulted in a draft compromise text, representing a political synthesis of the proposals, which

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[6] Sustainable Aviation Fuels – ReFuelEU Aviation

[7] RCF comprise liquid and gaseous fuels that are produced from liquid or solid waste streams of non- renewable origin.

was approved by the Permanent Representative Committee on June 16, 2023. After Parliament has given its final approval, the regulation will eventually enter into force

2.2.3 FuelEU Maritime regulation

The FuelEU Maritime initiative[8] is a new regulation proposal presented by the European Commission in July 2021, within the "Fit for 55" package. The initiative mandates that all ships with a gross tonnage (GT) of 5,000 and above must begin reducing the GHG intensity of their onboard energy consumption. The proposal outlines a step-by-step approach to decreasing the average carbon intensity from 2025 to 2050, with 5-year intervals, using the 2020 fleet average of 91.16 gCO_2/MJ as a reference point (Table 2).

Table 2. GHG Reduction trajectory for the average fleet emissions, compared to 2020 average emission baseline of 91.16 gCO2/MJ.

	Year	***2025***	***2030***	***2035***	***2040***	***2045***	***2050***
ReFuel Maritime	GHG intensity reduction	2%	6%	14.5%	31%	62%	80%

Furthermore, it is mandated that all ships progressively increase their usage of renewable and low-carbon fuels. The proposal stipulates that in cases where biofuels, biogas, renewable fuels of non-biological origin, and recycled carbon fuels, as defined in Directive (EU) 2018/2001, are considered, they must adhere to the sustainability and GHG reduction standards outlined in Directive (EU) 2018/2001 itself.

The FuelEU Maritime proposal underwent the same Trilogue process as the other proposals in the Fit For 55 package; in April 2023, an informal agreement was reached between the European Council and the European Parliament on this proposal; to be finalized, it must be approved by both the Parliament and the Council as a whole.

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[8] Sustainable maritime fuels | FuelEU Maritime Initiative

3 State of the art for key technologies for advanced biofuels production

This chapter strongly builds on earlier tasks of WP3 of the BIKE project, along with reference to the JRC Technical Report on Advanced Biofuels[9]. Its primary objective is to assess the opportunities for a market uptake of advanced biofuels, with particular attention to the technologies linked to the BIKE case studies.

3.1 Advanced biofuels conversion pathways

Advanced biofuels may be produced using various methods, including biochemical, thermochemical, and oleochemical processes; the most promising conversion pathways available at present are represented in the following two flowcharts (Figure 5).

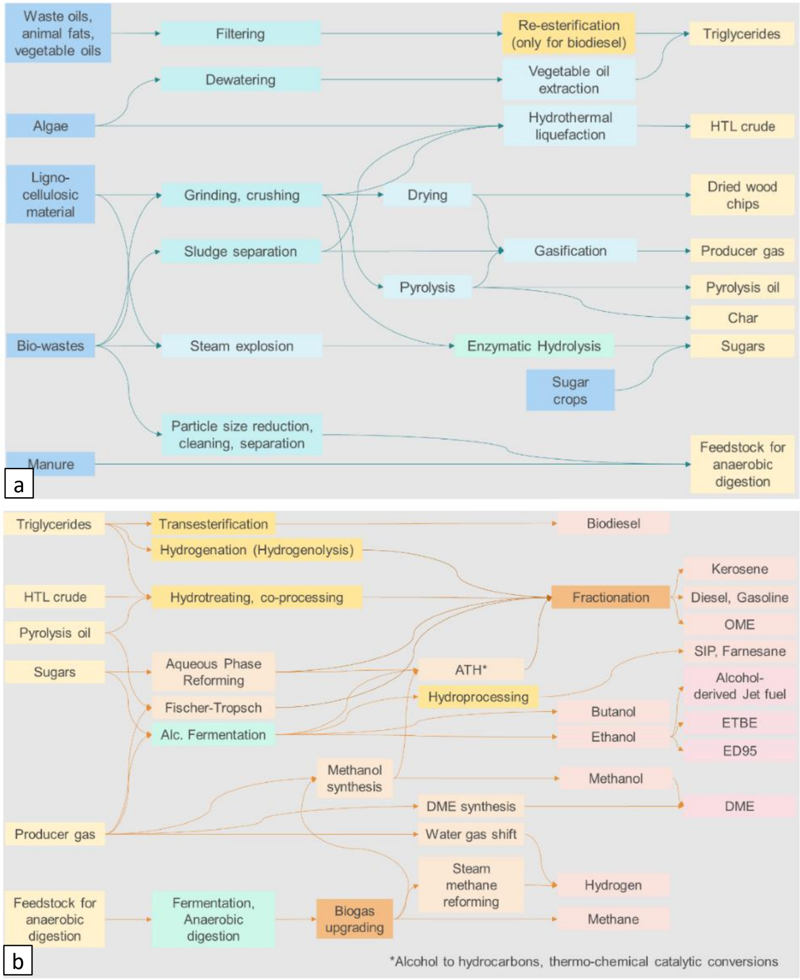

Figure 5. Selected pathways to produce biofuels from eligible feedstock. The flowchart is divided in a pretreatment section (a) and a conversion section (b). Source: JRC Technical Report, 2022.

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[9] European Commission, JRC, Hurtig, O. et al., *Clean Energy Technology Observatory, Advanced biofuels in the European Union : status report on technology development, trends, value chains and markets : 2022*, Publications Office of the European Union, 2022, https://data.europa.eu/doi/10.2760/938743

As known, the activities of BIKE are organised around four case studies, representing two value chains that match the definition for additionality, as defined by the Delegated Act of the European Commission 2019/807, supplementing the RED II Directive.

The following paragraph will focus on investigating the Technology Readiness Level (TRL) of the conversion pathways related to the BIKE case studies. These pathways include: (i) the conversion of lignocellulosic biomass to ethanol, (ii) the conversion of vegetable oils to renewable diesel, and (iii) the conversione of biomethane from decentralized Anaerobic Digestion (AD) plants to liquid biofuels (i.e. FT liquids and MeOH).

3.2 Technology Readiness Level (TRL)

The Technology Readiness Level (TRL) assesses the technology's maturity for new production pathways. A TRL level of 3-5 suggests a route in the development phase, a TRL level of 5-7 indicates stages in demonstration mode, a TRL level of 6-8 indicates phases of system and subsystem development, and a TRL level of 7-9 indicates phases of systems testing for launch and operations. Technology with a TRL level of 10 is a proven and established technology[10].

Lignocellulosic biomass to ethanol

The conversion pathway that allows for production of ethanol from lignocellulosic biomass involves a first step of pretreatment and enzymatic hydrolysis and a second step of sugars fermentation. Pretreatment, usually thermal or thermochemical, removes lignin and enables the disruption of the cellular structure. The enzymatic hydrolysis breaks the large molecules of cellulose and hemicellulose in monomeric sugars. Afterwards, the sugars obtained from the pretreatment section can be processed into ethanol through the well-established technology of fermentation. In 2022, Europe accounted for a total lignocellulosic ethanol production capacity of 125 million liters[11], with 12 operating plants (of which 6 commercial plants and 6 demo plants). On the other side, first-generation ethanol, produced via fermentation of plant sugars and starches and obtained from crops such as wheat and corn, is considered as "non-advanced" but accounted for a total bioethanol production of 5.63 billion liters[11]. Although the process of ethanol production from lignocellulosic biomass is not yet fully commercial, it is considered one of the most promising for the future production of advanced biofuels.

Process description	
Input	Lignocellulosic material
Output	Ethanol
Technical development	
TRL (2019)	8/9
TRL (2030)	9/10
Plant example	Clariant, Podari (Romania); Versalis, Crescentino (Italy)

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[10] European Maritime Safety Agency (2022), Update on potential of biofuels in shipping, EMSA, Lisbon

[11] United States Department of Agriculture (USDA), Biofuels Annual, 2023

Transesterification of triglycerides

Fatty Acid Methyl Ester (FAME), the most widely used biofuel in the EU, was formerly mostly produced from vegetable oils like rapeseed and palm oil, while now there is a rising interest in using waste cooking oils and animal fats. The process involves a first step of pretreatment which allows for removal of water and various contaminant, and a second step of transesterification, which converts the oil molecules (triglycerides) into methyl ester (biodiesel) and glycerol. The transesterification processes take place mixing oils to alcohol (usually methanol) and at the presence of a catalyst. Methanol is typically fossil-based, and even if use of bioethanol instead of fossil methanol has been investigated, the production of FAEE (Fatty Acid Ethyl Ester) is not commercially successful due to a series of reasons, including high price of ethanol compared to methanol and technical difficulties of the process if compared to FAME production. In 2022, Europe accounted for a total production capacity of 12.2 billion liters of FAME[12], with 170 operating plants.

Process description	
Input	Triglycerides and waste oils
Output	Biodiesel
Technical development	
TRL (2019)	10
TRL (2030)	10
Plant example	Agroinvest, Greece

Hydroprocessing of oil

Another established route for conversion of vegetable oils into renewable diesel is represented by *hydroprocessing* (also called *hydrotreating*), an alternative process to esterification which brings to the production of HVO (Hydrotreated Vegetable Oil). HVO is also called HEFA (Hydroprocessed Esters and Fatty Acids). Hydroprocessing consists in a range of catalytic processes including hydrocracking and hydrogenation. Hydrocracking breaks big molecules into smaller ones using hydrogen, simultaneously removing sulphur and nitrogen. Hydrogenation saturates the double bonds present in a lipid molecule through catalytic addition of hydrogen.

In 2022, Europe accounted for 3.96 billion liters of HVO/HEFA total production[12], with 10 operating plants and several commercial-size plants currently in production.

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[12] United States Department of Agriculture (USDA), Biofuels Annual, 2023

Process description	
Input	Triglycerides from waste oils, animal fats, vegetable oils or algae, HTL crude, pyrolysis oil, hydrogen
Output	HVO
Technical development	
TRL (2019)	9/10
TRL (2030)	10
Plant example	La Mede (Total), France; ENI raffineria di Gela, Italy

Biomethane from anaerobic digestion

Anaerobic Digestion (AD) is a process in which microorganisms convert feedstock under anaerobic conditions, through a sequence of biological processes such as: hydrolysis, acidogenesis, acetogenesis, and methanogenesis. The resulting biogas comprises methane (50 - 70%), carbon dioxide (30 - 40%), as well as other gases like hydrogen, nitrogen, hydrogen sulphide, ammonia, and trace quantities of carbohydrates and organic silicon compounds (e.g., siloxanes).

