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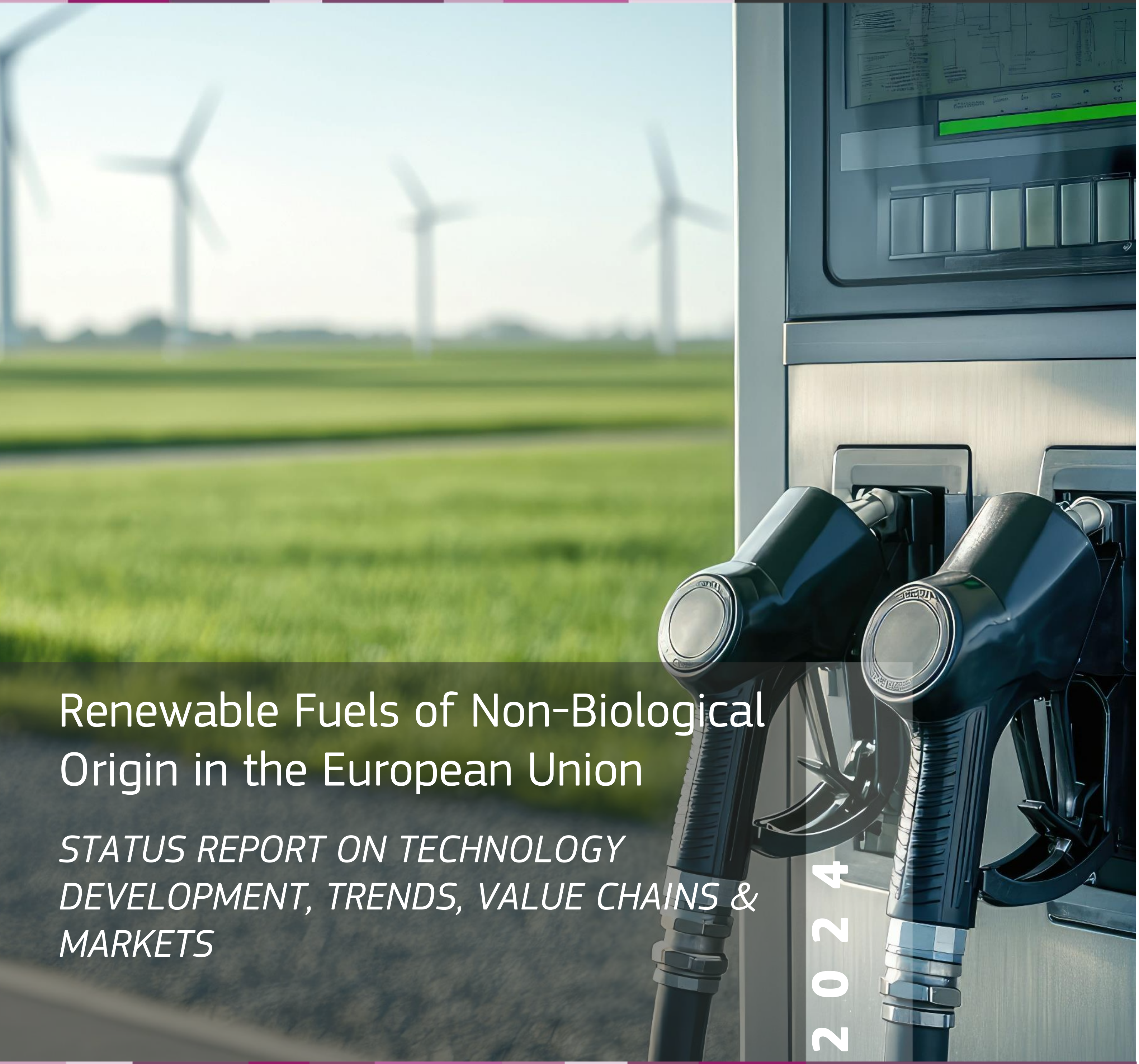

Renewable Fuels of Non-Biological Origin in the European Union

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

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Contents

Abstract

This report investigates the status and trend of Renewable Fuels of Non-Biological Origin (RFNBO), except hydrogen, which are needed to cover part of the EU's demand for low carbon renewable fuels in the coming years. The report is an update of the CETO 2023 report. Most of the conversion technologies investigated have been already demonstrated at small-scale, and the current EU legislative framework under the recast of the Renewable Energy Directive (EU) 2018/2001 (Directive EU 2023/2413) sets specific targets for their use. As a pre-requisite, well-established solid hydrogen supply chains are needed, together with carbon capture technologies to provide carbon dioxide as Carbon Capture and Use (CCU). Fuels that may be produced starting from H_2 and CO_2 or N_2 are hydrocarbons, alcohols and ammonia. RFNBO may play a crucial role in the energy-transition towards decarbonisation, especially in hard-to-abate sectors where direct electrification is not possible. In addition, most RFNBO can use existing infrastructure. The growing interest in these fuels is witnessed by the many funding programmes which are today available. Moreover, EU leads the sector in terms of patents, companies and demonstration activities. Finally, the report considers the major challenges and the opportunities for a rapid market uptake of such fuels.

Foreword on the Clean Energy Technology Observatory

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

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

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

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

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

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

More details are available on the *CETO web pages.*

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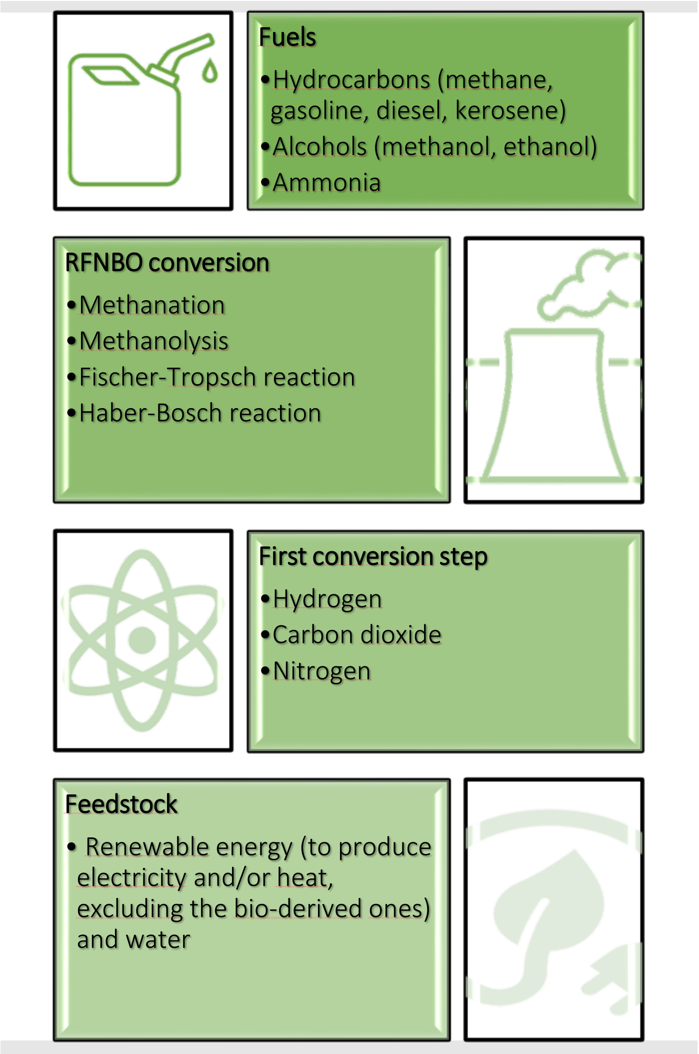
Executive Summary

Renewable Fuels of Non-Biological Origin (RFNBO) are synthetic fuels produced from hydrogen derived from water and renewable energy (except biomass sources) in the form of heat or electricity. RFNBO consist in either i) liquid and gaseous fuels derived from hydrogen and CO_2 produced from fossil or biological sources (e.g. flue gases, biomethane separation from syngas, etc.), DAC (Direct Air Capture) technologies and other non-renewable and natural sources, or ii) liquid and gaseous fuels derived from hydrogen combined with N_2 captured from air in the case of ammonia (NH_3) production. However, since CO_2 and N_2 are not energy carriers, all energy transferred into such carbon- or nitrogen-based fuels derives from hydrogen. Hence the present report focuses on the downstream processes after hydrogen production and carbon capture, i.e. the synthesis reactions that lead to methane (CH_4), drop-in liquid fuels such as gasoline, kerosene or diesel, and other fuels/chemicals such as alcohols and ammonia. The report is an update of the CETO 2023 report.

Figure 1. Production pathway from renewable feedstock (bottom) to RFNBO (top).



Source: JRC Elaboration

Specifically, this study is based on assessments of TRL, energy needs and environmental impact of the conversion pathways already available from the fossil fuel refining and chemical industry. It also provides a brief overview on the current legislation and market situation for this specific category of fuels. Other promising novel processes such as artificial photosynthesis, microbial electrolysis and bio-CO_2 splitting are also being investigated, but they are still limited to small scale demo activities.

RFNBO consist in hydrocarbons produced from synthesis processes are mainly paraffins, hence drop-in fuels which can already be used in the existing fuel infrastructures and vehicles. An extensive technology review shows that such technologies would be ready for the market uptake, but the upstream processes of H_2 production and CO_2 capture still need to be developed at large scale for commercial production. As a consequence, the overall current TRL of the whole conversion pathways is about 6-7, i.e. pilot scale projects. Some conversion technologies as Fischer-Tropsch synthesis, Haber-Bosch process and others are already at high TRL as they were developed over the years to operate with fossil-based feedstock. As such, they can be easily retrofitted to processes powered by a renewable feedstock. Energy balance and environmental impacts are evaluated considering the most recent findings from peer-reviewed papers, technical reports and the JECv5 Well-to-Tank. At EU level, the main requirements for classifying a fuel as RFNBO are based on renewable electricity as input and a minimum 70% GHG emissions reduction compared to 94 gCO_2e/MJ (fossil fuel comparator) as specified by the Delegated Regulation (EU) 2023/1184 of the Renewable Energy Directive EU (2018/2001, also called RED II), which provides the methodology for calculating life-cycle greenhouse gas emissions. Under this regulation, when the electricity used to produce RFNBO is fully renewable, the carbon intensity of electricity is assumed to be zero.

The analysis on the past and current public and private funding mainly focuses on EU Horizon 2020 and Horizon Europe framework programmes for research and innovation, where specific project descriptions are provided (focusing on TRL and scale of production). Several of these demonstrated that the current technologies are ready to be scaled up. The Innovation Fund topic B.2 will promote the commercial demonstration and deployment of small- and large-scale low carbon, innovative projects.

Data on current available plants producing RFNBO in EU are mainly extracted from BEST-IEA Bioenergy Task 39' database and other mapping exercises integrating data from other recent technical reports. The analysis shows that the current capacity is still low and dedicated only to demonstration initiatives.

Bibliometric trends and collaboration networks are investigated by means of SCOPUS' web tool, focusing on specific keywords that address to feedstock, processes and fuel type. From the analysis it emerges that EU is the leader for both number of publications and for active international collaboration networks.

The analysis on patenting trend is included in the CETO' report on "Advanced Biofuels", since most of synthesis processes used for RFNBO production coincide with processes converting bio-based molecules into fuels, while the production of hydrogen is investigated in CETO report on "Water Electrolysis and Hydrogen" and CO2 capture is addressed specifically in the report "Carbon Capture, Utilisation and Storage". The present classification of CETO reports is based on fuel type or technology deployed, so there is no differentiation based on feedstock or energy origin, making some analyses outside the boundaries of each report.

Market assessment is only briefly considered since there is still no trade of RFNBO. Hence the present analysis is limited to investigating the main initiatives developed by the relevant trade associations.

Finally, the report addresses challenges, opportunities and barriers to further develop the sector, indicators to monitor the trend, and current limiting factors towards the RFNBO' market uptake.

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

Strengths:	**Weaknesses:**
• several technologies (HB and FT) are already available and can be easily retrofitted to work with renewable hydrogen; • contribution to energy diversification and energy security; • use of existing fuel infrastructure with no additional investment needed; • solution for hard to electrify sectors (e.g. aviation, maritime) and heavy road transport; • can be blended with fossil fuels, or used as drop-in fuels without technical modifications in the engines.	• large additional renewable electricity capacity and generation needed and robust power connections and grid infrastructure; • several technologies are not yet demonstrated for the unavailability of hydrogen/CO_2 supply; • high conversion and efficiency losses associated with the production and use of RFNBO from renewable electricity compared to the direct use of such electricity; • high initial investment for plant construction; • high fuel production cost, well above fossil fuels; • intermittent production of renewable electricity like solar and wind necessitates for backup power resources.
Opportunities:	**Threats:**
• flexibility in the use of solar and wind electricity production; • energy storage solution/grid balancing and way to use the surplus of renewable electricity; • contribution to energy diversification and energy security; • contribution to the decarbonisation of hard to abate sectors such as aviation, shipping and heavy road freight transport, and the reduction of dependency on fossil fuel imports; • job opportunities along the supply chain, including skilled labour.	• challenging investments in specific value chain due to the recent development of long-term policies and still evolving mechanisms of funding/rewarding schemes; • potential barriers in the investments of CO_2 recovery from fossil sources, which will not be eligible post-2035 for power companies and post-2041 for steel, cement companies; • slow market uptake due to insufficient incentives; • failure to reach cost competitiveness through technology improvement; • competition in renewable electricity use; • insufficient development of the electricity grid infrastructure; • low availability of cheap-enough hydrogen; • risk of certifying renewability even if not generated with renewable energy electricity.

Source: JRC Analysis

1 Introduction

1.1 Scope and context

Renewable fuels of non-biological origin (RFNBO) have been defined for the first time in the recast Renewable Energy Directive (European Parliament and the Council of the European Union, 2018) (RED II, 2018/2001), that introduced this category of fuels as those produced from hydrogen deriving from renewable energy (except biomass sources) in the form of heat or electricity, and CO_2 deriving from fossil sources such as flue gases, from Direct Air Capture (DAC) technologies and from other non-renewable, biological and natural sources, or N_2 captured from air. The RFNBO category includes synthetic hydrocarbons-, alcohols- and ammonia-based fuels. Together with advanced biofuels, RFNBO consist in a viable alternative to fossil liquids fuels for the market being fully drop-in (Panoutsou *et al.*, 2021), so they do not require dedicated infrastructure for distribution and storage (Yugo and Soler, 2019). They can also be blended with existing fuels so long as they meet fuel quality and safety standards.

The present report describes and analyses the conversion pathways for producing RFNBO, starting from the main process inputs, i.e. hydrogen and CO_2 (captured by CCU), whose conversion pathways will be reported in other CETO reports. It is an update of the CETO 2023 report on RFNBO (Buffi *et al.*, 2023).

1.2 EU legislative framework

The Renewable Energy Directive recast (EU 2018/2001) or RED II (European Parliament and the Council of the European Union, 2018) sets the framework towards targets and sustainability criteria for alternative renewable transport fuels, including RFNBO.

In February 2023 the Commission has adopted two Delegated Acts (DAs), as required under Article 27(3) of the Renewable Energy Directive (2018/2001), defining the rules to produce RFNBO (European Commission, 2024). Such documents integrated EU regulatory framework for hydrogen and set a new framework to develop supporting schemes and State aids to develop the hydrogen sector.

In particular, the first Delegated Act defines when hydrogen, hydrogen-based fuels or other energy carriers can be considered as a renewable fuel of non-biological origin, or RFNBO. The rules are to ensure that these fuels can only be produced from “additional” renewable electricity generated at the same time and in the same area as that of the fuel production.

The second Delegated Act sets the methodology to calculate GHG emissions savings from RFNBO and recycled carbon fuels (RCFs). The methodology takes into account the full lifecycle of the fuels to calculate the emissions and the associated savings. It also establishes that the greenhouse gas emissions savings from the use of RFNBO and RCFs shall be at least 70%, compared to the fuels they are replacing.

The European Commission periodically updates a “Q&A” document available online that clarifies the rules reported in such documents (European Commission, 2024). Today, three voluntary schemes are available to certify RFNBO according to the EU rules (European Commission website, 2024).

The last revision of the Renewable Energy Directive set by the Fit-for-55 package (Directive (EU) 2023/2413) (European Parliament and the Council of the European Union, 2023a) raises the EU's binding renewable target for 2030 to a minimum of 42.5% of the gross final energy consumption and almost doubling the existing share of renewable energy in the EU. However, the Member States shall strive to increase the share of energy from renewables in the gross final consumption of energy in 2030 to 45 %.

On transport, the updated targets gives the possibility for Member States to choose between:

- a binding target of 14.5% reduction of greenhouse gas intensity in transport from the use of renewables by 2030;
- or a binding target of at least 29% share of renewables within the final consumption of energy in the transport sector by 2030.

The Directive 2023/2413 also sets a binding combined sub-target of 5.5% for advanced biofuels (generally derived from non-food-based feedstock) and RFNBO (including the targets for aviation and maritime sector described later in the text) in the share of renewable energies supplied to the transport sector.

Within this target, there is a minimum requirement of 1% of RFNBO (including hydrogen) in the share of renewable energies supplied to the transport sector in 2030.

The Directive 2023/2413 requires that industry would increase their use of renewable energy annually by 1.6%. The Directive also requires that the contribution of RFNBO used for final energy and non-energy purposes shall be at least 42 % of the hydrogen used for final energy and non-energy purposes in industry by 2030, and 60 % by 2035.

The directive introduces the possibility for Member States to discount the contribution of RFNBO in industry use by 20% under two conditions:

- if the member states' national contribution to the binding overall EU target meets their expected contribution
- the share of hydrogen from fossil fuels consumed in the member state is not more than 23% in 2030 and 20% in 2035.

RFNBO and advanced biofuels can also contribute to the targets imposed by ReFuel EU Aviation (European Parliament and the Council of the European Union, 2023c) and FuelEU Maritime (European Parliament and the Council of the European Union, 2023b), which set a target of 70% of SAFs (in terms of energy) and -80% as GHGs reduction intensity (compared to the fossil fuel comparator for the maritime fuel) respectively, by 2050. It is worth mentioning that both regulations have minimum targets for RFNBO supply to meet the RED requirements by 2030 and growing targets towards 2050. Specifically, ReFuelEU Aviation set a minimum share of RFNBO at 35% within the commercial blend by 2050, while FuelEU Maritime has a mandate of RFNBO use at 2% (minimum) starting from 2035. To promote the uptake of the RFNBO in aviation and maritime sectors, the share of RFNBO supplied in the aviation and maritime transport modes shall be considered to be 1.5 times their energy content towards the RED transport targets. The RFNBO that count towards that target include those used directly in transport, in biofuel production, and in petroleum refining.

Aviation and maritime sectors have also obligations for the Emission Trading System that has been amended by the Fit-for-55, and new rules for RFNBO accounting within the Monitoring and Reporting Regulation have been recently introduced (The European Commission (EC), 2024).

Finally, it is worth mentioning that in March 2024, the EU adopted the Regulation (EU) 2023/851 for CO_2 emission performance standards for cars and vans (European Parliament and the Council of the European Union, 2023d) which potentially depicted a new scenario for RFNBO and advanced biofuels beyond 2035, making them a decarbonisation solution only for those sectors where electrification is challenging, as aviation and maritime. Differently, for heavy duty vehicles, electrification is not mandatory and 90% GHG reduction by 2040 is required (European Parliament and the Council of the European Union, 2023e). In the recent report of Mario Draghi (Draghi, 2024) on the future of the European competitiveness, it has been reported that alternative fuels can play a role to decarbonize the road sector to compensate for the slow market uptake of electric vehicles, in particular in some countries or areas where electrification is more challenging.

1.3 Methodology and Data Sources

This document summarizes the state-of-the-art, ongoing and future initiatives that regard RFNBO production, using hydrogen from renewable energy and non-biological CO_2 (or N_2) captured from industrial off-gases, biological sources as biomethane supply chain, flue gases and DAC technologies.

The main information sources consist in scientific publications, knowledge gained through the JRC's work on this topic, material from international institutions (IEA, IRENA, etc.), and previous CETO and LCEO (Low-Carbon Energy Observatory) reports. Hydrogen production and carbon capture & storage/utilization are outside the scope of this report but are considered from the point of view of their use as feedstock providers to produce RFNBO.

The analysis focuses initially on the currently available conversion technologies, which have technological readiness levels (TRLs) approaching commercial opportunities, but due to the emerging nature of these fuel production pathways, it was found that most development is happening at lower TRLs. The information on knowledge gained through EU-co-funded research projects has been collected from the CORDIS and the COMPASS tool websites and the project's websites where available. Relevant keywords have been used to define proper queries in the tools, in order to identify projects, under the Horizon 2020 (H2020) and Horizon Europe programmes. Further analysis, to describe objectives and main achievements was conducted, to define the projects impact on the technology development. A search was carried out for relevant national projects and SET-Plan 'flagship projects/activities', provided by the Set4Bio initiative - working group 8 - on Bioenergy and Renewable Fuels for Sustainable Transport' and have been included in the analysis. Most of the projects under analysis are on-going and therefore the assessment of their impact is limited to the available deliverables. Full value chains analyses cannot be performed so far, since RFNBO market penetration is still far from the commercial activities. However, some highlights from recent studies providing forecasts towards 2030 and beyond, are discussed.

2 Technology status and development trends

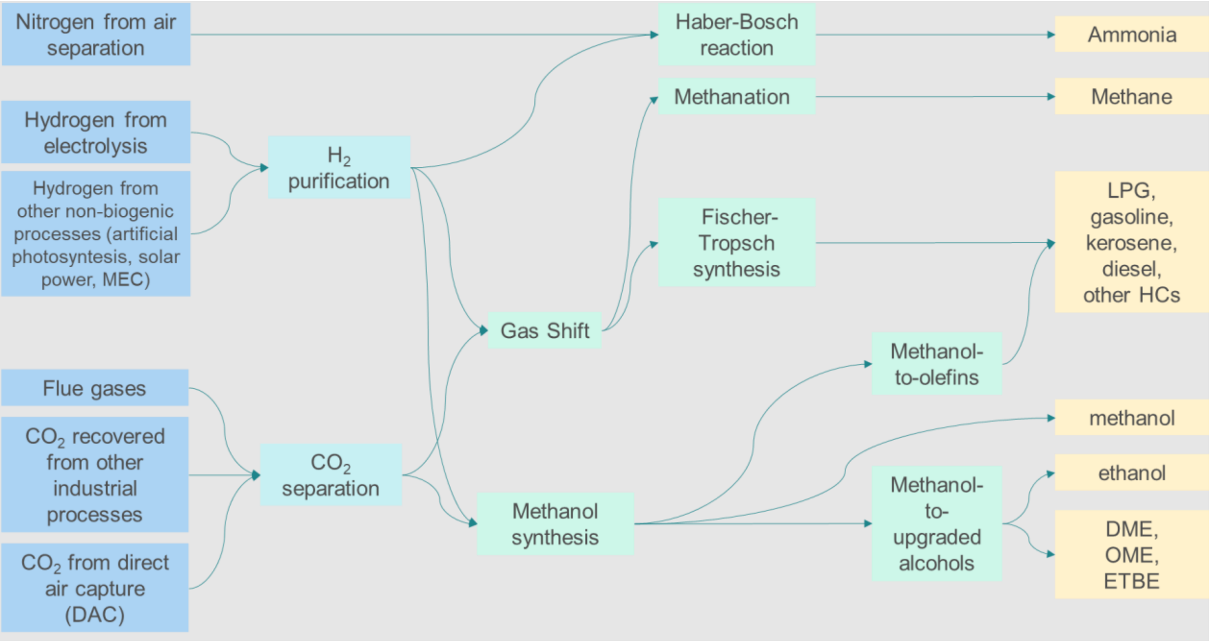
2.1 Technology readiness level

The supply chain of RFNBO (also called electrofuels (e-fuels), Power-to-Gas (PtG) and Power-to-Liquid (PtL) when not-necessarily produced by renewable electricity) is generally associated to several conversion steps starting from renewable electricity and non-biological carbon or nitrogen sources (generally CO_2 or N_2). According to their definition, RFNBO can also derive from hydrogen produced from other non-biological sources (still at very low TRL) as solar power, microbial electrolysis cells or artificial photosynthesis. On the other hand, the CO_2 recovery is also referred to Carbon Capture and Utilization (CCU) value chains, meaning that the recovered carbon is incorporated into either a fuel, or for other scopes.

Several routes are available for the production of RFNBO, consisting in a series of technological steps that include (a) hydrogen production; (b) carbon capture from various sources or nitrogen separation from air, and (c) chemical fuel synthesis through several conversion steps in which hydrogen is reacted with carbon dioxide or nitrogen to produce methane, ammonia, methanol or hydrocarbons (gasoline, diesel or kerosene), as shown in Figure 2, followed by cleaning and purification steps. Some fuels as alcohols or paraffins may be further refined by ATJ (Alcohol-to-Jet) and isomerization respectively, to meet the quality requirements of refined fuels as SAF.

The present report focuses on the second stage of conversion, assuming both hydrogen and CO_2/N_2 as feedstock for production of hydrocarbons, ammonia or alcohol fuels. The production of carbon-based fuels starts with a gas shift reaction followed by other specific reactions depending on the fuels required. In the case of production of methanol, CO_2 and H_2 can be reacted directly through the methanol synthesis, while for other products such as methane and Fischer-Tropsch (FT) hydrocarbons, a reverse water gas shift reaction is needed to convert CO_2 to CO, prior to the catalytic synthesis process where the products are formed, see Figure 2.

Figure 2. Elaboration of the investigated pathways.



Source: JRC Elaboration

The TRL evaluation considers the processing steps afterwards the hydrogen production and CCUS processes (in which hydrogen assumes the role of intermediate energy carrier). According to the assessments of IEA (AMF Annex 58 and IEA Bioenergy Task 41, 2020; International Energy Agency (IEA), 2024), the average TRL of RFNBO conversion pathways is around 6-7, but technologies included in commercial fossil-based supply chains have high values (for example the chemical industry producing ammonia and alcohols).

2.1.1 Hydrogen production

Hydrogen can be produced via several production pathways including thermochemical processing of fossil or biomass resources, biological processes and water electrolysis. Most of the hydrogen produced today stems from fossil feedstocks via steam reforming of natural gas, partial oxidation of methane and coal gasification. Global hydrogen demand of 90 Mt in 2020 was responsible for 900 Mt of direct CO2 emissions (International Energy Agency (IEA), 2021a). A brief description of the most relevant technologies producing hydrogen is provided in this section, with the scope to briefly investigate renewable hydrogen from non-biological sources towards RFNBO production. This report does not investigate bio-hydrogen based pathways, which have been described by the some authors of this report in a specific peer-reviewed paper (Buffi, Prussi and Scarlat, 2022).