The process of biogas upgrading to biomethane involves the removal of carbon dioxide to enhance the energy density, as well as the elimination of water, hydrogen sulphide, and other impurities. Various technologies are employed for this purpose, including Pressurized Water Scrubbing (PWS), Pressure Swing Adsorption (PSA), physical absorption, chemical absorption, membrane separation, and cryogenic separation. Some commercially operating upgrading technologies include membrane separation and water/chemical scrubbing.

Anaerobic digestion followed by biogas upgrading to biomethane has been effectively demonstrated, leading to significant progress in Europe. In 2022, 1322 biomethane-producing facilities were surveyed in total, marking an increase of nearly 30% compared to the facilities in 2021[13]. Currently, the EU-27 produces 3 billion cubic meters (bcm) of biomethane and 15 bcm of biogas [14].

Process description	
Input	biowastes, animal manure
Output	biomethane
Technical development	
TRL (2019)	10
TRL (2030)	10
Plant example	Fattoria della Piana, Italy

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[13] European Biogas Association (EBA) statistical report, 2022

[14] A Gas for Climate Report, 2022

As known, one of the BIKE case studies involves the production of biomethane in decentralized AD plants and subsequent conversion into liquid biofuels in centralized plants. The most commercially successful technologies for this conversion pathway are represented by the Fisher-Tropsch plants and MeOH plants. The production of Fischer-Tropsch fuels and Methanol necessitates the use of syngas, which is a mixture of carbon monoxide (CO) and hydrogen (H_2), as a feedstock. Consequently, the production chain must include a step to reform biomethane into syngas. Various methods can be employed to convert methane to syngas, including:

a) Steam methane reforming;

b) Partial oxidation;

c) Autothermal reforming;

d) Dry methane reforming.

Currently, steam methane reforming (SMR) and partial oxidation (POX) represent the most industrially established approaches to produce syngas. The SMR method produces syngas by reaction of hydrocarbons with water. The reaction is strongly endothermic and represented by this equilibrium:

$$CH_4 + H_2O = CO + 3H_2$$

In the POX process, biomethane is mixed with a limited amount of oxygen in an exothermic process. The reaction is the following:

$$CH_4 + \frac{1}{2} O_2 = CO + 2H_2$$

__Biomethane to FT diesel__

Fischer-Tropsch (FT) synthesis utilizes syngas derived from biomethane reforming to produce diverse hydrocarbons, including gasoline and diesel. Optimal H_2/CO ratio and effective syngas treatment are crucial for this process. The FT reaction, catalyzed by specialized catalysts, is fundamentally an exothermic dehydration reaction. Operating pressures ranging from 10 to 40 bar and the choice of catalyst and temperatures influence the nature of hydrocarbons produced. For instance, iron catalysts at higher temperatures (300–350 °C) favor gasoline production, while cobalt catalysts at lower temperatures (200-240 °C) promote diesel formation. Higher H_2/CO ratios promote the synthesis of lighter hydrocarbons. After FT liquids production, further processing is necessary to obtain finished fuels, typically involving hydrotreating, hydrocracking, isomerization, and fractionation (Figure 6).

FT synthesis is a well-established technology, proven and operational in coal-to-liquid or gas-to-liquid plants for decades. Commercial-scale FT plants include the Pearl GTL from Shell and Qatar Petroleum in Qatar (140,000 bpd capacity), the Mossel Bay GTL from PetroSA in South Africa

(36,000 bpd capacity), and the Bintulu GTL from Shell in Malaysia (14,700 bpd capacity), all of which located outside of Europe. These examples represent massive facilities that would not fit in the European biomethane-to-liquid fuels production model. However, by taking advantage of new technologies, GTL-FT plants could be scaled down and provide a cost-effective way to make use of smaller biogas and biomethane resources in Europe[15].

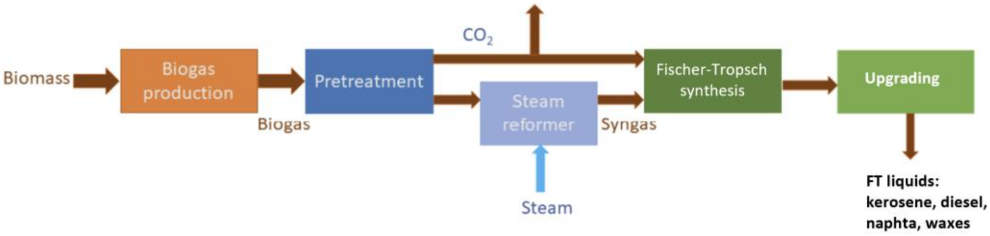

Figure 6. A general schematic of reformer-based FT liquids production.

Biomethane to biomethanol

An alternative to FT synthesis of syngas for producing liquid fuel is related to the production of methanol. Methanol is a global chemical commodity and an emerging energy source. The majority of current methanol production stems from fossil fuels, with approximately 65% coming from natural gas reforming and 35% from coal gasification, while less than 1% is derived from renewable sources[16]. The potential of renewable methanol holds promise in reducing emissions within the transportation sector. Biomethanol can be produced through three primary pathways: gasification, reforming from biogas, and extraction from the pulping process in pulp mills. Established routes for producing methanol from fossil resources can be readily applied to renewable feedstocks. The production of biomethanol through gasification and reforming exhibits strong parallels with non-renewable methanol production, differing primarily in the syngas generation step. Consequently, efficient and cost-effective generation of syngas from renewable sources is key for successful biomethanol production. Figure 7 provides an overview of biogas-based biomethanol production.

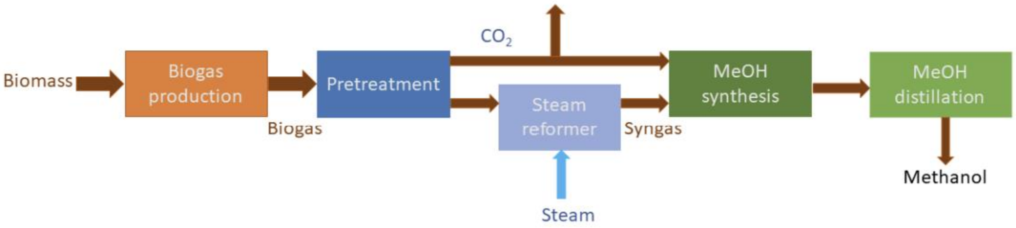

Figure 7. A general schematic of reformer-based biomethanol production. Source: ETIP bioenergy, 2021.

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[15] *Brancaccio, E. (2018): Small Scale and Modular Technologies for Gas to Liquid Industry*
[16] ETIP Bioenergy (2021), *Biomethanol production and use as a fuel.*

Presently, there is a growing interest towards employing methanol within the maritime sector, driven by the tightening emissions legislation (2.2.3 FuelEU Maritime regulation). At a global level, the International Maritime Organization (IMO) has implemented new regulations to reduce sulfur content within marine fuels and mitigate NO_X emissions within controlled emission regions, notably coastal zones[17]. This has led to the development of novel technologies to meet these mandates, with methanol emerging as a leading candidate as an alternative fuel. Methanol is indeed sulfur-free and upon combustion produces low particulate matter and low amounts of NOx.

3.3 Sustainable aviation fuels (SAF) production routes

As already mentioned in Chapter 2 (EU policies shape biofuels development) the term "Sustainable Aviation Fuel (SAF)" refers to the following three categories of liquid fuels: Annex IX Part B biofuels, advanced biofuels (Annex IX Part A biofuels) and Recycled Carbon Fuels (RFC), which comprise liquid and gaseous fuels that are produced from liquid or solid waste streams of non- renewable origin.

The production and utilization of Sustainable Aviation Fuel (SAF) are subject to certification by the ASTM (American Society for Testing and Materials). ASTM is the primary aviation fuel certification body, responsible for certifying both conventional fossil fuels and sustainable aviation fuels. To obtain ASTM certification for a new production pathway, the technology developer must go through various stages known as "Tiers". In these Tiers, the developer must describe the production process and present test results demonstrating the feasibility of the pathway. Once all requirements are successfully met and filed to the ASTM committee, the pathway is granted an approved Annex under ASTM D7566[18]. The approved Annex signifies that the pathway meets the necessary standards and is approved for use in commercial aviation.

Among the certified conversion pathways are Hydroprocessed Esters and Fatty Acids (HEFA), which has already been approved for commercial aviation use. Additionally, Alcohol-to-Jet (AtJ) and Fischer-Tropsch to Synthetic Paraffinic Kerosene (FT-to-SPK) are also approved conversion pathways for sustainable aviation fuels.

Hydroprocessed Esters and Fatty Acids (HEFA)

At present, the most commercially conversion pathway for Sustainable Aviation Fuels (SAF) production is HEFA. which produces SAF using vegetable oils and waste lipids like used cooking oil and animal fats. In order to make HVO/HEFA suitable as an aviation fuel, additional downstream processes (e.g., isomerization and fractionation) are required to meet the strict specification of the sector. Currently, about 15-50% of the fuel output from HVO/HEFA facilities could be separated and used as Biojet/SAF, provided some additional infrastructure is

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[17] European Maritime Safety Agency (2022), *Update on potential of biofuels in shipping*, EMSA, Lisbon

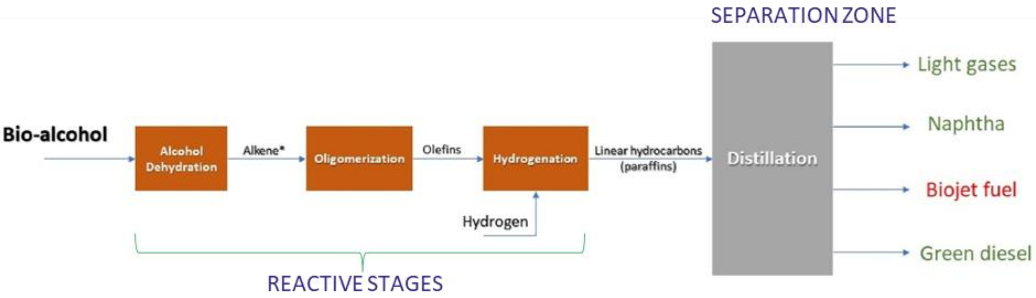
[18] ASTM D7566 | Standard Specification for Aviation Turbine Fuel Containing Synthesized Hydrocarbons

established in the refinery [19].The blend of SAF with fossil kerosene is restricted to a maximum of 50%, according to the limitations imposed by certification.

Annex IX Part B biofuels can play a significant role in decarbonising aviation. However, their potential is limited by the availability of feedstock included in Annex IX Part B, and this limitation is expected to become more pronounced in the future. These feedstocks are in high demand for producing other transport biofuels, and their aggregation, including collection and supply chain management, lacks consistent organization at the EU level[20]. Moreover, there are concerns related to the use of used cooking oil, which might include imported fraudulent material, and inedible animal fats that carry high indirect greenhouse gas emissions. The decarbonisation potential of Part B biofuels is consequently relatively limited compared to that of advanced biofuels produced from Annex IX Part A feedstocks[21].

Alcohols to Jet (AtJ)

This route, currently at TRL 7-8, is certified by ASTM and consists of converting alcohol into jet fuel. The alcohol is the product resulting from the fermentation of sugar or starch crops (corn, sugarcane, wheat). Alternatively, the alcohol can also result from processed lignocellulosic feedstock (agricultural and forest residues). The ATJ process process involves three reactive stages: dehydration of alcohol, oligomerization and hydrogenation, along with the separation stage to purify naphtha, biojet fuel and green diesel. The certification currently limits the blend of alcohol in jet fuels to a maximum of 50%.



*according with alcohol selected

Figure 8. Block diagram of convention ATJ process. Source: Romero-Izquierdo et al, 2021.

In a recent study[22] the ATJ process has been modelled and studied in a simulation environment to produce biojet fuel from lignocellulosic bioethanol. Based on the results, **21 % biojet fuel yield** was reached at the end of the process.

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[19] IRENA (2021), Reaching Zero with Renewables: Biojet fuels, International Renewable Energy Agency, Abu Dhabi

[20] European Commission, 2021 | IMPACT ASSESSMENT Accompanying the Proposal for a Regulation of the European Parliament and of the Council on ensuring a level playing field for sustainable air transport

[21] ICCT, 2022 | Recommendations for the ReFuelEU aviation Trilogue

[22] Romero-Izquierdo et al., "*Intensification of the alcohol-to-jet process to produce renewable aviation fuel*", Chemical Engineering and Processing - Process Intensification, Volume 160, 2021, 108270, ISSN 0255-2701, https://doi.org/10.1016/j.cep.2020.108270

Fischer-Tropsch (FT) to Synthetic Paraffinic Kerosene (SPK)

This route was certified by the ASTM and currently stands at TRL 6-8. Syngas could be obtained from biomethane reforming, followed by Fischer-Tropsch synthesis for kerosene production. Blending with fossil jet fuel is limited to a maximum of 50%.

4 Evaluation of low ILUC perspectives in EU according to BIKE case studies

As known, the activities of BIKE are organized around two low ILUC-risk value chains that match the definition of additionality given by RED II Directive: 1) Cultivation on unused, abandoned or severely degraded lands and 2) Productivity increased through improved agricultural practices. The BIKE project identified two case studies per each value chain, i.e. four in total, where low ILUC-risk feedstocks are used for the production of three types of biofuels: cellulosic ethanol, renewable diesel (HVO), and biomethane. Two case studies refer to cultivation on unused lands and are: i) perennial grasses to advanced (lignocellulosic) ethanol, and ii) castor beans to renewable diesel (HVO). The other two case studies refer to implementation of sequential cropping systems and are: iii) brassica carinata for renewable diesel production and iv) the Biogas Done Right (BDR) model for biomethane-to-liquid fuels.

The following paragraphs build on the outcomes of Task 3.3 of the BIKE project, where the potential for replicability of the four BIKE case studies in the European Union was assessed. The assessment focused on a short to medium-term application, thus relying on existing infrastructure and technologies. For a more detailed comprehension of the results, please refer to Deliverable 3.3 of the BIKE project.

4.1 Cultivation in unused, abandoned or severely degraded lands

Case Study 1 – Perennial crops for bioethanol

The study has been performed on the whole EU territory. The target crops considered are switchgrass and miscanthus. First, attainable yields of the target crops have been simulated in the area of underutilized croplands of Europe, which is estimated to be approximately 5.3 million hectares. Secondly, two possible sustainable scenarios for biomass supply have been identified, consisting in supply distances of 70 km and 150 km from bioethanol refineries. The selected refineries consist in operational and planned/under constructions second generation bioethanol plants, and also first-generation bioethanol plants with possibility of upgrade to second generation. The assessment has been conducted considering a short-term period (i.e., 2030) as feasible for implementation of this value chain in second-generation bioethanol plants, and a mid-term period (i.e., 2050) for implementation of this value chain in existing first-generation bioethanol plants.

Example outputs of the assessment are shown in Figure 9.

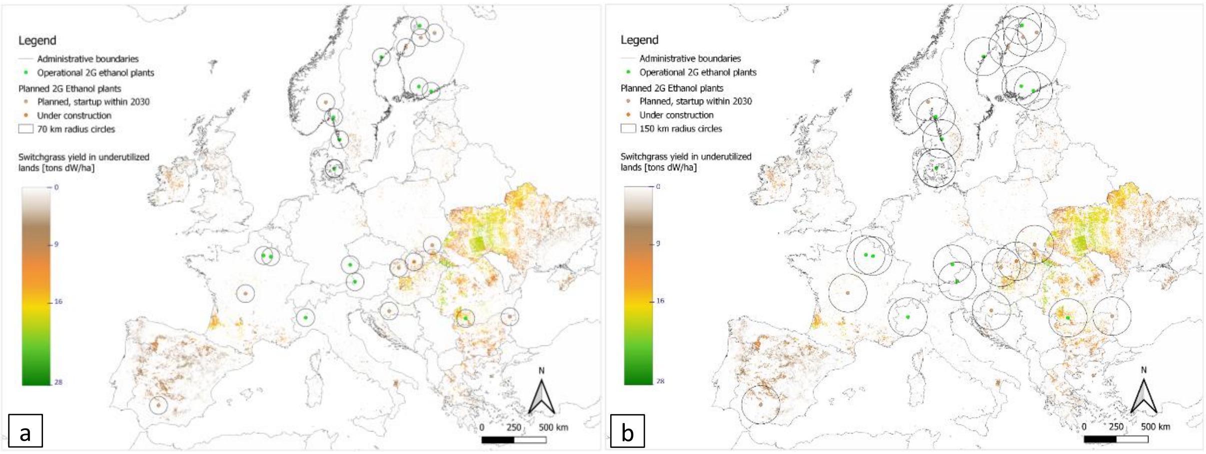

Figure 9. Output maps showing switchgrass attainable yield in EU unused lands and supply distance of 70 km (a) and 150 km (b) from second-generation bioethanol plants.

Results from estimation of the potential biomass and bioethanol productions are reported in Table 3 and Table 4. It is worth noting that only those cases for which a minimum annual dry biomass production of 100,000 tons was met or exceeded have been considered as promising and reported in the tables below.

Table 3. Summary of promising case studies identified for bioethanol production considering 70 km supply radius from biorefineries.

Name of refinery	**Type of refinery**	**Country**	**Supply distance**	**Target crop**	**Potential dry biomass production (tons/year)**	**Potential bioethanol production (tons/year)**	**Year**
Clariant Products	Second-generation	Romania	70 km	Switchgrass	498,623	68,651	2030
Vertex Bioenergy Babilafuente	First-generation	Spain	70 km	Switchgrass	347,467	47,839	2050
Vertex Bioenergy Galicia	First-generation	Spain	70 km	Switchgrass	157,321	21,660	2050
Hungrana Bioeconomy Company	First-generation	Hungary	70 km	Switchgrass	104,295	14,359	2050
Almagest AD	First-generation	Bulgaria	70 km	Switchgrass	219,866	30,271	2050
Essentica Ethanol Factory	First-generation	Bulgaria	70 km	Switchgrass	173,195	23,846	2050

Table 4. Summary of promising case studies identified for bioethanol production considering 150 km supply radius from biorefineries.

Name of refinery	Type of refinery	Country	Supply distance	Target crop	Potential dry biomass production (tons/year)	Potential bioethanol production (tons/year)	Year
Clariant Products	Second-generation	Romania	150 km	Switchgrass	1,131,775	155,823	2030
Sainc Energy Limited	Second-generation	Spain	150 km	Switchgrass	630,856	86,857	2030
Bioskoh	Second-generation	Slovakia	150 km	Switchgrass	341,731	47,050	2030
Envirals Leopoldov	Second-generation	Slovakia	150 km	Switchgrass	240,042	33,049	2030
Jedlicze Site	Second-generation	Poland	150 km	Switchgrass	544,118	74,914	2030
Vertex Bioenergy, Lacq	First-generation	France	150 km	Switchgrass	787,757	108,459	2050
Vertex Bioenergy	First-generation	Spain	150 km	Switchgrass	191,345	26,344	2050
Vertex Bioenergy Babilafuente	First-generation	Spain	150 km	Switchgrass	2,131,886	293,519	2050
Vertex Bioenergy Bioetanol Galicia SA	First-generation	Spain	150 km	Switchgrass	585,146	80,563	2050
Manchester Biorefinery (Cargill/Royal Nedalco)	First-generation	UK	150 km	Switchgrass	240,431	33,103	2050
Ensus UK	First-generation	UK	150 km	Switchgrass	179,926	24,772	2050
Agrar-beta	First-generation	Hungary	150 km	Switchgrass	272,385	37,502	2050
Pannonia Bio Zrt.	First-generation	Hungary	150 km	Switchgrass	288,697	39,748	2050
Hungrana Bioeconomy Company	First-generation	Hungary	150 km	Switchgrass	326,583	44,964	2050
Almagest AD	First-generation	Bulgaria	150 km	Switchgrass	754,676	103,904	2050
Essentica Ethanol Factory	First-generation	Bulgaria	150 km	Switchgrass	877,134	120,764	2050
Enviral	First-generation	Slovakia	150 km	Switchgrass	236,971	32,626	2050

According to the obtained results, the **estimated potential production of bioethanol** from perennial crops cultivation in unused lands would be of **about 397,700 tons in the year 2030** and of **1,340,000 tons in the year 2050,** considering the scenario of 150 km supply distance from biorefineries.