2.1.1.1 Electrolysis

The process of electrolysis supplied by electricity and water offers multiple options, both considering low-temperature (Alkaline Electrolysis – AEL, and Polymer Electrolyte Membrane Electrolysis – PEMEL) and high-temperature processes (Solid Oxide Electrolysis – SOEL and Molten Carbonate Electrolyser Cells - MCEC) (Dincer and Acar, 2015). Electrolysers are composed of several cells arranged in “cell stack” modules that can then be multiplied to reach the desired output capacity. The technologies vary with respect to efficiency, investment and maintenance costs, durability and lifespan, capacity, and flexibility (Yue et al., 2021). The hydrogen produced is then compressed or liquefied for storage or direct use. The production by means of alkaline electrolysers has been consolidated for more than a century and is a fully commercial technology. Another technology that has more recently been introduced is the PEMEL, which is now competing with alkaline electrolysers. The high temperature processes are still under development, but they have the potential to achieve higher conversion rates.

Electrolysers’ installations are going to be built above some MW in capacity, even considering that the current hydrogen demand is still limited. However, the increasing production of renewable electricity through wind and solar power will make possible the production of larger electrolysers capacity beyond 1 GW, as reported by IEA (International Energy Agency (IEA), 2021b, 2023).

2.1.1.2 Artificial photosynthesis

Artificial photosynthesis is the chemical transformation of sunlight, water, and carbon dioxide into high-energy-rich fuels (Mi and Sick, 2020). Usually there is a light-reaction side, where sunlight is used, and a dark-reaction side. There are two ways to perform the process. The first uses a multi-junction semiconductor for the light-reaction side, where water splits to oxygen and hydrogen ions in the presence of sunlight. Electrons and hydrogen ions move to the dark-reaction side, where gold nano-catalysts are used. Then, the hydrogen ion and CO_2 change to carbon monoxide and water. Efficiency of conversion is about 1.5%. Another method is to use a gallium nitride semiconductor for the light-reaction side and to use a metallic catalyst, typically copper, for the dark-reaction side. In the light-reaction side, water becomes oxygen and hydrogen ions with sunlight, and CO_2 becomes methane in the dark-reaction side. The conversion rate of this process is about 0.2%. Even though the conversion rate is getting higher, there is a thermodynamic limit set at 10% to scale up the process to commercial level (Mi and Sick, 2020). Another process of interest is the photo biological water splitting, which uses microorganisms to convert solar energy into hydrogen. Microorganisms, such as green microalgae or cyanobacteria, absorb sunlight to split water through direct photolysis routes. Despite the low conversion efficiencies (less than 2% (Nagy et al., 2018)) and long conversion times, many EU projects have been developed in the last years to test this process at pilot scale (Ludwig-Bölkow-Systemtechnik GmbH (LBST) and Hinicio S.A., 2015). The current TRL of this technology is about 3-4 (Walczak, Hutchins and Dornfeld, 2014).

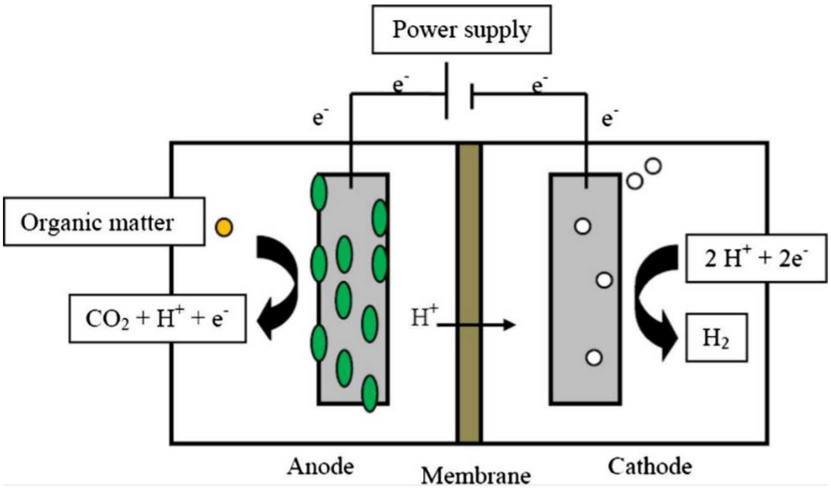
2.1.1.3 Solar powered derived hydrogen

The thermolysis process can be used efficiently to produce hydrogen using solar–thermal energy. An analysis of this topic is provided in the CETO report on solar fuels (Taylor, Tattini and Diaz Rincon, 2023). Many studies have been done considering various materials and catalysts, and the last findings suggested that a low-temperature cycle with abundant and low-cost materials should be selected for large-scale commercial applications (Dutta, 2021). The process uses metals as Zn or Ti to split hydrogen from water and producing a metal-oxide. A recent LCA studies (Sadeghi, Ghandehariun and Rosen, 2020) suggested that today hydrogen from solar thermal separation is environmentally attractive, but it cannot still compete economically with other solutions (i.e. SMR, electrolysis). The current TRL of this technology is about 2-4 (Boretti, 2021).

2.1.1.4 Microbial electrolysis cells

A microbial electrolysis cell (MEC) is when electrochemically active bacteria oxidize organic matter and generate CO_2, electrons and protons. The bacteria transfer the electrons to the anode, and the protons are released to the solution. Therefore, the electrons flow through a wire to a cathode and combine with the free protons in solution. In order to produce hydrogen at the cathode due to protons and electrons exchange, MEC reactors require an externally supplied voltage (⩾0.2 V) under a biologically assisted condition (pH = 7, Temperature about 30 °C, and 101320 Pa) (Boretti, 2021). This is done by the input of a voltage via a power supply. However, MECs require relatively low energy input (0.2–0.8 V) compared to typical water electrolysis (1.23–1.8 V). Schematic diagram of two-chamber MEC is reported here below.

Figure 3. Scheme of MEC operation starting from organic matter to electricity production (Kadier *et al.*, 2014)



Source: Kadier er et al, 2014

As regards the techno-economic assessment, the investments associated with microbial electrochemical systems are higher than that of the conventional technologies. Considering the current state-of-the-art, the TRL is about 5 (Dange *et al.*, 2021). However, some LCA studies already modelled the environmental impact and sustainability assessment for such systems, which may be potentially much lower than their fossil counterparts (Manish and Banerjee, 2008; Dai *et al.*, 2016; Mehmeti *et al.*, 2018; Borole and Greig, 2019; Chen *et al.*, 2019).

2.1.2 Carbon capture

The production of e-fuels requires CO_2 (except for ammonia), which can be obtained from various sources such as combustion gases (from both bio or fossil fuels), industrial processes (e.g. off gases), biogenic CO_2 (e.g. from ethanol fermentation, biomethane upgrading) and CO_2 captured directly from the air (Madejski et al., 2022).

Carbon capture and utilisation (CCU) is considered an important CO_2 mitigation strategy to support and complement carbon capture and storage (CCS) objectives for the abatement and sequestration of CO_2. It represents various pathways that use CO_2 as a feedstock in process systems or otherwise for the generation of value-added commodities (Dange et al., 2021). The main carbon capture technologies include post-combustion carbon dioxide capture (chemical absorption, physical absorption (Selexol, Rectisol), solid adsorption, membrane filtration and cryogenic processes) or Direct Air Capture (DAC). These technologies differ in many aspects such as the capture method (chemical or physical absorption, membrane separation, etc.), the regeneration step, temperature and pressure and, most importantly, the type of energy demand (electricity or/and heat). Several carbon dioxide capture technologies are already available at commercial level (TRL 9), including absorption using amine solvents, physical solvents (Selexol, Rectisol), Pressure Swing Adsorption (PSA), or gas separation membranes, since their use has been already consolidated in other sectors. More detailed analysis on this topic can be found on CETO CCUS report (Martinez Castilla *et al.*, 2024). Specific data on energy consumptions and CO_2 concentrations for different carbon capture options are available in the most recent Concawe' report on e-fuels (Soler et al., 2024).

Table 2. TRL analysis for adsorption, absorption, membrane separation and chemical capture technologies (Carbon capture, utilisation and storage - Fuels & Technologies - IEA, 2022; Vaz, Rodrigues de Souza and Lobo Baeta, 2022).

Category	TRL	Notes
Adsorption	7-9	Mainly applied in natural gas and ethanol processes, this technology is responsible for CO_2 capturing in large plants and has great application perspectives. Its advances are mainly due to the simple operation attributed to it.
Absorption	9	It is the most advanced technology. This is due to the research time and consequently its application in small and large power generation, fuel transformation and industrial production plants.
Membrane separation	6-9	Relatively new but promising technology and considered to be the most effective separation technology among the existing ones. Its advances depend on the type of gas emission source and its application. Currently, part of its applications is in the demonstration phase, and another part in the development phase, few are commercially available (from gas processing technology).
Chemical capture	3-6	The capture involving chemical reactions, are presented in that TRL for its time and research intensity. As it is relatively new, its level is justified by the need for large pilot scale tests.

Source: IEA, 2022; Vas et al, 2022

2.1.3 Nitrogen separation

Nitrogen for ammonia synthesis is produced commonly via air separation through fractional distillation by first cooling air until it liquefies, then selectively distilling the components at their various boiling points. Alternate, lower-energy approaches to air separation include Pressure Awing Adsorption (PSA) and membrane separation technologies. Ammonia is a product of the chemical industry with 185 Mt production in 2020, of which 72% was from natural gas-based steam reforming and 26% from coal gasification (IEA 2021).

2.1.4 Fuel synthesis: Power-to-Gas

This section reports the only process producing gaseous fuels from hydrogen and CO_2. Here following a list of the most common synthesis-based conversion technology, i.e. the production of e-CH_4.

2.1.4.1 e-CH4 (methanation with renewable hydrogen and CO_2)

Methanation is the easiest reaction to produce a hydrocarbon from hydrogen and CO, formerly CO_2. The general reaction is reported here below:

$CO_2 + 4\ H_2 \Rightarrow CH_4 + 2\ H_2O$ (where $\Delta H_R = -165$ kJ for steam; - 253 kJ for water (at 100 °C, 1 bar).

Methanation is a thermochemical process performed at elevated temperatures and pressures, using noble metals-based catalysts. The resulting methane could then be supplied as a substitute for natural gas through the gas grid, as compressed gas or as liquefied gas. The overall reaction (named Sabatier) is exothermic and shifts the equilibrium to the products at lower temperatures, hence the reactors need a heat removal system to work optimally (Ghaib, Nitz and Ben-Fares, 2016). The process can be driven by biological or chemical systems, but since the biological process is slower and less developed, this report is focused on the chemical route. At higher pressures, the process shows higher methane yields but can also produce more by-products that can be problematic for the system (e.g. a promotion of charring reaction producing carbon deposits that generate fouling) or other hydrocarbons that lower the purity of the final product. The formation of by-products depends strongly on the catalyst. An exhaustive review of the most common catalysts has been provided by Tan et al (Tan et al., 2022). Nickel-based catalysts are the most widely used for their low price and high conversion rate. The reactors are generally fixed bed reactors, and typical thermodynamic parameters are 8 bar and 180-350 °C of temperature (Lindorfer et al., 2019), but also, higher conditions can be reached. The theoretical process efficiency of conversion of hydrogen energy to the final product is 78% (Gorre, Ortloff and van Leeuwen, 2019), but from electricity to methane, the overall efficiency decreases depending on the electrolysers efficiency. Some key performance indicators, including TRL, have been reported by Jarvis et al (Jarvis and Samsatli, 2018).

Table 3. Main KPIs for the Sabatier' reaction for methanation.

Indicator/measure		**Value**
Technical	TRL	8-9
	Typical operating temperature (°C)	250-550
	Typical operating pressure (bar)	1-100
	Typical overall CO_2 conversion (%)	70-90
	Plant lifetime (years)	20
Economics	Fuel price (Euro/t_{fuel})	320
Energy	Electricity usage (MWh/t_{fuel})	55.6 (hydrogen production, the electricity for the methanation is supposed to be supplied by an internal turbine)
	Net CO_2 utilization (t/t_{fuel})	3

Source: (Jarvis and Samsatli, 2018; Chauvy et al., 2020)

Concawe (Soler *et al.*, 2022, 2024) proposed a full techno-economic assessment of e-fuels, including synthetic methane. The most relevant data are reported in Table 4.

Table 4. Technical parameters methanation using renewable Hydrogen

<table>
<tr><td colspan="7">Cradle-to-grave GHG emission</td></tr>
<tr><td>Years</td><td>2020</td><td colspan="2">2030</td><td colspan="3">2050</td></tr>
<tr><td>gCO_2eq/MJ</td><td>11.7</td><td colspan="2">10.7</td><td colspan="3">11.0</td></tr>
<tr><td colspan="7">Production input and output</td></tr>
<tr><td>Input</td><td>H_2</td><td colspan="2">CO_2</td><td colspan="2">Power</td><td>Heat</td></tr>
<tr><td>Amount</td><td>0.50 kg/kg fuel</td><td colspan="2">Up to 3.00 kg/kg fuel</td><td colspan="2">1.15 MJ/kg fuel</td><td>10.8 MJ/kg fuel</td></tr>
<tr><td>Output</td><td colspan="2">Methane</td><td colspan="2">Water</td><td colspan="2">CO_2 (emission)</td></tr>
<tr><td>Amount</td><td colspan="2">1.00 kg</td><td colspan="2">2.25 kg/kg fuel</td><td colspan="2">0.25 kg/kg fuel</td></tr>
<tr><td colspan="7">Synthesis production plant input and output</td></tr>
<tr><td colspan="7">Note: Methanation plant with a capacity of 1368 MW based on the LHV</td></tr>
<tr><td>Input</td><td colspan="2">H_2</td><td colspan="2">CO_2</td><td colspan="2">Electricity</td></tr>
<tr><td>Amount</td><td colspan="2">1.198 MJ/MJ_{CH4}, LHV</td><td colspan="2">0.06 MJ/MJ_{CH4}, LHV</td><td colspan="2">0.0229 MJ/MJ_{CH4}, LHV</td></tr>
<tr><td>Output</td><td colspan="3">Methane</td><td colspan="3">Heat (250-300℃)</td></tr>
<tr><td>Amount</td><td colspan="3">1.000 MJ</td><td colspan="3">0.0720 MJ/MJ_{CH4}, LHV</td></tr>
</table>

Source: Concawe 2022; Concawe 2024

Almost all power-to-methane plants are installed in the EU. According to LBST (Weindorf *et al.*, 2019), in late 2018, 11 power-to-methane plants with a capacity of about 7 MW of CH4 were in operation in the EU. More recently, EBA (European Biogas Association (EBA), 2024) reported that by the end of 2023, operational e-methane production plants were 35, with the largest concentration in Germany. Current production capacity is 449 GWh/year, and by 2027, it is expected to reach almost 3,000 GWh/year. Including plants under construction, planned, and announced plants the expected number of plants by 2027 is estimated at 55. In most of the plants the CO_2 is derived from biogas upgrading or CO_2 in biogas streams via direct methanation using the CO_2 fraction from biogas. However, there are a growing number of projects using direct air capture (DAC) of CO_2.