Case study 2 – Castor bean cultivation for renewable diesel production

The study has been performed considering only mediterranean regions of Europe. In accordance with the methodology employed for the case study on perennial crops, the castor bean case study involved integrating geospatial data regarding unused lands and corresponding target crop attainable yield, subsequently calculating the potential oil production within a certain supply radius from suitable biorefineries. The supply distances considered for this case study are 230 km and 500 km from existing HVO and biodiesel (FAME) refineries (the latter considered only in those areas in which HVO technology is not established at a commercial scale). To identify the most promising case studies, a minimum value of 20,000 tons of annual oil production has been set as a threshold. Obtained results are summarised in Table 5.

Table 5. Summary of most promising case studies identified and potential HVO/biodiesel production from castor oil.

Name of refinery	Type of refinery	Country	Supply distance	Potential oil production (tons/year)	Potential HVO/biodiesel production (tons/year)	Year
CEPSA plants	HVO	Spain	230 km	136,815	95,771	2030
Complejo Industrial de Cartagena de Repsol	HVO	Spain	230 km	191,876	134,313	2030
Eni raffineria di Livorno	HVO	Italy	230 km	29,411	20,588	2030
Biocom energia	Biodiesel	Italy	230 km	336,230	319,419	2030
Agroinvest s.a.	Biodiesel	Greece	230 km	267,168	253,810	2030
Eni raffineria di Gela	HVO	Italy	500 km	63,103	44,172	2030
CEPSA plants	HVO	Spain	500 km	927,695	649,387	2030
Agroinvest s.a.	Biodiesel	Greece	500 km	990,798	941,258	2030

According to the obtained results, in mediterranean areas could be produced a total of **824,000 tons of renewable diesel in the year 2030**, considering **a supply distance of 230 km**. **The amount would double to 1,635,0007 tons considering a supply distance of 500 km.** Of this latter amount, 693,600 tons would be of HVO and 941,000 would be of biodiesel.

4.2 Yield increased through improved agricultural practices

Case Study 3 – Brassica Carinata cultivation for renewable diesel production

The investigation for this case study was conducted in European Mediterranean areas. Since the successful establishment of *Brassica Carinata* in Mediterranean regions depends on its rotational fit into current cropping system, the methodology adopted for the replicability potential assessment involved the following steps:

- Identification of the most common sequential crop calendars in mediterranean areas and into which brassica carinata could be incorporated (Figure 10);

- Determination of the hectares of arable land involved in the selected cultivation schemes;
- Brassica yield modelling on these lands and estimation of the possible annual oil production, considering ranges of 230 km and 500 km from existing HVO and biodiesel refineries (the latter considered only in those areas in which HVO technology is not established at a commercial scale).

Brassica carinata can be grown either as a winter cover crop or as a summer cover crop: both varieties have been considered in the study. Moreover, as a conservative scenario, 25% of identified arable lands was considered as available every year for brassica cultivation. Finally, the identification of the most promising cases has been conducted considering an annual production of 20,000 tons of oil as a threshold to meet or exceed. Results are summarised in Table 6.

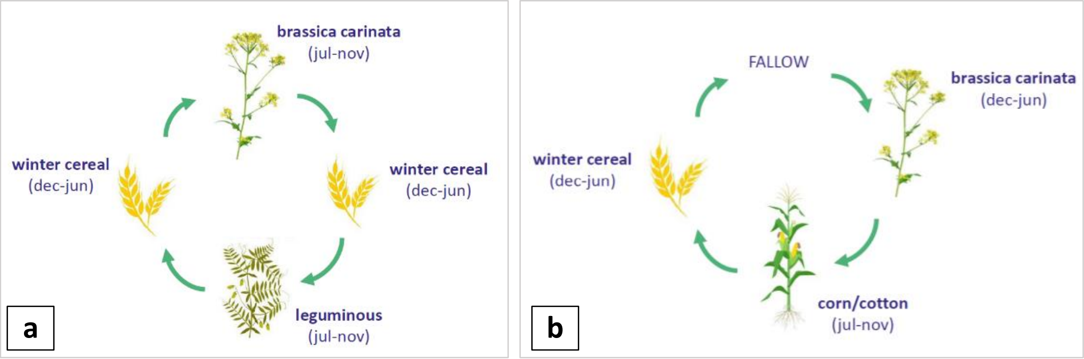

Figure 10. Identified rotation scheme for incorporating brassica carinata as a summer cover crop (a) or as a winter cover crop (b).

Table 6. Summary of most promising case studies identified and potential HVO/biodiesel production from brassica oil.

Name of refinery	Type of refinery	Scenario	Country	Supply distance	Oil production (t/y)	HVO/biodiesel production (t/y)	Year
Eni raffineria di Gela Spa	HVO	Brassica summer cover crop	Italy	230 km	31,856	22,299	2030
Eni raffineria di Livorno	HVO	Brassica summer cover crop	Italy	230 km	71,396	49,977	2030
CEPSA plants	HVO	Brassica summer cover crop	Spain	230 km	84,218	58,953	2030
Complejo Industrial de Cartagena de Repsol	HVO	Brassica summer cover crop	Spain	230 km	27,847	19,493	2030
Biocom Energia	Biodiesel	Brassica summer cover crop	Spain	230 km	88,444	84,022	2030
Greenswitch	Biodiesel	Brassica summer cover crop	Italy	230 km	75,483	71,709	2030
Agroinvest	Biodiesel	Brassica summer cover crop	Greece	230 km	33,630	31,949	2030
Eni raffineria di Gela Spa	HVO	Brassica summer cover crop	Italy	500 km	123,733	86,613	2030
Agroinvest	Biodiesel	Brassica summer cover crop	Greece	500 km	69,424	65,953	2030
CEPSA plants	HVO	Brassica summer cover crop	Spain	500 km	283,997	198,798	2030
Agroinvest	Biodiesel	Brassica winter cover crop	Greece	230 km	23,493	22,318	2030

Scheme of brassica carinata as a summer cover crop resulted as the more valuable to be implemented. Adopting this scheme, **in mediterranean areas could be produced a total of approximately 351,000 tons of renewable diesel by 2030**, considering a supply distance of 500 km from biorefineries. Of this amount, **66,000 tons** would be of biodiesel (FAME)and **285,000** would be of HVO.

Case Study 4 – BDR model for biomethane-to-bioliquids production

The case study is based on (i) the decentralized production of biomethane from implementation of BDR model, (ii) the enhancement of the natural gas grid and further biomethane injection into the grid and (iii) the biomethane processing in centralized biomethane-to-liquid conversion plants. As already explained in Chapter 3 (

State of the art for key technologies for advanced biofuels production), conversion of biomethane to liquid fuels by Fisher-Tropsch synthesis (FT synthesis) and MeOH synthesis represent established processes applicable at industrial scale. In the short-to-medium term, these conversion facilities can be thought as integrable within existing refineries and biorefineries through a valorization process. The production chain is summarized in Figure 11.

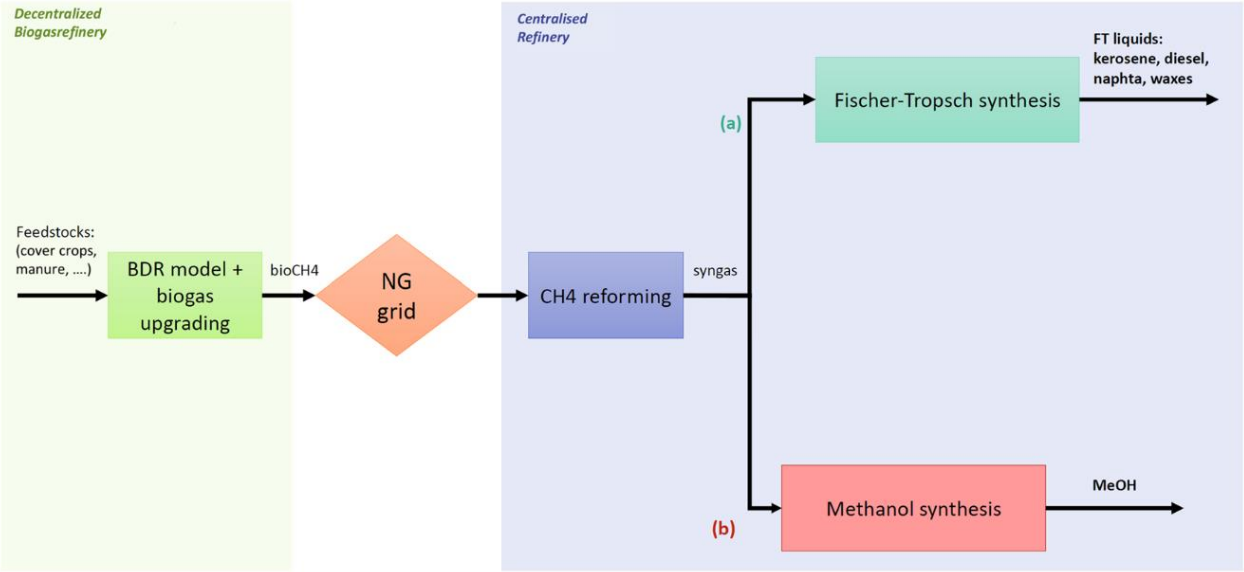

Figure 11.Scheme of BDR model for biomethane-to-liquid production.

Within Europe, the countries showing the highest potential for adopting the BDR model in the production of biomethane-to-liquid fuels are Italy, France, Germany, and the UK. Notably, these nations present the highest number of biomethane and biogas facilities, along with their respective installed capacities (as detailed in Table 7). Moreover, they exhibit a wider coverage of the natural gas network (Figure 12).

Table 7. Biogas and biomethane production capacity in the European top countries.