2.1.5 Fuel synthesis: Power-to-Liquid

This section reports the processes producing liquid fuels from hydrogen and CO_2/N_2. Some fuels can also be intended as chemicals, such as ammonia and methanol. Here following a description of the most common synthesis-based conversion technologies, which can be also used to produce advanced biofuels, when CO and H_2 derive from biomass or other organic matter from gasification processes.

2.1.5.1 e-NH3 (ammonia) from renewable electricity via Haber Bosch process

Ammonia is the simplest hydride of nitrogen (NH3), and is a colourless gas with a strong smell, commonly associated with degradation of organic matter. Ammonia has a very low boiling point (-33.5°C) so quickly turns to a gas when exposed to air (Soler and Yugo, 2020; IRENA and AEA, 2022). Its calorific value is significantly lower than that of most conventional hydrocarbon fuels. Ammonia has many applications as chemicals, but only recently has been studied also as fuel (Valera-Medina et al., 2021).

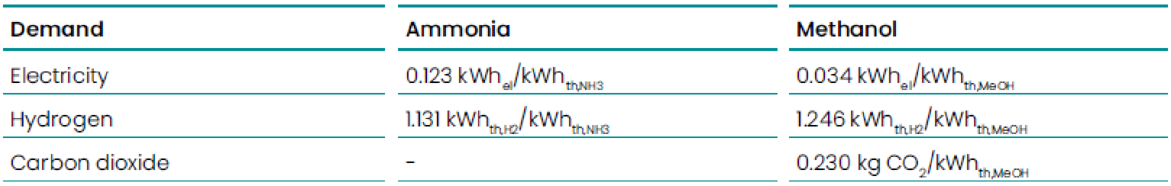
Ammonia has been formerly used as refrigerant since almost two centuries, and as a feedstock for nitrogen fertilizers for a century. NH_3 can be also combusted in ICEs (Internal Combustion Engines) and turbines, leading to a higher fraction of NOx compared to carbon-based fuels (Salmon and Bañares-Alcántara, 2021), but recent developments in the combustion chambers design and oxygen distribution, allowed to reduce to very low level such emissions (Guteša Božo et al., 2019; Elbaz et al., 2022). The current challenge in ammonia-based engines is to reduce fuel-NOx and maintain low levels of thermal-NOx (Jiang *et al.*, 2024).

Ammonia is produced in commercial plants through the Haber-Bosch process based on a reaction of nitrogen with hydrogen using a metal catalyst under high temperatures and pressures. The world's first ammonia plant was commissioned in 1913 by BASF in Oppau, Germany (Rouwenhorst, Travis and Lefferts, 2022).

Ammonia is used as a feedstock for nitrogen fertilizers, can be used as a hydrogen carrier and as a fuel for transport and also directly in fuel cells. It is worth mentioning that many innovative applications in fuels cells are currently under development (Jeerh, Zhang and Tao, 2021). E-ammonia as a fuel has the advantage of not generating any CO_2 when used and can therefore be attractive if CO_2 exhaust emissions are limited. A very interesting and promising application consists in the ammonia use in the maritime sector, that can be used in internal combustion engines with small modifications and can also be used directly in fuel cells (Al-Aboosi et al., 2021). However, new standards as regards its safety use and distribution should be developed (International Energy Agency (IEA), 2024), as well as much ship equipment should be re-designed (e.g. fuel storage, fuel injection, engine emissions after treatment) . Thus, ammonia use as fuel is still at very low TRL. Nevertheless, many engine manufacturers and shipbuilders are working on this fuel and showing great interest in its potential for decarbonisation (Klüssmann *et al.*, 2020; Imhoff, Gkantonas and Mastorakos, 2021).

Today's modern plants still retain the same basic configuration as in the past, reacting to a hydrogen-nitrogen mixture on an iron catalyst at elevated temperature in the range 400-500°C and operating pressures above 100 bar (Rouwenhorst, Travis and Lefferts, 2022). The ammonia synthesis is a downstream process of the hydrogen production, where most of the electricity (95%) is used for hydrogen production, while a small amount is needed to separate nitrogen gas from air and to separate the gas mixture for the ammonia synthesis loop. No direct CO_2 emissions are produced as a result of the HB process, and zero-emission ammonia production is possible if the used electricity is essentially carbon-free. Steam for high temperature electrolysers is generated by recovering heat from the ammonia synthesis to boost the overall integrated-process efficiency. Higher efficiency, combined with a prospect of lower CAPEX, could improve the economics of the process, though the technology is presently in the development phase and is therefore limited to small scales.

Table 5. Electricity and hydrogen demand in the production of ammonia and methanol.



Demand	Ammonia	Methanol
Electricity	$0.123\ kWh_{el}/kWh_{th,NH3}$	$0.034\ kWh_{el}/kWh_{th,MeOH}$
Hydrogen	$1.131\ kWh_{th,H2}/kWh_{th,NH3}$	$1.246\ kWh_{th,H2}/kWh_{th,MeOH}$
Carbon dioxide	-	$0.230\ kg\ CO_2/kWh_{th,MeOH}$

Source: (Ram et al., 2020)

In late 2022, (Concawe, 2022) proposed a full techno-economic assessment of e-fuels, later updated in 2024 (Soler *et al.*, 2024), including synthetic ammonia, for which the most relevant data are reported in Table 6.

Table 6. Technical parameters e-ammonia production

Production input and output			
Input	H_2	N_2	Power
Amount	0.178 kg/kg$_{NH3}$	0.822 kg/kg$_{NH3}$	2.16 MJ/kg$_{NH3}$
Output	Ammonia		Heat
Amount	1.00 kg		2.18 MJ/kg$_{NH3}$
Cradle-to-grave GHG emission			
Years	2020	2030	2050
gCO$_2$eq/MJ	11.4	11.2	9.2

Source: Concawe 2022, Concawe 2024

It is worth reporting also that Sphera recently published a full-LCA study of ammonia as maritime fuels (Schuller, Bopp and Rapp, 2024), including a detailed LCI to gather specific information for further LCA studies.

2.1.5.2 e-methanol via methanolysis

Methanol is the simplest alcohol (CH3OH), liquid at ambient temperature and atmospheric pressure, but with a high volatility. Differently than ethanol, it is toxic and dangerous for human health even in small quantities (Verhelst *et al.*, 2019). It can be produced in different ways, both from fossil sources as well as from biomass (Pirola, Bozzano and Manenti, 2018; IRENA and Methanol Institute, 2021). Moreover, hydrogen can be converted to methanol via synthesis directly with CO_2, without requirement of reverse water gas shift (as for methane), according to the methanolysis as follows:

$CO_2 + 3 H_2 => CH_3 OH + H_2O$

The reaction is exothermal, generally carried out at a temperature of 240 to 270°C and a pressure of 8 MPa, but depending on the catalysts used, it can be performed at different thermodynamic conditions (Guil-López et al., 2019). As regards physical properties, methanol has just half of the (volumetric) energy density of gasoline (based on the lower heating value (LHV)).

Summarizing, 2 litres of methanol contain about the same energy contained in one litre of gasoline, making its use as fuel more challenging than gasoline or diesel. Its density corresponds to the density of most other liquid fuels, but with a lower boiling point at 64.7°C (at atmospheric pressure conditions).

Methanol produced through methanol synthesis could be used directly as a transport fuel in low blends with petrol or used for further chemical processing to drop-in fuels through the methanol route following sequential processes of olefin synthesis, oligomerisation and hydrotreating. Depending on process conditions and catalysts type, the process can lead to different products.

When used as fuel, methanol has a high-octane rating, which theoretically would allow higher pressure ratio in spark-ignition engines (making it more efficient than gasoline), but low cetane number, so less suitable for diesel engines. Under the Fuel Quality Directive, European fuels standard EN228 limits on the oxygen content of gasoline which then restrict the amount of methanol to a maximum of 3% vol for EU transport fuels, but in China is also used at M85 (a mixture of 85 vol.% methanol and 15 vol.% gasoline) or M100 (pure methanol) in commercial blends for dedicated spark-ignited combustion engines of light-duty vehicles (Schorn et al., 2021). Moreover, methanol could be also used as blending components for maritime fuels (Svanberg et al., 2018), thus, several oceangoing vessels are already equipped with dual fuel, two-stroke engines, which can operate also with the traditional maritime fuels and methanol blends.

For this scope, the international organization developing the standards' guidelines (ISO) is currently developing a standard for methyl/ethyl alcohols as a marine fuel under the reference ISO/AWI 6583 (ISO, 2023). However, the low density and the poor miscibility into the commercial fuel blends, make its use more suitable for other applications. For this scope, e-fuels technologies should not be intended only to produce e-fuels, but also chemicals that could be of high interest for industry. For instance, biodiesel production today uses fossil-derived methanol that has a strong impact on its carbon footprint (Sebos, 2022); therefore, adding a full renewable reagent as e-methanol at the transesterification reaction, the same biofuel comes out with strongly reduced environmental impact. Methanol is also largely used in the chemical industry as a solvent or as initial feedstock for alcohols isomers (DME, ETBE) and ethers.

In conclusion, this pathway is already at full commercial level (TRL 9 (Schorn et al., 2021) for fossil-based methanol) and well-established for many years (Dieterich et al., 2020)), so, the only market barriers to fully substitute the fossil-based methanol are based only on H_2 and CO_2 supply and economy (Weindorf et al., 2019; Yugo and Soler, 2019).

Table 7. Main technical specifications and KPIs for the hydrogenation to methanol.

Indicator/measure		**Value**
Technical	TRL	6-7 (referring to the whole supply chain of RFNBO)
	Typical operating temperature (°C)	225
	Typical operating pressure (bar)	50
	Typical overall CO_2 conversion (%)	93.85
	Plant lifetime (years)	20
Economic	Fuel price (Euro/t_{fuel})	360
Environmental	Electricity usage (MWh/t_{fuel})	0.4
	Net CO_2 utilization (t/t_{fuel})	1.46
	Total water use (t/t_{fuel})	26.4

Source: (Pérez-fortes and Tzimas, 2016; Jarvis and Samsatli, 2018)

In late 2022, proposed a full techno-economic assessment of e-fuels, later updated in 2024 (Soler *et al.*, 2024), including e-methanol, for which the most relevant data are reported in Table 8. The same study also calculated the cradle-to-grave GHG emissions, which showed an increasing trend over the time due to the use of Direct Air Capture for CO_2 supply.

Table 8. Technical parameters e-methanol production (for industrial production).

Production input and output				
Input	H_2	CO_2	Power	Heat
Amount	0.193 kg/kg fuel	1.40 kg/kg fuel	1.07 MJ/kg fuel	1.72 MJ/kg fuel
Output	Methanol		Water	
Amount	1.00 kg		0.59 kg/kg fuel	
Synthesis production plant input and output				
Note: methanol synthesis plant including compressors and methanol purification with a capacity of 1368 MW based on the LHV				
Input	H_2	CO_2	Electricity	
Amount	1.161 MJ/MJ$_{CH3OH}$, LHV	0.0702 MJ/MJ$_{CH3OH}$, LHV	0.0499 MJ/MJ$_{CH3IH}$, LHV	
Output	Methanol		Heat (250-300℃)	
Amount	1.000 MJ		0.0720 MJ/MJ$_{CH3OH}$, LHV	
Cradle-to-grave GHG emission				
Years	2020	2030	2050	
gCO_2eq/MJ	10.6	10.4	11.5	

Source: Concawe 2022, Concawe 2024

2.1.5.3 e-diesel, e-kerosene and e-gasoline via Fischer-Tropsch route

Fischer-Tropsch (F-T) synthesis is a technology that has a long history of production of gasoline and diesel from coal. In the last 20 years great interest has been generated in using this relatively well-established technology downstream to other bio- or non bio-conversion pathways producing syngas (Steynberg and Dry, 2004). This process has been originally developed to overcome the lack of petroleum by means of the synthesis of Germany's abundant coal supplies in the beginning of the 20th century (Mahmoudi *et al.*, 2017). Afterwards the First World War, Germany and Britain were the most successful and pioneering in developing the generation of liquid synthetic hydrocarbons through F-T technology. This solution allowed up to the end of the Second World War to supply large quantities of liquid fuels for military scopes, in particular on the EU territory.

FT synthesis is an alternative route for producing drop-in hydrocarbon fuels (gasoline, diesel, kerosene) from syngas (hydrogen and carbon monoxide) through a catalytic synthesis process. Carbon monoxide for the FT reaction can be produced by the reverse water-gas-shift reaction from carbon dioxide and hydrogen. The FT products are upgraded to lighter hydrocarbons (diesel or kerosene) by hydrocracking, isomerization, and distillation.

Today the Fischer-Tropsch pathway to synthetic, liquid hydrocarbons is commonly used in biomass-to-liquid (BtL), gas-to-liquid (GtL) and coal-to-liquid (CtL) processes (Schmidt and Weindorf, 2016), where an upstream gasification process produces gases mainly composed by CO and H_2 to be processed into the FT-reactors.

Generally, such gases must be cleaned by tars and other contaminants to produce a high purity syngas to run the desired reactions as follows (Basu, 2018):

Paraffins: $nCO + (2n + 1)H_2 \rightleftharpoons CnH_2n+2 + nH_2O$ $\Delta H = n(-146.0)\ kJ\ mol^{-1}$

Olefins: $nCO + (2n)H_2 \rightleftharpoons CnH_2n + nH_2O$

Alcohols: $nCO + (2n)H_2 \rightleftharpoons CnH_2n+1\ OH + (n - 1)H_2O$

In some cases, additional hydrogen may be required depending on the reaction stoichiometry as well as on the type of catalysts used (Jahangiri et al., 2014), in particular to produce e-SAF, which requires additional hydrogen for the isomerization (Colelli et al., 2023; Bube et al., 2024). In synthesis pathways like BtL and CtL, CO is provided from the gasification of biomass and coal respectively. In the FT-PtL case, CO_2 from concentrated sources or extracted by DAC technologies is used as carbon source, where it is converted to CO via an inverse CO-shift reaction using the reverse water gas shift process. Upgrading the FT-derived crude product to specific classes of liquid hydrocarbons requires specific downstream processes such as hydrocracking, isomerization, and distillation. These processes are already commercially used at large scale in oil refineries today, as well as in CtL and GtL plants, so this solution could be easily integrated into a biorefinery concept. The share of products from the Fischer-Tropsch synthesis ranges from light naphtha to heavy diesel components, but further reactions of oligomerization and isomerization can be applied to meet the required fuel standards (Schmidt and Weindorf, 2016). For instance, Fischer-Tropsch synthetic paraffinic kerosene is an ASTM approved pathway which can be blended up to 50% (in volume) into the commercial jet fuel blend (Chiaramonti, 2019).

As regards e-fuel production, there is already the possibility to perform direct FT-fuel synthesis from CO_2-based feed gas, but this pathway is still at a very early stage of development (requiring further catalyst developments and first lab scale demonstration). On the other hand, several PtFT-fuels demo plants that include a shift from CO_2 to CO have been operated successfully and further larger-scale plants have been announced (BEST and IEA Bioenergy Task 39, 2022). For the short-term future this will remain the dominant process design for FT-based PtL plants (Dieterich *et al.*, 2020). According to Concawe (Yugo and Soler, 2019), the mass balance to produce 1 litre of liquid e-fuel is estimated at 3.7–4.5 litres of water, 82–99 MJ of renewable electricity and 2.9–3.6 kg of CO_2.

According to CONCAWE report (Concawe, 2022), later updated in 2024 (Soler *et al.*, 2024), 11.7 g of hydrogen, 88 g of CO_2 and 0.0441 MJ of electricity are needed to produce 23.2 g of e-Diesel (i.e. 1 MJ) and 0.2139 MJ of heat. The same study also calculated the carbon intensity of FT-kerosene and diesel, which showed an increasing trend of emissions (from 12.5 to 12.8 gCO2eq/MJ for FT kerosene between 2020 and 2050) because of the use of Direct Air Capture for CO_2 supply. Differently, other GHG assessment studies, such as the one proposed by LBST (Schmidt *et al.*, 2023) show a decreasing carbon intensity of PtL-SAF, up to few grams per MJ fuel by 2050.

Table 9. Main KPIs for the Fischer-Tropsch' reaction for liquid fuels production (Jarvis and Samsatli, 2018).

Indicator/measure		**Value**
Technical	TRL	5-9
	Typical operating temperature (°C)	200-350
	Typical operating pressure (bar)	20-40
	Typical overall CO_2 conversion (%)	51.5
	Plant lifetime (years)	20

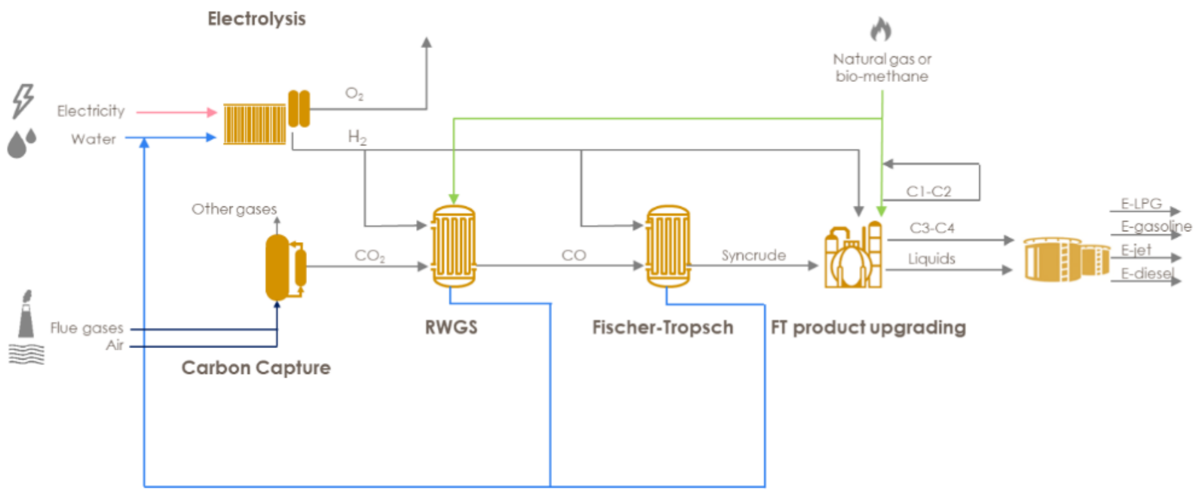
Economic	Fuel price (Euro/t_{fuel})	1375
Environmental	Electricity usage (MWh/t_{fuel})	6.8
	Net CO_2 utilization (t/t_{fuel})	2.6

Source: Jarvis and Samsatli, 2018

As regards the current EU legislation, it is worth noting that, depending on the initial energy and carbon sources, the renewable fuels from FT-process can belong to different RED II categories. For instance, biomass gasification leads to advance biofuels, non-recyclable wastes gasification/pyrolysis or the recovery of industrial off-gases lead to RCFs, and the generic CO_2, derived by both bio- and fossil-source reacted with hydrogen from renewable electricity, leads to RFNBO. Moreover, if the overall feedstock is a mix between non-bio renewable hydrogen, bio- and non-bio renewable carbon, the final fuel share will belong to the different categories previously mentioned in a proportional fraction (on energy basis) depending on its origin.

It is worth to mention that Norsk e-Fuel is commissioning a demo plant producing FT-synthesis liquid hydrocarbons supplied by CO_2 from DAC and hydrogen from SOEC, that will be gradually scaled to produce 25 million litres within 2026 (*Our Technology | Norsk e-Fuel*, 2022). Here the expected TRL is about 7-8, which is relevantly increased from the recent updated figures from LBST (TRL 6 for both low/high temperature electrolysis) (Weindorf *et al.*, 2019). According to the Transport and Environment observatory of e-kerosene (Transport & Environment, 2024b), 45 e-kerosene projects in the EEA (Economic European Area), including 25 large-scale industrial projects and 20 smaller pilot projects. The large-scale projects should deliver 1.7 Mt of e-kerosene by 2030. According to an estimation of EASA (European Union Aviation Safety Agency, 2024) to achieve 5% of SAF by 2030 for all flights departing from EU airports, about 2.3 Mt of SAF would be required.

Figure 4. FT-fuels production from electricity and carbon capture (Alfonso García de las Heras, 2021).



Source: Heras (Concawe), 2018

2.1.5.4 e-diesel, e-kerosene and e-gasoline via Methanol route

An alternative conversion route to FT-process which directly produces hydrocarbons is through further chemical reactions starting from methanol. The pathway is built on industrially proven processes which have already been used for decades in various large-scale applications (Yarulina et al., 2018), such as natural gas reforming and synthesis to methanol (including methanol-to-gasoline conversion in some cases). Conversion and upgrading of methanol to liquid hydrocarbons includes several process steps, notably DME synthesis, olefin synthesis, oligomerization, and hydrotreating (Weindorf et al., 2019). The main reaction mechanism to produce paraffins is reported here below.

Syndiesel production from methanol as DME-Synthesis: $2\ CH_3OH \Rightarrow CH_3\text{-}O\text{-}CH_3 + H_2O$

Olefin synthesis: $CH_3\text{-}O\text{-}CH_3 \Rightarrow (CH_2)_2 + 2\ H_2O$

Oligomerization: $0.5\ n\ (CH_2)_2 \Rightarrow C_nH_{2n}$

Hydrogenation: $C_nH_{2n} + H_2 \Rightarrow C_nH_{2n}+2$

Depending on process conditions and catalysts type, the process can lead to different products (Atsbha et al., 2021). Many technologies have been studied and demonstrated so far (Keil, 1999), but this process does not find a market collocation yet.

Gasoline and diesel produced via the methanol pathway would be compatible to conventional commercial fuel blends used for road transports, but specific standards setting their quality have not been developed so far. Moreover, neither jet fuel has yet been produced via the methanol pathway, and technical approval of this pathway according to ASTM D7566 is still pending (Schmidt et al., 2018).

Summarizing, the rationale behind this concept lays on the fact that market demand can rapidly change, specifically during the last years after Covid-19 crisis and Ukrainian war. This solution has an enormous potential to cover a broader range of products with quick adaptation. Specifically, this concept would allow to shift methane/methanol or hydrocarbons production with a limited capital investment (CAPEX), since e-gas and e-liquids production affects only the 15 and 17 % of the total plant investment (Yugo and Soler, 2019).

As regards the TRL, LBST reported that this process has TRL 6 when supplied by high temperature electrolysers, while 8-9 when supplied by low temperature, traditional electrolysers (Weindorf *et al.*, 2019). First plants started producing hydrocarbons from fossil-derived methanol (MGT reactor of ExxonMobil), but today this technology is used also for plants producing gasoline from wastes-derived methanol (e.g. Primus Green Energy, Canada (Chakraborty, Singh and Maity, 2022) and from hydrogen and oxygen from electrolysis in a large-scale methanol-to-gasoline plant (2.5 million litres of gasoline per day) based on natural gas reforming (Dieterich *et al.*, 2020).

According to CONCAWE report (Concawe, 2022), later updated in 2024 (Soler *et al.*, 2024), for every kilogram of kerosene or diesel fuel produced in the methanol-to-kerosene/diesel process, 2.32 kg of methanol and 0.01 kg of hydrogen are consumed. The process yields 1.00 kg of kerosene, produces 1.31 kg of water, consumes 0.718 MJ of power, and generates 1.314 MJ of heat. The same study also calculated the carbon intensity of methanol-to-gasoline/kerosene, which showed an increasing trend of emissions (from 11.3 to 12.2 gCO2eq/MJ between 2020 and 2050) for the same reason of FT-kerosene. According to the analysis of Bube et al (Bube *et al.*, 2024), the efficiency of this pathway is a bit higher than for kerosene compared to FT-based conversion, but a bit lower in terms of overall products. Therefore, the recent GHG assessment of LBST (Schmidt *et al.*, 2023) did not show differences among these two pathways due to the conversion efficiency of methanol-to-fuel, but to the combined effect of lower carbon intensity of hydrogen and higher CCU efficiency (expected by 2050), that reduced the values up to 1.8 gCO2eq/MJ.

2.1.5.5 e-DME and e-OME

DME (Dimethyl ether), also known as methoxymethane, is the simplest ether (CH3-O-CH3). As potential diesel fuel substitute, DME has a cetane number of 55-60, which is higher than the European diesel specification EN 590. Since the boiling point is −24.8°C, DME could be potentially used as admixture to Liquefied Petroleum Gas (LPG) for spark ignition engines. However, the lower heating value (LHV), its gaseous form at room temperature and blending walls due to its full miscibility make of its use still challenging. However, DME can be used as a stand-alone, clean high-efficiency compression ignition fuel, generating reduced NOx emissions and particulate matter. It can also be efficiently reformed to hydrogen at low temperatures, and is not considered toxic (Putrasari and Lim, 2022).

DME can be synthesised from CO_2 via two main routes. By Route 1 it can be synthesised through the formation of syngas in the reverse water gas shift reaction (RWGSR) where it is then converted to DME through direct or indirect synthesis. Route 2 involves the synthesis of DME directly from CO_2 (Styring, Dowson and Tozer, 2021). Both routes have been already investigated into the previous sections.

Differently, Oxymethylene ethers (OME) are more complex compounds of carbon, oxygen, and hydrogen ($CH_3O(CH_2O)nCH3$). Due to their high oxygen concentration, they suppress pollutant formation in combustion.

OMEs' properties depend on their chain length, which has no carbon-carbon linkage and a high oxygen content between 42 – 48 wt.% (Soler and Yugo, 2020). Their volumetric energy density is low, there is no compatibility with the existing fuel infrastructure and current European diesel specifications (e.g. EN 590, EN15940). While for DME service in vehicles, only moderate modifications of engine and injection systems are required, OME-powered engines require significant adaptations. So far mainly small commercial vehicle fleets (buses and heavy-duty vehicles) have used DME as a transport fuel, where Germany has been the most active MS in developing recent initiatives (De Falco *et al.*, 2022). Despite the potential role of these fuels, especially in the heavy-duty segment, most of the publications do not consider e-DME and e-OME as part of their assessment. Further details these pathways can be gathered from the last Concawe report 2024 (Soler *et al.*, 2024), where energy and GHG emissions assessments are available.