Parameter	Italy	France	Germany	UK	U.M.
Number of existing biogas plants*	2006	797	9770	404	-
Installed capacity of biogas plants	1,339	182	5,926	343	MWe
Number of existing biomethane plants**	27	337	198	98	-
Biomethane production	0.21	0.53	0.89	0.63	bcm/year

bcm – billion cubic meters

** Reported numbers refer to different years of reference (i.e., 2017 for Italy, 2020 for France, 2022 for Germany, 2019 for UK) ;*

*** Reported numbers refer to the year 2021.*

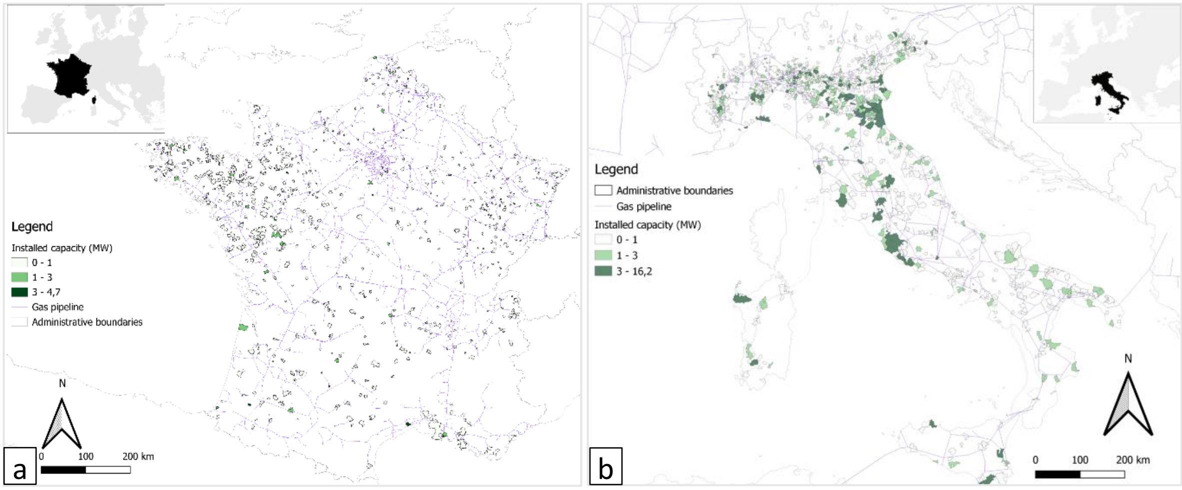

Figure 12. Natural gas network and biogas installed capacity in France (a) and Italy (b).

The assessment of the potential for replication of this case study consists of two distinct steps:

1. Initial estimation of the number of decentralized biomethane plants (and corresponding installed capacity) required to support an industrial production of either FT liquids or MeOH;
2. Estimation of the potential production for MeOH and FT liquids in 2030 and 2050, focusing on the EU top countries.

The outcomes and relevant considerations are presented in the subsequent sections.

Step 1: Possibilities for large-scale production of FT Liquids and MeOH

The first step involved the determination of the required number of decentralized biomethane plants to yield 10,000 barrels per day (bdp) of FT products or 2,000 tons per day of methanol. Among the various processes available for converting biomethane into syngas (as detailed in Chapter 3, "State of the Art for Key Technologies for Advanced Biofuels Production"), partial oxidation (POX) was selected for the assessment. Figure 13 and Figure 14 illustrate the mass balance schemes detailing the pathways that lead to the production of 10,000 bpd of FT liquids and 2,000 tons/d of MeOH, respectively. Calculations were conducted based on biomethane plants with an installed capacity of 1 MWe.

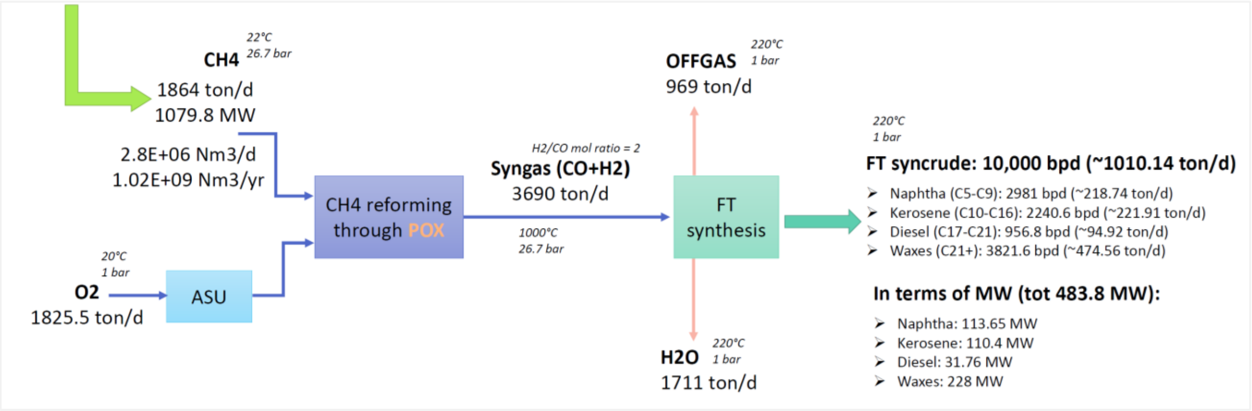

Figure 13. Mass balance scheme for the production of 10,000 bpd of FT products (POX pathway).

As shown in the previous figure, biomethane is conveyed to the reforming unit at a flow rate of 1864 ton/d. The FT synthesis of the obtained syngas (3690 ton/d) results in the production of around 1010 ton/d of FT liquid. The latter is in turn made up of hydrocarbons of different chain lengths, namely: naphtha (218.7 ton/d), kerosene (221.9 ton/d), diesel (94.9 ton/d), and waxes (474.6 ton/d). In accordance with the certified ASTM route, the resulting kerosene, when blended with 50% jet fuel, can be used in the production of sustainable fuels for aviation (SAF).

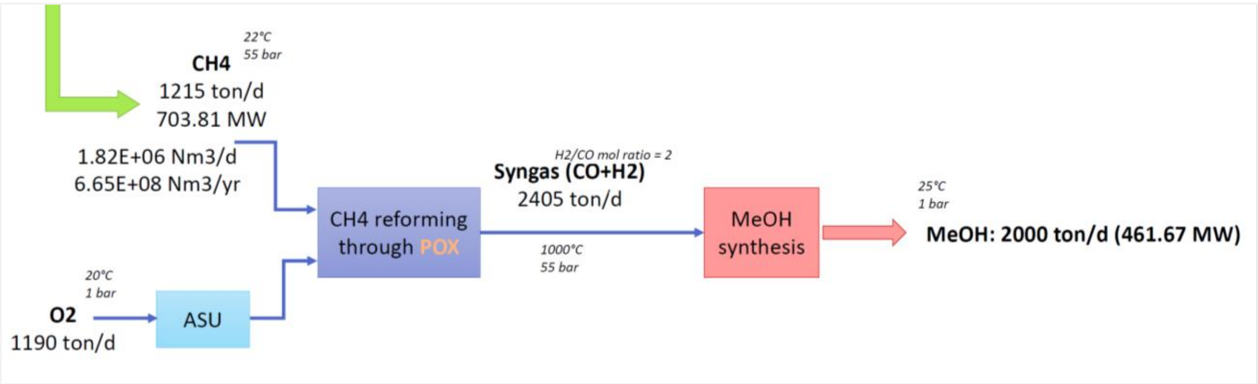

Figure 14. Mass balance scheme for the production of 2000 ton/d of MeOH (POX pathway).

In the scheme illustrated in Figure 14 the flow rate of methane conveyed to the reforming unit is equal to 1215 ton/d. The obtained syngas (2405 ton/d) is then conveyed to the MeOH synthesis unit, yielding the final output of 2000 ton/d of methanol. This end product represents a valuable candidate as alternative fuel for maritime transport sector [23].

Table 8 outlines the estimated numbers of biomethane plants, each with 1MWe of installed capacity, required to support the two conversion routes described.

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[23] ETIP Bioenergy (2021), *Biomethanol production and use as a fuel.*

Table 8. Number of required biomethane plants for production of valuable outputs through GTL-FT and GTL-MeOH conversion pathways.

Conversion pathway	**Number of required biomethane plants***	**Main Valuable outputs**	**Conversion efficiency**
GTL-FT (10,000 bpd) POX route	~ 516	naphta, kerosene, diesel, waxes	0.54 ton (FT prod)/ton(CH4)
GTL-MeOH (2,000 t/d) POX route	~ 336	methanol	1.65 ton(MeOH)/ton(CH4)

**Assuming 1 MWe of installed capacity*

Ultimately, biomethane production from 516 decentralized plants – each with 1 MWe installed capacity – could produce 10,000 bpd of FT products. Biomethane production may also yield 2,000 ton/d of MeOH starting from 336 biomethane decentralized plants – each with 1 MWe installed capacity.

An important highlight emerges when the number of existing biogas/biomethane facilities and their corresponding installed capacities (Table 7) are compared to the estimated numbers of required biomethane plants/installed capacity for adoption of the biomethane-to-liquids value chain at an industrial scale (Table 8). In particular, Germany, Italy, and the UK already exhibit the capacity to implement the GTL-MeOH conversion route, while only Italy and Germany have the capacity to implement the GTL-FT conversion pathway.

Step 2: Estimation of MeOH and FT liquids production potentials in 2030 and 2050

In this second phase an overview of the biomethane-to-liquid fuels potentials is provided per country in 2030 and 2050. The 2022 Gas for Climate Report [24] provided the information on the short- and medium-term potential of biomethane production in each EU Member State (plus Norway, Switzerland, and the UK), through anaerobic digestion or thermal gasification. In particular, the following data have been collected:

- Biomethane potential in 2030 from cover crops;
- Biomethane potential in 2050 from cover crops;
- Biomethane potential in 2050 from: cover crops, animal manure, agricultural residues, sewage sludge, biowaste, industrial wastewater, roadside verge grass, permanent grassland.

The data have been gathered for the previously identified EU top countries, namely: Italy, France, Germany, UK. Next, numbers obtained from Gas for Climate Report (2022) have been integrated within the biomethane-to-liquid fuels model, in order to estimate the potentials for FT liquids and MeOH production in 2030 and 2050. Outcomes of the assessment are listed in Table 9, Table 10, Table 11. Overall results are also illustrated in Figure 15, Figure 16 and Figure 17.

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[24] Alberici, S.; Grimme, W. and Toop, G., "*Biomethane production potentials in the EU*", Gas for Climate (2022).

Table 9. 2030 biomethane-to-liquid fuels potential from cover crops in EU top countries.

Country	Biomethane potential [bcm/year]	FT liquids potential [mcm/year]	MeOH potential [mcm/year]
Italy	3.2	1.75	3.80
France	1.65	0.90	1.96
Germany	1	0.55	1.19
UK	0.25	0.14	0.30
Total	**6.1**	**3.33**	**7.25**

mcm – million cubic meters
bcm – billion cubic meters

Table 10. 2050 biomethane-to-liquid fuels potentials from cover crops in EU top countries.