2.1.5.6 Renewable jet fuel via innovative processes

There are also several novel, alternative processes for converting CO_2 to CO, to form syngas that together with e-hydrogen can lead to fuels, alcohols or other compounds. Many companies are studying such innovative pathways even if they are at early stage of development, in particular to produce SAF. For instance, Topsoe developed eCOs™ process (i.e. electrolytic Carbon Monoxide solution), where a solid oxide electrolysis cell (SOEC) is used to reduce CO_2 to CO through the electrochemical process of electrolysis (Haldor Topsoe, 2022). Together with green hydrogen, CO can be then converted to other fuels. However, Topsoe recently developed another specific technology to directly produce hydrocarbon, i.e. the G2L™ technology that produces paraffins from H_2 and CO_2 (Topsoe, 2024).

Another novel conversion pathway, developed by the carbon transformation company Twelve and the biotechnology company LanzaTech, is based on a process converting CO_2 emissions into ethanol partnership (Green Car Congress website, 2022; renewablesnow.com, 2022). This relies on a new class of CO_2-reducing catalysts and a novel device that splits CO_2 with just water and renewable electricity as inputs, and subsequently the LanzaTech's small Continuous Stirred Tank Reactor (CSTR) to convert CO to ethanol. This approach is highly scalable and could ultimately produce ethanol at an industrial scale, while simultaneously eliminating CO_2 emissions. The process can also be coupled with "Alcohol to Jet Synthetic Paraffinic Kerosene" (ATJ-SPK) pathway, which has been approved by ASTM D7566 (Standard Specification for Aviation Turbine Fuel Containing Synthesized Hydrocarbons) that sets requirements for the alternative jet fuels (Geleynse et al., 2018). The Lanzatech' process can also be coupled with other upstream CO sources. For instance the ATJ produced from ethanol using the LanzaTech-PNNL hybrid process (Dagle, Dagle and Saavedra Lopez, 2020; Green Car Congress, 2021), even if under ASTM review process, may be another option to add ethanol as a qualified ATJ feedstock for D7566 Annex A5 (Harmon *et al.*, 2017). It is worth noting that the first ATJ commercial plant in US powered by the Lanzatech technology was opened at the beginning of 2024 (Energy.gov, 2024).

There are also many other ongoing initiatives which may be of high interest to produce competitive e-SAF considering both novel and a combination of the previously mentioned technologies (Küngas, 2020; Saravanan *et al.*, 2021; Braun, Grimme and Oesingmann, 2024; Ozkan *et al.*, 2024). However, the main barrier remains the need to produce hydrogen at low cost, together with the need to be close to CO_2 sources. This is still a difficult combination to achieve for several reasons e.g. availability, logistics, economics, etc.

2.2 Current Installed Capacity and Potential Production

Most of the e-fuels facilities are still at demo-scale, as discussed in the previous sections. Only a few plants are currently operated in the EU, and the overall production is a few tons of fuel per year, which is used for demonstration activities (Agora Verkehrswende and PtX Hub, 2024). According to the IEA Bioenergy' map (BEST and IEA Bioenergy Task 39, 2022) and the ETIP databases (ETIP Bioenergy website, 2024), there are some existing projects (principally at small scale) that deliver e-fuels in EU, mainly funded by private companies or EU-funded programmes (Table 10).

Table 10. E-fuels plants available and planned today in EU according to IEA Bioenergy and ETIP databases.

Project name	Project owner	Country	Technology	Production capacity	TRL	Product	Start year
NAMOSYN - OME35 plant	TU Munich	Germany	E-Fuels Biomass Hybrids		4-5	oxymethylene ether 3-5 (OME35)	2021
Exytron Demonstrationsanlage	EXYTRON GmbH	Germany	Methanation - electrolysis and catalytic methanation	1 m^3/h	4-5	SNG	2015
Commercial synthetic kerosene facility	Synkero	Netherlands	E-Fuels Biomass Hybrids	50,000 t/y		SAF	2027
Jupiter 1000	GRTgaz	France	Water electrolysis (alkaline and PEM), methanation, CO_2 capture from flue gas	CH4 25 Nm^3 /h	3-4	H_2 and CH4	2019
Store&Go-Falkenhagen	Uniper	Germany	Alkaline water electrolysis, catalytic methanation, direct air capture of CO_2	CH4 57 Nm^3 /h	3-4	CH4 and H_2	2019
STORE&GO Falkenhagen	STORE&GO	Germany	Isothermic catalytic honeycomb technology	1,400 cubic meters of SNG / day	3-4	H_2 and CH4	2019
GEORGE OLAH RENEWABLE METHANOL PLANT	Carbon recycling International	Iceland	alkaline water electrolysis, methanol synthesis from H_2 and CO_2 , CO_2 capture from a geothermal power plant	4000 t/year	8	Methanol	2012
FReSMe project (H2020)	Swerim	Sweden	Electrolysis	50 kg/h of methanol	6	methanol	2021
ALIGN-CCUS	A consortium of 31 companies	Germany	Methanol synthesis from H_2 and CO_2	50kg of DME per day	4-5	(DME), synthetic diesel substitute	2019
Sunfire PtL – Dresden	Sunfire PtL – Dresden	Germany	High temperature electrolysis with SOEC, DAC, reverse	180 l/day	3-4	bio-oil	2014

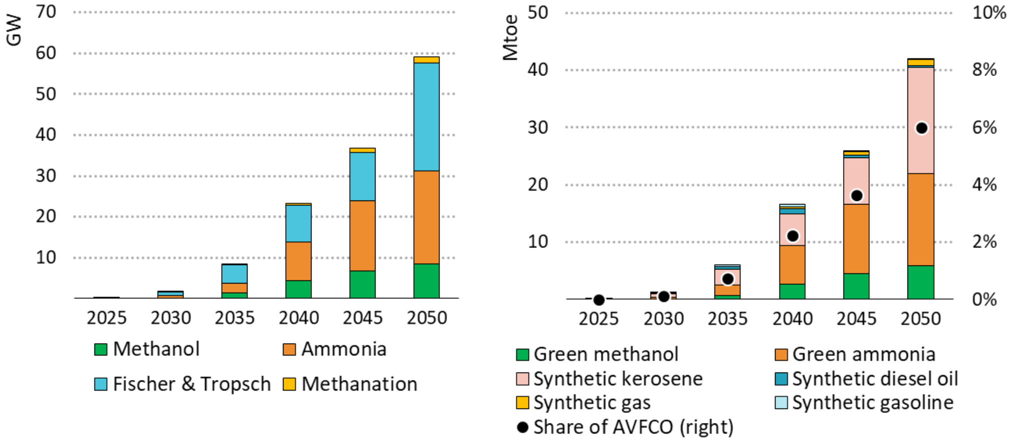
Project name	**Project owner**	**Country**	**Technology**	**Production capacity**	**TRL**	**Product**	**Start year**
			water gas shift (RWGS), F-T synthesis				
GreenPower2 Jet	Airbus, BP Lingen, BP Air, Dow, DLR, Hoyer Logistic, Easyjet, DHL	Germany	50 MW Electrolyser	JET Fuel quantity N.A.	7-8	Hydrogen, Jet fuel	2024
Synhelion Solar Fuels Spain	Synhelion	Spain	Sun-to-Liquid	500000 litres/year	7-8	eKerosene, eGasoline, and eDiesel	2025

Source: (BEST and IEA Bioenergy Task 39, 2022); ETIP B Database

However, it is worth mentioning that other databases report additional projects under development, as shown in the Annex 3, where the fuels and their projects are classified on the final use (including also projects under development and evaluation). Currently there is still no effective commercial production of RFNBO since the voluntary schemes which can certify such fuels received a positive technical assessment only in September 2024 (European Commission website, 2024). From now on, a rapid scale up is expected as plants strive to meet the stringent targets of the regulations such as ReFuelEU Aviation and FuelEU Maritime.

According to JRC's POTEnCIA[1] modelling under the *POTEnCIA CETO 2024 Scenario,* a sharp increase in RFNBO production in the EU is foreseen (see Annex 2 for a detailed description of the scenario and of the POTEnCIA model). The installed capacity of RFNBO synthesis processes scales up rapidly from 2035, achieving more than 20 GW in 2040 and almost 60 GW in 2050 (see Figure 5). Such uptake is mirrored by the RFNBO production, which exceeds 40 Mtoe in 2050 representing almost 6% of energy consumption in final energy, final non-energy[2] and in international aviation and shipping.

Figure 5. RFNBO installed capacity (left) and production (right) in the EU under the *POTEnCIA CETO 2024 Scenario*, 2025-2050.



*AVFCO stands for Available for Final Consumption and includes energy consumption contributions from: final energy, final non-energy and international aviation and shipping.

Source: POTEnCIA model

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[1] POTEnCIA (Policy Oriented Tool for Energy and Climate Change Impact Assessment) is a modelling tool that allows a robust assessment of the impact of different policy futures on the EU energy system developed by the JRC. Description of the model and the scenarios are given in Annex 3

[2] Final non-energy consumptions include fuels that are used as raw materials and are not consumed as fuel or transformed into another fuel

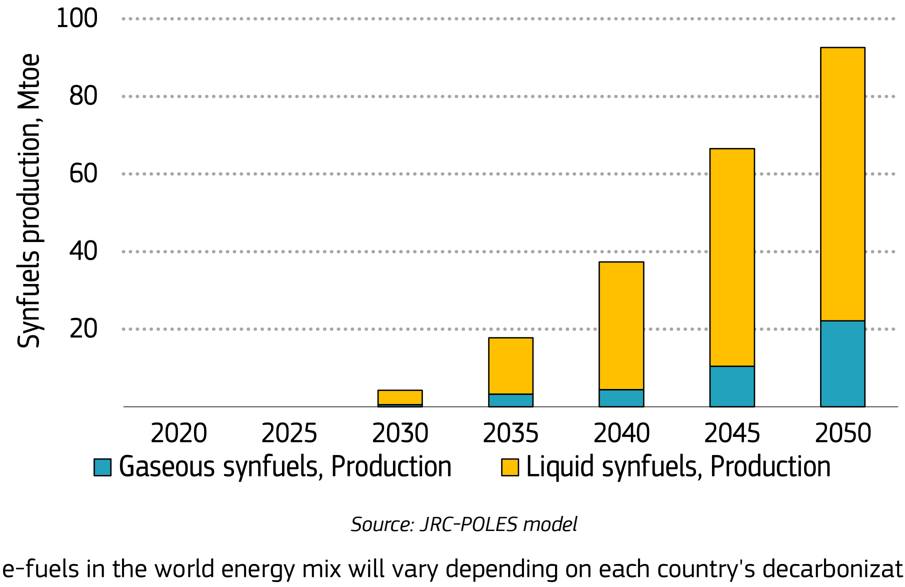
Besides targeting a gradual decrease in GHG emissions leading to carbon neutrality in 2050, the *POTEnCIA CETO 2024 Scenario* includes specific penetration targets for RFNBO, for instance those defined by the Renewable Energy Directive or by the ReFuelEU Aviation regulation, which are properly reflected in the scenario results shown. Besides these levers, the growing consumption of synthetic fuels as RFNBO in the different energy sectors is also the result of a direct competition with other alternative fuels (e.g. advanced biofuels), based on assumed techno-economic projections, to meet the overall GHG reduction target or sector specific targets (for instance the FuelEU Maritime reduction targets for GHG intensity of energy use on vessels).

More specifically, in aviation the consumption of e-kerosene increases progressively, reaching almost 19 Mtoe in 2050. For the maritime sector (including bunkers and domestic navigation), the RFNBO demand is assumed to be covered by e-ammonia and e-methanol, with ammonia being the predominant e-fuel, and to a much lower extent by e-methane and e-diesel. The model incorporates the versatility of e-methanol, not just as a fuel for the maritime sector, but also as a feedstock in the chemicals sector. By 2050, more than 2 Mtoe of synthesized methanol are used for chemicals production replacing oil and natural gas products, compared to 3 Mtoe of e-methanol consumed in the maritime sector. Minor amounts of e-methane, e-diesel and e-gasoline are consumed in other end-use sectors. Lastly, renewable hydrogen, beside of being used as feedstock for liquid RFNBO production, is also consumed in maritime, heavy duty vehicles and in industries both as energy carrier and as feedstock.

The POTEnCIA model explicitly considers the eligibility of renewable electricity sources for RFNBO production, which is limited to additional capacity beyond existing installations. Biogenic CO2 and CO2 from direct air capture are the sources of CO2 considered for RFNBO production[3].

As regards the worldwide potential production, POLES-JRC modelled the renewable e-fuels demand up to 2050 in the *Global CETO 2°C scenario 2024* as reported in Figure 6.

Figure 6. Global synfuel production (considering only e-fuels) under the *Global CETO 2°C scenario 2024* of the POLES-JRC model.



Source: JRC-POLES model

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

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[3] For a limited period of time, fossil CO2 captured from power plants and from specific industrial installations is also allowed as feedstock for RFNBO production, in particular until 2035 in the case of CO2 captured in power plants and until 2040 in the case of CO2 captured in specific industrial installations.

Moreover, it will be challenging to evaluate the quantity of e-fuels generated from renewables compared to the ones generated by low-carbon hydrogen (i.e. produced from nuclear electricity or fossil-based sources with CCS). For instance, the IEA Net Zero scenario (International Energy Agency (IEA), 2021a) considers a broader category for low carbon hydrogen (including renewables), and the quantity of e-fuels produced towards 2050 results higher than the JRC-POLES' *Global CETO 2°C scenario 2024* projection. The transition to a sustainable e-fuels economy will require coordinated effort among national governments, companies, and international organizations to ensure that production is ramped up sustainably and equitably, including collaborative efforts in developing infrastructures. Other model exercises can lead to very different results, for instance, when the demand of e-fuels and e-chemicals at 2050 considers the full replacement of their respective fossil-based counterparts, results in extremely higher supply than the previous models (Galimova et al., 2023). A detailed analysis of the current and upcoming initiatives is reported in the following sections.

e-Methanol

Several PtX projects have been announced that will introduce e-methanol in the fuel market. Among these projects, the Megaton project led by GreenGo Energy in Denmark is a significant initiative aiming to produce 1 million tonnes or 2.87 Mtoe of green hydrogen by 2030, which is expected to be dedicated to the production of green fuel, including methanol. The San Roque Ammonia project in Spain, developed by Cepsa and Yara, while primarily focused on ammonia, is also significant due to the scale and the potential for methanol production as part of the broader e-fuels category, aiming to produce 750,000 tonnes or 0.33 Mtoe of e-ammonia annually by 2027 if the final investment decision is received.

The Green Fuels for Denmark (GFDK) project is a partnership of companies across the value chain for e-methanol. It involves several Danish companies, from power generation, such as Orsted, to leading off-takers of the green fuel, such as the shipping companies Maersk and DFDS. The project also aims to use the e-methanol as an input for aviation fuel, producing e-kerosene. To secure the off-take of the aviation fuel, the project also counts with the partnership of SAS and Copenhagen Airport. The project aims to produce about 30,000 t/y of mainly e-methanol, being scalable to up to 60,000 t/y in the future. The project has been granted IPCEI status, with a total funding of DKK 850 million (€114 million) (Transport & Environment, 2024a).

Similarly, the Port of Gothenburg project involves several companies across the value chain. It has been set up by the Gothenburg Port Authority, Sweden, and involves companies such as Stena Line, Orsted, DFDS, and Liquid Wind, in order to make it Europe's first e-methanol hub. The port will be fed with e-methanol produced by the project FlagshipONE, the first commercial-scale PtX facility, which will come into operation stage by 2025, producing circa 50,000 t/y of e-methanol. It has been calculated that e-methanol reduces the shipping emissions in the port area by 70% (Transport & Environment, 2024a). However, a recent update reported that Orsted abandoned the project in favour of RFNBO hydrogen production (S&P Global, 2024).

Hynetherlands is another project involving a value chain of green hydrogen. The project is being developed in the Netherlands and involves deployment of renewable energy to produce green hydrogen, of carbon capture and of e-methanol production facilities. The project plans to deliver e-methanol for the maritime sector as the first users, and later include the demand of chemical, plastic, steel, glass and other industries. Engie is the company driving the project, and it counts with the collaboration of OCI, a methanol producer, and EEW, a waste-to-energy company (Transport & Environment, 2024a).

Some of the main companies in the e-methanol value chain are listed below (this is an illustrative list):

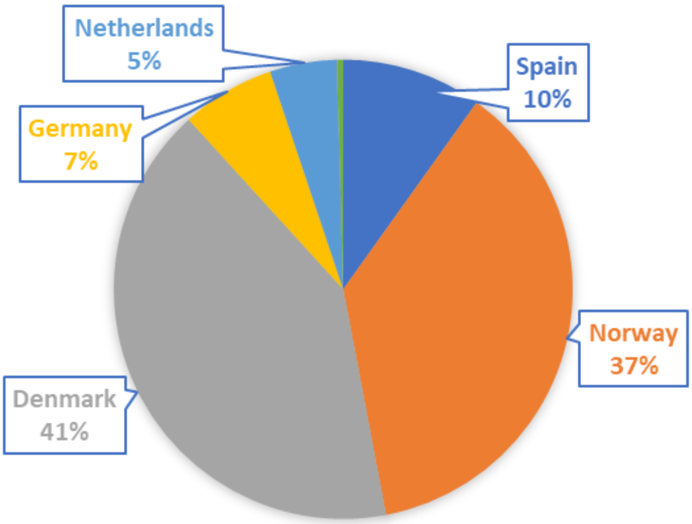
- European Energy (Denmark)
- Orsted (Denmark)
- CIP (Denmark)
- Total Energies (France)
- Maersk (Denmark)

- HMM (South Korea)
- MAN Energy Solutions (Germany)
- Siemens Energy (Germany)
- Engie (France)
- Enel (Italy)
- OCI (Netherlands)
- EEW (Germany)
- Haldor Topsoe (Denmark)
- Stena Line (Sweden)
- DFDS (Denmark)
- Liquid Wind (Sweden)
- Inter Terminals (Sweden)
- Alfa Laval (Sweden)
- Perstop (Sweden)
- HIF Global (US)
- Carbon Clean (UK)
- Celanese (US)
- Porsche (Germany)
- Mitsui & Co (Japan)
- Shenergy Group (China)
- CHN Energy (China)
- Henan Shuncheng Group (China)

e-Ammonia

Thirteen of the announced projects are to be developed in Europe, amounting to a total production of approximately 1,600,000 t/y (some of the projects do not yet have their production capacities disclosed). 36 projects have been announced outside of Europe, amounting to a total production of approximately 69,400,000 t/y. Of these projects, 16 are to be developed in Australia.
Based on the announced projects so far, Denmark is expected to be the largest producer of e-ammonia in Europe, accounting 655,000 t/y. Norway has the second highest production capacity announced, expecting to produce 590,000 t/y, and having two development projects yet to disclose their production capacity.

Figure 7. E-ammonia planned capacity in Europe



Source: (IRENA and AEA, 2022)

According to the Ammonia Energy Association's website, 20 e-ammonia projects have been announced. Based on these, the total global e-ammonia production capacity is expected to reach approximately 90,000,000 t/y by 2035. Approximately 1,105,000 t/y is expected to be produced in Europe. This would account for 1.2% of the global production in 2035.

IRENA report on Renewable Ammonia (IRENA and AEA, 2022) mapped a total of 54 existing and planned production plants, being both brownfield and greenfield investments. More recent estimations mapped up to 66 projects worldwide (Sia Partners, 2024), but many of these novel projects or initiatives under developments still need further data assessment. The largest ammonia companies in the world (CF Industries and Yara) have announced projects to revamp their existing production facilities to substitute their ammonia production fully or partially with e-ammonia, as well as to build new production facilities for the green chemical.

The 54 projects identified by IRENA are expected to have a total production of 15 Mt per year by 2030, which would account for 6% of the total global ammonia production by then. By 2040, the announced projects are expected to deliver up to 71 Mt/y globally. The HØST PtX Esbjerg project, to be developed in Esbjerg, Denmark, is the largest of the European projects. This project is being developed by Copenhagen Infrastructure Partners, Maersk, and DFDS, and is expected to have a production over 600,000 t/y. The project aims to produce the ammonia for both maritime fuel and fertilizer applications, yielding either 600,000 tons of bunkering fuel, or 1.5m tons of fertilizer. It has an estimated CAPEX of EUR 1.4 billion and is expected to start operating by 2028-2029. This project will create circa 100 to 150 permanent jobs (Transport & Environment, 2024a). The San Roque Ammonia project in Spain, as mentioned earlier, is also a significant initiative in the e-ammonia space, aiming to produce 750,000 tonnes or 0.33 Mtoe of e-ammonia annually by 2027, if the expected investment funds materialise.

The largest announced project in the world so far is the Western Green Energy Hub to be developed by the Singapore-based company InterContinental Energy in Western Australia. The project will deploy 50 GW of renewable electricity, 30 GW from wind and 20 GW from solar, to generate 3,500,000 tons of green hydrogen per year, which will be converted to 20,000,000 t/y of e-ammonia.

Table 11. E-Ammonia supply and demand projections

Supply			
Source	(IRENA and AEA, 2022) Mega-project – Ammonia Energy Association		
Number of projects		Expected production	
54		~71- 90 million t/y by 2040 (1-2% in Europe)	
Demand			
Source	(Ram *et al.*, 2020)		
Year	2030	2040	2050
TWh	78	2,249	3,340
Market share (of TWh demand among RFNBO in 2050)		7.8%	

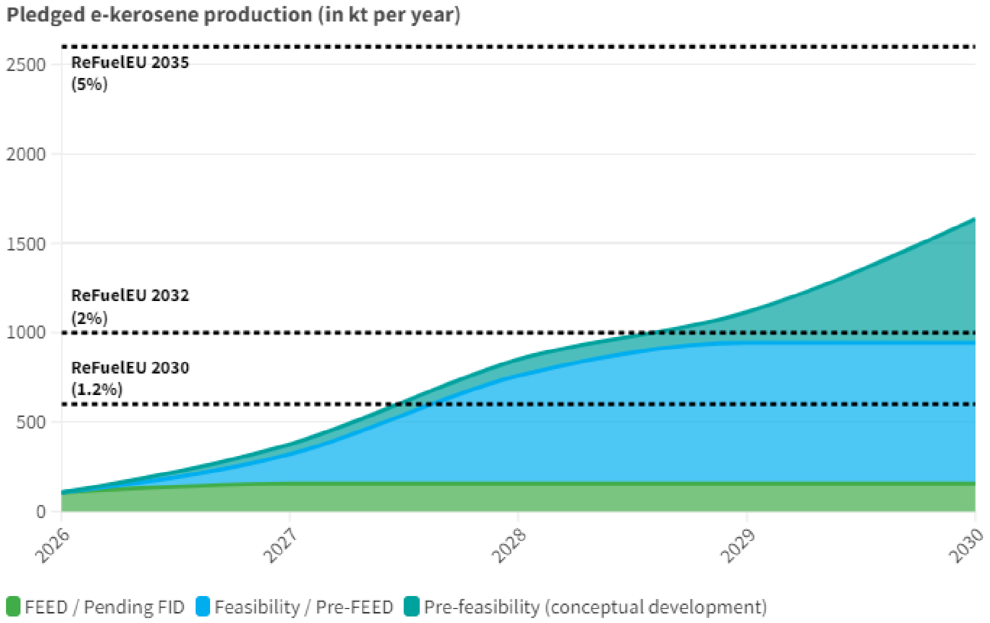
Source: (IRENA and AEA, 2022)

e-Kerosene

The use of SAF in EU is regulated by the REFuelEU aviation Regulation (EU) 2023/2405, which provides a mandate for EU SAF demand and the corresponding fuel production up to 2030 and beyond. According to the ASTM rules for blending synthetic jet fuel into the commercial blend (Moriarty and Mccormick, 2023), the fuel blending limits are 50/50 for almost all certified pathways. Among these, e-SAF produced from FT- and ATJ is already recognized, and the methanol-to-jet pathway is in the pipeline for ASTM approval (Van Dyk and Saddler, 2024).

According to the IEA Bioenergy T39 report, several companies have already started on the production of SAF, but these are mostly bio-derived jet fuels. The European NGO Transport and Environment identified 45 e-kerosene projects in the EEA in 2023 (Transport & Environment, 2024b), adding 17 since November 2022, and including 8 major new announcements. These 25 industrial and 20 pilot projects are expected to produce 1.7 Mt of e-kerosene by 2030, exceeding the ReFuelEU target of 1.2% and aiming for 2% by 2032. However, today production is still far below this target. The EU's new Net Zero Industry Act (NZIA) (European Parliament and the Council of the European Union, 2024) included SAF as essential for the 2040 climate goals, ensuring aviation's role in the EU's climate strategy. However, the absence of final investment decisions (FID) for these projects means their capacities remain provisional. The NZIA, together with EU funding and private investments, is set to enhance SAF market uptake, supporting a sustainable aviation industry transition.

Figure 8. E-kerosene planned capacity in the EEA per advancement stage compared with ReFuelEU blending mandates



Source: NGO Transport and Environment (Transport & Environment, 2024b)

The Sasol, DHL, and HH2E project in Eastern Germany is a significant e-kerosene project with an announced annual production of 200,000 tons of e-fuels starting in 2030. This project is one of the largest new announcements and is expected to fulfil the entirety of the 2% quota set by the German national PtL roadmap (Transport & Environment, 2024b).

The Norsk e-Fuel project in Norway, with its Alpha, Beta, and Gamma plants, is planning to produce a total of 160,000 tons of e-kerosene by 2030. The Alpha plant is expected to start operations in 2026 with a production capacity of 32,000 tons, followed by the Beta and Gamma plants with similar capacities.

The Green Fuels for Denmark project is a partnership between the energy and transport industries with Ørsted, DSV, Maersk, DFDS, Copenhagen Airports and Scandinavian Airlines. It will produce a slate of PtL products for the road, aviation and maritime sectors. The project plans to start production in 2025 with over 30,000 tons of PtL fuel from wind power. The European Commission recognized Green Fuels for Denmark as an important project of common European interest (IPCEI), allowing the Danish government to support the project with public funding (DKK 850 million) (Transport & Environment, 2024a).

Atmosfair started operation at a PtL aviation fuel plant in 2021. The plant is located in Werlte, Germany, and the transport companies Lufthansa and Kuehne+Nagel will purchase the annual production of 25,000 litres of aviation fuel (Transport & Environment, 2024b).

The Hyskies project in Sweden with energy company Vattenfall, Scandinavian Airlines and fuel producer Lanzatech will produce power-to-liquid (PtL) SAF from 2025-26. The planned production volume reaches 50 000 tonnes per year, or 30% of kerosene used on domestic flights in Sweden. Based nearby Arlanda airport, the production will use renewable electricity and point-source carbon capture from a nearby power plant." (International Transport Forum, p.28, 2023).