Country	Biomethane potential [bcm/year]	FT liquids potential [mcm/year]	MeOH potential [mcm/year]
Italy	4.8	2.62	5.71
France	8.2	4.48	9.75
Germany	5	2.73	5.95
UK	2.5	1.36	2.97
Total	**20.5**	**11.19**	**24.38**

mcm – million cubic meters
bcm – billion cubic meters

Table 11. 2050 biomethane-to-liquid fuels potentials in EU top countries from: cover crops, animal manure, agricultural residues, biowaste, industrial wastewater, sewage sludge, perennial grasses and roadside verge grasses.

Country	Biomethane potential [bcm/year]	FT liquids potential [mcm/year]	MeOH potential [mcm/year]
Italy	8.3	4.53	9.87
France	16.5	9.01	19.62
Germany	14.8	8.08	17.60
UK	6.1	3.33	7.25
Total	**45.7**	**24.95**	**54.34**

mcm – million cubic meters
bcm – billion cubic meters

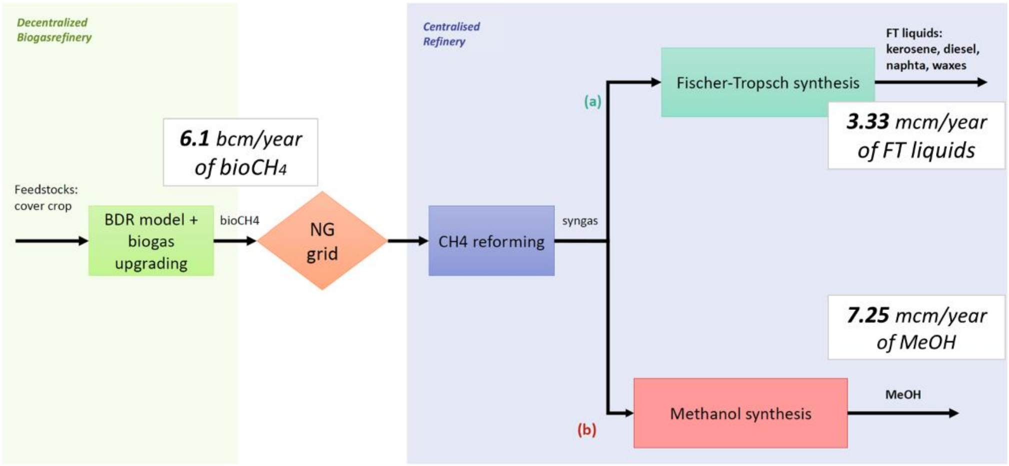

Figure 15. 2030 biomethane-to-liquid fuels potential from cover crops in EU.

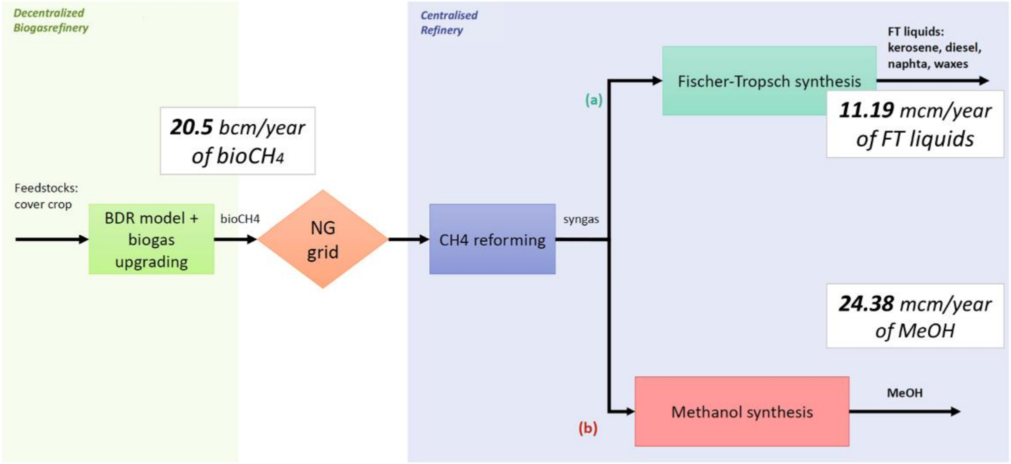

Figure 16. 2050 biomethane-to-liquid fuels potentials from cover crops in EU.

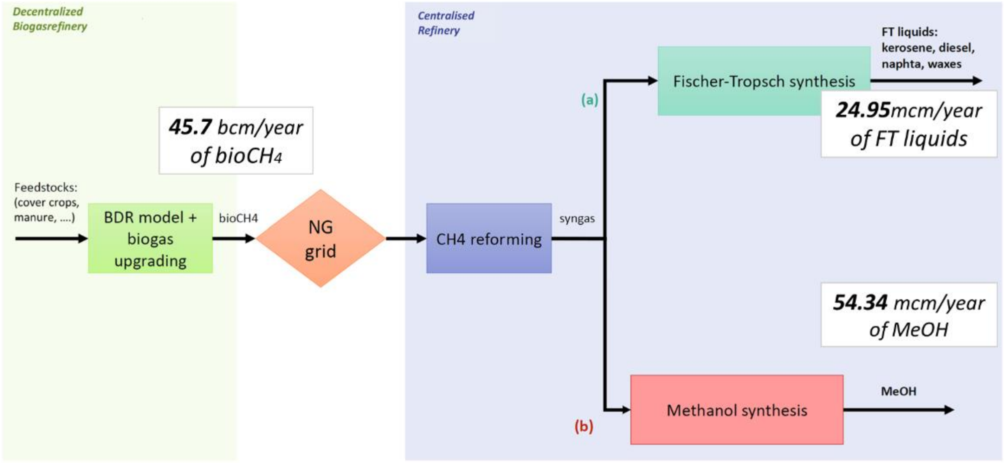

Figure 17. 2050 biomethane-to-liquid fuels potentials in EU top countries from: cover crops, animal manure, agricultural residues, biowaste, industrial wastewater, sewage sludge, perennial grasses and roadside verge grasses.

4.3 Summary of biofuels potentials in 2030 and 2050

Table 12 provides a summary of the estimated production capacities of low ILUC-risk biofuels within the European Union, in accordance with the four BIKE case studies. Numbers listed in the table apply to short- and mid- term periods (i.e., 2030 and 2050). The methodology adopted to assess the potential of replication of each case study has been shorty described in earlier sections and extensively detailed in Deliverable 3.3 of the BIKE project.

Table 12. Estimated EU potential biofuels production according to BIKE case study, in 2030 and 2050.

Low ILUC-risk pathway	**Case study**	**Type of advanced biofuel**	**Potential production in 2030**	**Potential production in 2050**	**U.M.**
Cultivation in unused, abandoned or severely degraded lands	Perennial crops for bioethanol	Second-generation bioethanol	397,693	1,343,691	tons
	Castor bean for renewable diesel	Renewable diesel *of which:*	1,634,817	-	tons
		HVO	*693,559*	-	tons
		Biodiesel	*941,258*	-	tons
Yield increased through improved agricultural practiced	Brassica Carinata for renewable diesel	Renewable diesel *of which:*	351,364	-	tons
		HVO	*285,411*	-	tons
		Biodiesel	*65,953*	-	tons
	BDR model for biomethane-to-liquid fuels	FT liquids	3.33	11.19	mcm
		MeOH	7.25	24.38	mcm

mcm – million cubic meters

As regards the case study related to perennial crops cultivation for bioethanol production, an amount of 397, 693 tons of bioethanol is estimated as producible by 2030 and amount of 1,343,691 tons of bioethanol is estimated as producible by 2050. Second-generation bioethanol is considered as a promising advanced biofuel for the production of alcohol-to-jet (AtJ) fuel, according to the conversion pathway described in Paragraph 3.3, “Sustainable aviation fuels (SAF) production routes”. **Adopting a AtJ yield from lignocellulosic bioethanol of 21% [25], the potential production of biojet fuel would be of 83,516 tons by 2030 and of 282,175 tons by 2050**.

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[25] Romero-Izquierdo et al, “Intensification of the alcohol-to-jet process to produce renewable aviation fuel”, Chemical Engineering and Processing - Process Intensification, Volume 160, 2021, 108270, ISSN 0255-2701, https://doi.org/10.1016/j.cep.2020.108270

In the case studies related to castor bean and brassica carinata cultivation, Biojet/SAF can be separated from the produced HVO through implementation of additional downstream processes, such as isomerisation and fractionation. The potential biojet production from estimated volumes of HVO/HEFA is **between 195,794 and 489,485 tons by 2030, based on 20%-50% jet fraction from HEFA production.**

As regards the case study related to BDR model for biomethane-to-liquid fuels production, Fischer-Tropsch synthesis of syngas obtained from biomethane reforming determines the production of kerosene, which can be used as SAF according to the certified ASTM route of Fischer-Tropsch to Synthetic Paraffinic Kerosene (FT to SPK). The percentage of kerosene within the range of FT liquids (i.e., kerosene, naphta, diesel, waxes) is considered to be of 22.41%, in accordance with the numbers reported in the block schemes of Figure 13. Consequently, by **adopting the FT to SPK conversion route**, **the potential production of *biokerosene* would be of 83,516 tons by 2030 and 282,175 tons by 2050**.

5 Focus on aviation and maritime transport sectors

5.1 Aviation sector

To achieve significant emissions reductions, the aviation sector must shift away from its reliance on fossil jet fuel and accelerate the adoption of innovative and sustainable fuel and technology solutions. While zero-emission aircraft technologies, such as electric or hydrogen-powered aircraft, are not expected to mature in time to have a significant influence on commercial aviation in the near future, sustainable aviation liquid fuels are expected to play a crucial role.

The goal of this paragraph is to provide an insight into the real possibilities for low ILUC-risk biofuels in the aviation sector. To do this, a comparison was made between the estimated biofuel production capacities achievable through implementation of the four BIKE case studies (see Chapter 4, "Evaluation of low ILUC perspectives in EU according to BIKE case studies"), and the forecasted energy demand in the aviation sector. This evaluation was made within the boundaries established by the ReFuelEU aviation proposal.

SAF policy actions

According to the REFuelEU regulatory proposal (see Paragraph 2.2.2 REFuelEU aviation), starting from 2025 and until 2050 aviation fuel suppliers would be required to use a progressively increasing share of SAF, namely 2% by 2025, 6% by 2030 and at least 70% by 2050. Moreover, according to the proposal, synthetic aviation fuels have the highest potential for decarbonisation and therefore a dedicated sub-mandate is provided with the aim of upscaling their production (Figure 18).

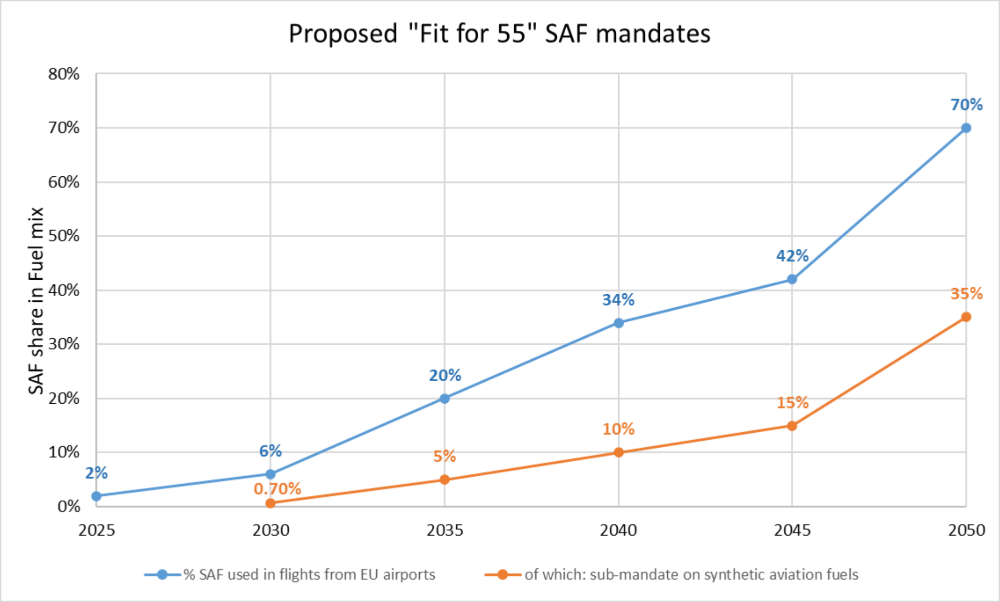

Figure 18. Proposed "Fit for 55" SAF mandates and sub-mandate on synthetic aviation fuels.

Current SAF production capacity and 2030 aviation fuel demand

At present, the SAF industry is still in its initial phase of growth, accounting for less than 0.05% of the total demand for jet fuel in the European Union during 2020[26] (Figure 19). However, a trend toward increased investment and innovation in this sector is emerging, and more companies have announced plans to enter the SAF market by 2030.

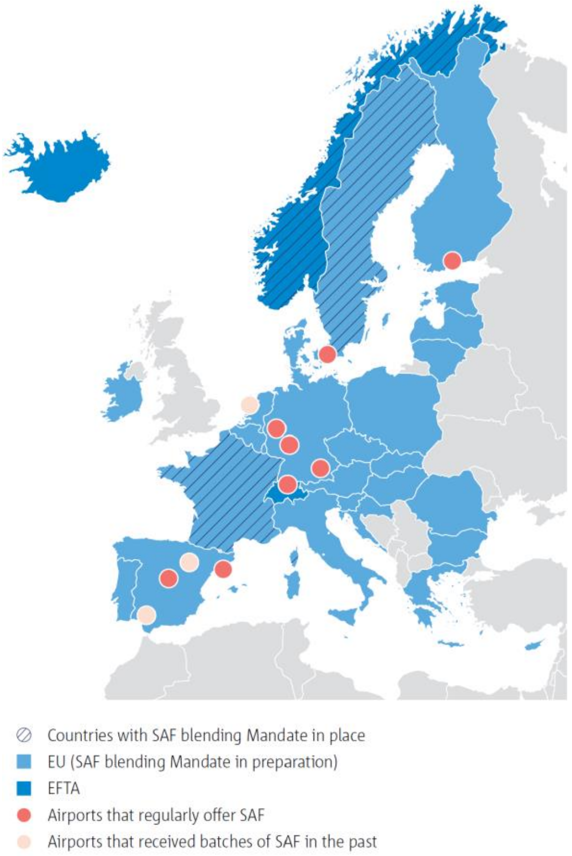

Figure 19. SAF suppliers in Europe, March 2022. Source: EASA, 2022.

The forecasted energy demand for aviation fuel at EU airports is expected to reach approximately 46.9 Mtoe by 2030[27]. This amount takes into account both extra-EU aviation and intra-EU aviation, with extra-EU flights responsible for around two thirds of the final energy consumption (Figure 20).

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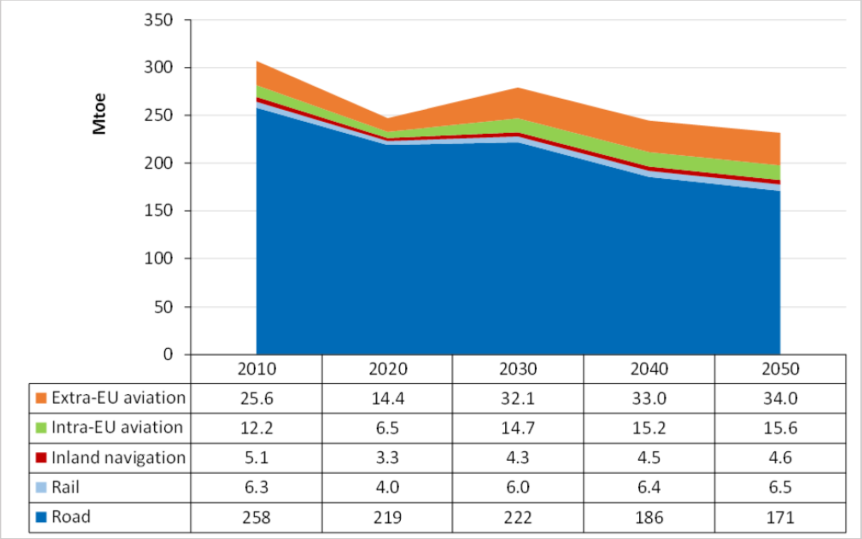
[26] European Union Aviation Safety Agency (EASA), 2022, *European Aviation Environmental Report*.

[27] European Commission (2021), Directorate-General for Mobility and Transport, Tsiropoulos, I., Humphris-Bach, A., Statharas, S., et al., *Study supporting the impact assessment of the ReFuelEU Aviation initiative : final report*.



	2010	2020	2030	2040	2050
🟧 Extra-EU aviation	25.6	14.4	32.1	33.0	34.0
🟩 Intra-EU aviation	12.2	6.5	14.7	15.2	15.6
🟥 Inland navigation	5.1	3.3	4.3	4.5	4.6
🟦 Rail	6.3	4.0	6.0	6.4	6.5
🟦 Road	258	219	222	186	171

Figure 20. Energy demand in transport sector in the EU27. Source: EC, 2021.

In order to determine the role that advanced biofuels could play in meeting the 46.9 Mtoe energy demand, the following two values have been calculated:

1. Share of advanced biofuels required from REFuelEU Aviation proposal in relation to the forecasted aviation demand in 2030;
2. Total amount of jet fuel producible from implementation of the BIKE case studies.

Since the mandates for SAF shares from REFuelEU Aviation proposal are given on a volume basis, all the values related to above mentioned calculations have been converted into volumetric units of measurement. As regards the forecasted energy demand of 46.9 Mtoe, conversion was made considering conversion factors given in literature for jet kerosene (i.e., 1.053 toe/ton conversion factor and 0.81 ton/m^3 density). The same factors were applied to convert on a volume basis the tons of AtJ fuel derived from lignocellulosic bioethanol. As regards the tons of HVO/HEFA producible from cultivation of castor bean and brassica carinata, conversion was made considering a conversion factor of 1.051 toe/tons and a density 0.78 ton/m^3. Results are shown in Table 13 and Table 14.

Table 13. 2030 demand for aviation fuel and share of SAF from advanced biofuels.

Parameter	**Value**	**U.M.**
Energy demand for aviation	46.9	Mtoe
Fuel demand for aviation in terms of volume	54.9	mcm
Share of SAF from advanced biofuels	5.3%*	%
Advanced biofuel mandate for aviation	**2.9**	**mcm**

mcm – million cubic meters
**Calculated as a difference between the total 2030 SAF mandate of 6% and the sub-mandate of 0.7% for synthetic aviation fuels.*

Table 14. Advanced biofuels production achievable in 2030 through implementation of BIKE case studies.

Advance biofuel	**Value**	**U.M.**
AtJ fuel from CS1	83,516	ton
Volume of AtJ fuel from CS1	0.1	mcm
Biojet fuel from CS2	138,712 – 346,780*	ton
Volume of Biojet fuel from CS2	0.18 – 0.44*	mcm
Biojet fuel from CS3	57,082 – 142,706*	ton
Volume of Biojet fuel from CS3	0.07 – 0.18*	mcm
Kerosene from CS4	0.746	mcm
Total volume of advanced biofuels	**1.1 – 1.5***	**mcm**

mcm – million cubic meters
**Range based on 20%-50% jet fraction from HEFA production*

According to the results showed in the above tables, in order to reach 5.3% of SAF from advanced biofuels by 2030 for all flights departing from EU airports, approximately 2.9 million cubic meters of SAF would be required. The potential SAF production capacity in the EU from BIKE low ILUC-risk case studies is estimated at 1.1 – 1.5 million cubic meters, i.e. between 34% and 52% of the SAF required to meet the proposed mandate by 2030.

Aviation fuel demand in 2050 and share of SAF

Within the ReFuelEU Aviation initiative the aviation energy demand has been modelled and projected to be approximately 49.7 Mtoe in 2050[28] (Figure 20).

By 2050, the ReFuelEU Aviation proposal would require that 70% of jet fuel consumed by flights departing from EU airports be SAF, of which 35% synthetic aviation fuels. Adopting the same methodology and conversion factors described in the previous section, values listed in Table 15 and Table 16 have been obtained.

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[28] European Commission (2021), Directorate-General for Mobility and Transport, Tsiropoulos, I., Humphris-Bach, A., Statharas, S., et al., Study supporting the impact assessment of the ReFuelEU Aviation initiative: final report.

Table 15. 2050 demand for aviation fuel and share of SAF from advanced biofuels.

Parameter	Value	U.M.
Energy demand for aviation	49.7	Mtoe
Fuel demand for aviation in terms of volume	58.3	mcm
Share of SAF from advanced biofuels	35.0%*	%
Advanced biofuel mandate for aviation	**20.4**	**mcm**

mcm – million cubic meters

**Calculated as a difference between the total 2050 SAF mandate of 70% and the sub-mandate of 35% for synthetic aviation fuels.*

Table 16. Advanced biofuels productions achievable in 2050 through implementation of BIKE case studies.

Advance biofuel	Value	U.M.
AtJ fuel from CS1	285,175	ton
Volume of AtJ fuel from CS1	0.35	mcm
Biojet fuel from CS2	138,712 – 346,780*	ton
Volume of Biojet fuel from CS2	0.18 – 0.44*	mcm
Biojet fuel from CS3	57,082 – 142,706*	ton
Volume of Biojet fuel from CS3	0.07 – 0.18*	mcm
Kerosene from CS4	2.507	mcm
Total volume of advanced biofuels	**3.0 – 3.3***	**mcm**

mcm – million cubic meters

**Range based on 20%-50% jet fraction from HEFA production*

According to the results showed in the above tables, in order to reach 35.0% of SAF from advanced biofuels by 2050, approximately 20.4 million cubic meters of SAF would be required. The potential SAF production capacity in the EU from BIKE low ILUC-risk case studies is estimated at around 3.0 – 3.5 million cubic meters, i.e. between 15% and 16% of the SAF required to meet the proposed mandate by 2050.

5.2 Maritime sector

Environmental impacts of maritime sector represent today a major concern at both EU and global level. The maritime sector is responsible for approximately 2% of global GHG emissions [29]. At EU level, ship traffic constitutes 11% of the CO_2 emissions within the transportation sector[30], with a marine fuel consumption of around 50,000 million tonnes in 2022 (Figure 21).

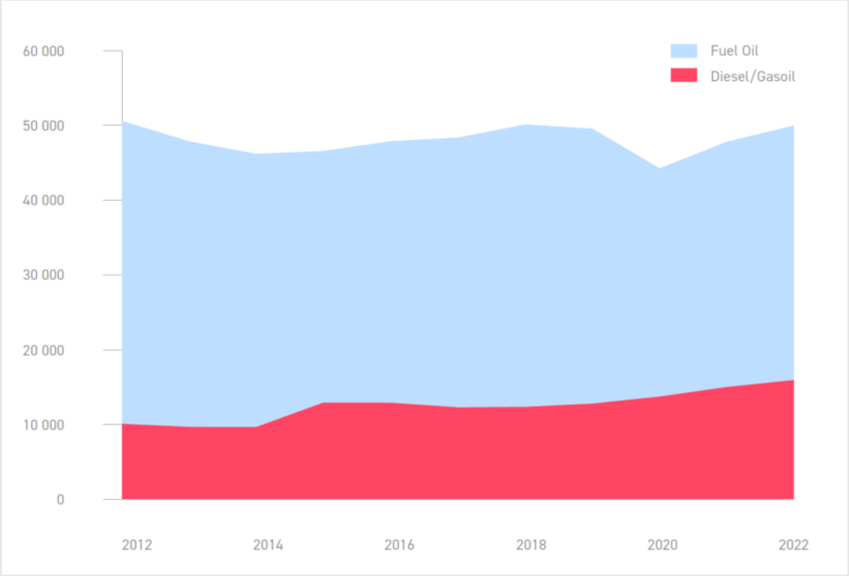

Figure 21. EU-27 marine fuel consumption (unit: Million tonnes per year). Source: Fuels Europe, 2023.

Both the International Maritime Organization (IMO) and the European Commission are actively engaged in supporting the transition toward substantial reduction in GHG emissions. Failure to implement regulations effectively could lead to a projected increase of at least 10% in EU shipping emissions by 2050 [31].

Differently from the ReFuel EU Aviation proposal, the FuelEU maritime initiative does not specify volume-based mandates for the minimum share of renewable fuels within the sector; instead, it adopts a step-by-step approach to reduce the average carbon intensity from 2025 to 2050. Specifically, the initiative stipulates that all vessels with a gross tonnage (GT) of 5,000 or more must decrease the average carbon intensity by 6% by the year 2030 and **by a significant 80% by 2050** (2.2.3 FuelEU Maritime regulation).

Advanced biofuels could readily be adopted by the shipping industry, since current TRL allows for fuel blends of up to 20% without engine modifications, and tests have been conducted using a maximum blend of 30%. Additionally, when compared to Marine Gasoil (MGO), biofuels

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[29] International Energy Agency (IEA), International shipping

[30] FuelEU Maritime Initiative, Provisional agreement resulting from interinstitutional negotiations, 26.4.2023

[31] Transport & Environment (2023). Modelling The Impact Of FuelEU Maritime On EU Shipping.

generated from second-generation feedstock have a life cycle GHG emissions reduction of 70–100%[32].

Biomethanol for shipping industry

Methanol has seen rising interest in recent years as an alternative fuel for shipping. This alcohol has one of the lowest carbon contents compared to other fuels. Furthermore, methanol could reduce SO_X and NO_X emissions by up to 60% in comparison to heavy fuel oil (HFO), with an additional reduction in particulate matter emissions of 95%. The global methanol production represents a well-established industry, but its current uses mainly involve formaldehyde synthesis (25%), production of olefins used in making plastic products, fuel production such as blending for gasoline, and DME. As demand for methanol as a shipping fuel increases, production and supply must be scaled up significantly; however, the existing infrastructure for transportation and storage of methanol provides an advantage for its adoption in the maritime sector. Additionally, renewable methanol, i.e. bio-methanol and renewable e-methanol, requires little to no engine modification[28]. Existing commercial ships have been retrofitted with methanol engines, and further expansion is planned to reduce greenhouse gas emissions.

According to the outcomes of the replicability potential assessment of BIKE case studies, the Biogas Done Right (BDR) model implementation for biomethane-to-liquid production could yield 7.25 mcm of MeOH within 2030 and 24.38 mcm of MeOH within 2050, if considering cover crops as the only feedstock for biomethane production in AD plants. **This amount could double to 54.34 mcm of MeOH by 2050** when considering also other types of feedstock (e.g., animal manure, sewage sludge, agricultural residues, etc.). Hence, adopting the BDR model for MeOH production may provide a potentially useful route for supporting the decarbonisation of the EU shipping industry, and the achievement of the carbon intensity reduction goals established by FuelEU maritime initiative.

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[32] IRENA (2021), A pathway to decarbonise the shipping sector by 2050, International Renewable Energy Agency, Abu Dhabi.

6 Conclusions

This report explores the perspectives for low ILIUC-risk biomasses and biofuels in European transport sector, with particular attention to the aviation industry. All the evaluations have been done considering the framework set out by European legislation, in particular the Renewable Energy Directive (REDII) currently in force and the “Fit for 55” package, that proposes new pieces of legislation such as the revision of the above mentioned REDII and the ReFuel EU Aviation proposal. These legislations define promising opportunities for both biofuels generated from advanced feedstocks (i.e., feedstocks classified in Part A of Annex IX), and biofuels delivered to the aviation industry.

The four BIKE case studies demonstrated interesting potentials for replication in the short- to mid- term across European territory. This was especially evident for the two case studies involving the production of renewable diesel (HVO), i.e. the case study related to the cultivation of castor beans in unused lands and the case study related to integration of brassica carinata as a cover crop in the rotational systems of mediterranean areas. According to the outcomes of Task 3.3, the potential production of HVO within 2030 could be of 979,000 tons of HVO. Within the same year, the cultivation of perennial crops in unused lands across the EU could result in the production of 398,000 tons of advanced (lignocellulosic) bioethanol. The Biogas Done Right (BDR) model for biomethane-to-liquid production could contribute to a production volume of 3.33 million cubic meters of FT liquids by 2030. The strength of all these case studies lies in the high TRL of all the considered technologies, coupled with the possibility of utilizing existing infrastructure.

In order to determine the potential contribution of the four BIKE case studies to the production of low ILUC-risk Sustainable Aviation Fuels (SAF), the following conversion routes – certified by the America Society for Testing and Materials (ASTM) – have been considered: Alcohol-to-Jet (AtJ) fuel (TRL 7-8) , Hydroprocessed Esters and Fatty Acids (HEFA) to Biojet fuel (TRL 9), and Fischer-Tropsch (FT) to Synthetic Paraffinic Kerosene (SPK) (TRL 6-8).

Second-generation bioethanol is considered as a promising advanced biofuel for the production of alcohol-to-jet (AtJ) fuel. Adopting an AtJ yield from lignocellulosic bioethanol of 21% resulted in a potential biojet fuel production of approximately 84,000 tons (or 0.1 billion liters) by 2030 . As regards the case studies related to castor bean and brassica carinata cultivation, Biojet/SAF can be separated from the produced HVO through implementation of additional downstream processes, such as isomerisation and fractionation. The potential biojet production from estimated volumes of HVO/HEFA is between 196,000 and 489,000 tons by 2030 (or 0.3 – 0.6 billion liters) , based on 20%-50% jet fraction from HEFA production. As regards the case study related to BDR model for biomethane-to-liquid fuels production, Fischer-Tropsch synthesis of syngas obtained from biomethane reforming determines the production of kerosene, which can be used as SAF according to the certified ASTM route of Fischer-Tropsch to Synthetic Paraffinic Kerosene (FT to SPK). The percentage of kerosene within the range of FT liquids (i.e., kerosene, naphta, diesel, waxes) was considered to be of 22.41%. Consequently, by adopting the FT-to-SPK conversion route, the potential production of *biokerosene* would be of around 0.7 billion liters by 2030.

With aviation's fuel demand projected to reach 54.9 billion liters by 2030, achieving the 5.3% SAF share from advanced biofuels, as mandated by the ReFuelEU Aviation proposal, would require approximately 2.9 billion liters of SAF. Findings suggest that a potential exists to produce about 1.1 – 1.5 billion liters of Sustainable Aviation Fuel (SAF) by 2030; consequently, the replication of BIKE low ILUC-risk case studies **could contribute to up to 52% of the SAF required to meet the proposed mandate by 2030.**

In conclusion, the adoption of the four distinct case studied identified by the BIKE project may represent an important tool for the decarbonisation of the transportation sector – particularly for the decarbonisation of the aviation industry – thus significantly supporting the achievement of the European legislation's targets. Furthermore, it is key to understand that the promotion of the low ILUC-risk pathways may present a chance to restore Europe's unused or degraded lands by raising soil organic carbon (SOC) levels and lowering the use of inorganic fossil-based fertilisers. This would have positive effects on soils, the climate, and the economy that go beyond bioenergy.