The SAF production capacity target by 2050, according to SAF producer estimations, need 104-106 SAF plants to be built, requiring an estimated investment of circa €10.4-10.5 billion. Furthermore, it is estimated that this emerging market will create around 202,100 additional jobs and will reduce external costs from air pollution (due to the lower content of aromatics of synthetic fuels) by €1.5 billion by 2050 (Transport & Environment, 2024b).

e-Methane

According to the Global Alliance Powerfuels, e-methane will account for almost 20% of the e-fuels global energy demand by 2050, having a total of 8,590 TWh of final thermal energy demand. E-methane could be applied in the areas of transportation, power generation, and industrial heating. Use of e-methane fuel is being explored in the maritime sector, as it is suitable for dual-engine vessels running in LNG. A few projects have started exploring this solution. Synthetic methane is also being widely considered, especially in gas-dependent regions, as a new source of gas supply, for power generation and heating. Several initiatives have started projecting and demonstrating the application of e-methane to the gas grid, as a form of broadening its gas-sourcing and decarbonizing the heating sector. The list of the current EU initiatives, both ongoing and planned, has been thoroughly prepared by the EBA (European Biogas Association (EBA), 2024) and summarized in the appendix.

In the maritime sector, the French company, Engie, entered a partnership with the shipping company CMA CGM to develop synthetic methane production and distribution for the shipping sector. The shipping company currently has 20 dual-fuel engines vessels running on LNG, which are "e-methane ready". By the end of 2024, the company expects to have 44 vessels ready to run on e-methane.

In the gas sector, the Japanese company, Mitsubishi Corporation, is developing a project with Tokyo Gas, Osaka Gas and Togo Gas, to build a complete supply chain, from hydrogen production and carbon capture, in order to produce e-methane. The project is targeting its production facility to be placed in the US, which would then produce 130,000 t/y of e-methane, all which would be then exported to Japan, utilizing existing gas infrastructure for transport and storage. The project aims to decarbonize its heat sector, and is expected to start operations by 2030. Another Japanese initiative comes through the Australian company Santos Energy Solutions entering an agreement with the Japanese Osaka Gas to develop a demonstration-scale plant in Australia. The project will use green hydrogen and either point source CO_2 or DAC. Operations are expected to commence by 2030, when it will export about 60,000 t/y of e-methane to Japan.

In Europe, the Belgian company, Tree Energy Solutions, is developing a green energy hub by the German port of Wilhelmshaven, where around 20,000 t/y of e-methane will be imported by 2025, which will be a small share of LNG import. The synthetic fuel will be imported as a carrier for green hydrogen, meaning that upon arrival, the fuel will be once again broken down into hydrogen and CO_2. Almost the whole amount of this CO_2 (depending on the CCU efficiency) can be captured and re-sent to produce a new batch of e-methane, making it a closed loop. The company claims that this is the most cost-effective way to import hydrogen.

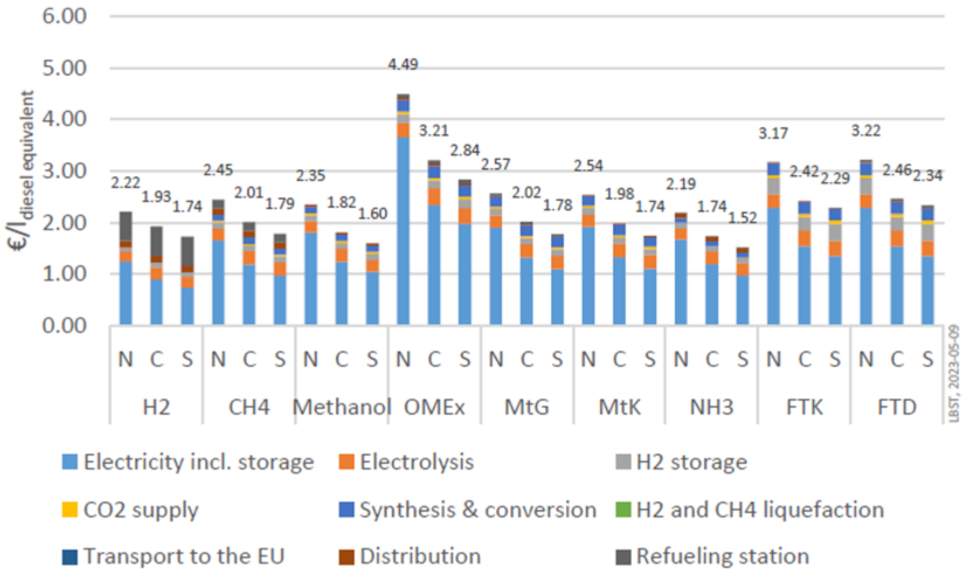
The French project, Jupiter 1000, is a demonstration project of hydrogen production through electrolysis and e-methane production through methanation and CO2 captured on a nearby industrial site. The project counts with a range of companies expanding through the whole value chain of e-methane production. The project planned ending its trials in 2024, and has a methane production of 25m^3/h.

2.3 Technology Costs

This section uses to technology costs published in 2024 by Concawe and Aramco in their report no 4/24 (Soler *et al.*, 2024) replacing the previous analysis referring to earlier studies (Yugo and Soler, 2019; Soler *et al.*, 2022). The figure below is extracted from the report. The chart was elaborated by LBST in 2023 (Schmidt et al., 2023). Each of the 9 e-fuels is represented by 3 values corresponding to production costs for north, central and south-Europe in 2030, where each region uses a different electricity mix. The chart shows that the lowest costs are found in southern Europe, and the highest production costs are estimated to be in northern Europe. In 2030, the second cheapest after e-ammonia is e-methanol, with potential future production cost for e-methanol around 1.60 - 2.35 €/l diesel equivalent[4].

The chart shows that the dominant factor impacting e-fuels production costs is electricity cost (blue fields). The chart shows that southern Europe has the most favorable regional conditions to produce renewable electricity at relatively low electricity prices. The second main factor is electrolyser cost (orange color on the chart). The values of the Figure 9 are summarised in the table below.

Figure 9. Costs of e-fuels produced inside Europe by zone in 2030 (N: North EU; C: Central EU; S: South EU)



Source: Concawe and Aramco report no 4/24, figure 28 of the report

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[4] the equivalent amount of fuel with the same energy content

Table 12. Costs of e-fuels produced in Europe in 2020, in 2030, in 2050

E-fuel pathways	**2020** **[€/l diesel equivalent]**	**2030** **[€/l diesel equivalent]**	**2050** **[€/l diesel equivalent]**
Note: the ranges below reflect the spread of north, central and south-Europe projected costs			
H2	2.08-3.11	1.74-2.22	1.51-1.87
CH4	2.06-3.47	1.79-2.45	1.71-2.33
Methanol	1.92-3.48	1.60-2.35	1.62-2.37
OMEx*	3.44-6.78	2.84-4.49	2.79-4.33
MtG*	2.12-3.77	1.78-2.57	1.77-2.55
MtK*	2.09-3.75	1.74-2.54	1.73-2.51
NH3	1.77-3.19	1.52-2.19	1.30-1.87
FTK*	2.68-4.59	2.29-3.17	1.95-2.77
FTD*	2.73-4.63	2.34-3.22	1.99-2.81

*OMEx: Oxymethyleneether, MtG: Methanol-to-gasoline, MtK: Methanol-to-kerosene, FTK: Fischer-Tropsch kerosene, FTD: Fischer-Tropsch diesel

Source: Concawe and Aramco report no 4/24, figures 27, 28, 29 by LBST, 2023/05

The Concawe and Aramco report no 4/24 also included estimations on the e-fuels production costs in the e-fuel synthesis plants to 2050. The data are summarised in the Table 12.

The data show a potential for cost reductions from 2020 to 2050 for the following e-fuels (Table 13):

- For e-methane the CAPEX upper value (to reach the capacity) of the range reflecting north, central and south-Europe projected costs is EUR 1422 million in 2020 and EUR 998 million in 2050. This represents a reduction of 30 %. The annual OPEX is assumed to be 3% of the CAPEX.
- For e-methanol the CAPEX upper value of the range reflecting north, central and south-Europe projected costs is EUR 1356 million in 2020 and EUR 900 million in 2050. This represents a reduction of 34%. The annual OPEX is assumed to be 3% of the CAPEX.
- For e-OME the CAPEX upper value of the range reflecting north, central and south-Europe projected costs is EUR 518 million in 2020 and EUR 344 million in 2050. This represents a reduction of 34%. The annual OPEX is assumed to be 4.5% of the CAPEX.
- For e-MTG (e-gasoline) the CAPEX upper value of the range reflecting north, central and south-Europe projected costs is EUR 537 million in 2020 and EUR 358 million in 2050. This represents a reduction of 33%. The annual OPEX is assumed to be 4.5% of the CAPEX.
- For e-MTK (e-kerosene) the CAPEX upper value of the range reflecting north, central and south-Europe projected costs is EUR 537 million in 2020 and EUR 358 million in 2050. This represents a reduction of 35%. The annual OPEX is assumed to be 4.5% of the CAPEX.
- On the other hand the data show an increase of the production costs for e-Ammonia and e-FT.
- For e-Ammonia the CAPEX upper value of the range reflecting north, central and south-Europe projected costs is EUR 975 million in 2020 and EUR 986 million in 2050. This represents an increase of 1%. The annual OPEX is assumed to be 3% of the CAPEX.

- For e-FT the CAPEX upper value of the range reflecting north, central and south-Europe projected costs is EUR 1678 million in 2020 and EUR 1958 million in 2050. This represents a reduction of 17%. The annual OPEX is assumed to be 3% of the CAPEX.

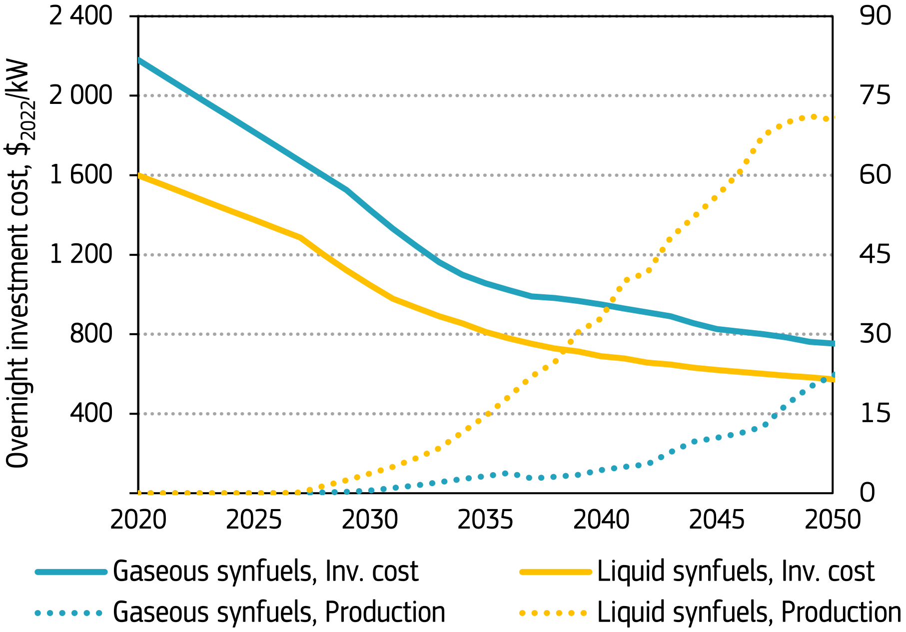
Table 13. E-fuel production costs: CAPEX and OMEX overview for the e-fuel synthesis plants in Europe

E-fuel	**Year**	**Capacity [MW, LHV]**	**CAPEX [€/kW, LHV]**	**CAPEX [million €]**	**Fixed O&M: 3% of CAPEX/yr**	**Table where the source is available**
		Note: range reflects north, central and south-Europe projected costs				
Methanation plant	2020	1615-1796	792	1279-1422	3% of CAPEX/yr	[Table 88]
	2030	1615-1810	704	1137-1275	3% of CAPEX/yr	
	2050	1648-1844	541	892-998	3% of CAPEX/yr	
Methanol plant	2020	1606-1765	768	1234-1356	3% of CAPEX/yr	[Table 97]
	2030	1615-1776	672	194-1114	3% of CAPEX/yr	
	2050	1634-1800	500	817-900	3% of CAPEX/yr	
OME synthesis plant	2020	1594-1687	307	490-518	4.5% of CAPEX/yr	[Table 107]
	2030	1604-1707	269	431-459	4.5% of CAPEX/yr	
	2050	1609-1722	200	322-344	4.5% of CAPEX/yr	
MTG synthesis plant *	2020	1603-1747-	307	493-537	4.5% of CAPEX/yr	[Table 116]
	2030	1610-1770	269	433-476	4.5% of CAPEX/yr	
	2050	1627-1792	200	325-358	4.5% of CAPEX/yr	
MTK synthesis plant	2020	1603-1747	307	420	4.5% of CAPEX/yr	[Table 116]
	2030	1610-1770	269	368	4.5% of CAPEX/yr	
	2050	1627-1792	200	273	4.5% of CAPEX/yr	
Ammonia synthesis plant	2020	1620-1811	n/a	902-975	3% of CAPEX/yr	[Table 121]
	2030	1624-1820	n/a	903-978	3% of CAPEX/yr	
	2050	1653-1840	n/a	914-986	3% of CAPEX/yr	
FTK, FTD: FT synthesis plant	2020	1489-1526	1098-1099	1637-1678	3% of CAPEX/yr	[Table 130]
	2030	1488-1516	1098-1099	1635-1666	3% of CAPEX/yr	[Table 131]
	2050	1621-1789	1094-1097	1778-1958	3% of CAPEX/yr	[Table 132]

Source: Concawe and Aramco report no 4/24

Figure 10 shows overnight investment cost at global level based on the *Global CETO 2°C scenario* calculated with the POLES-JRC model (details available in Annex 2). The strongly decreasing cost from the of end 2020's to about 2035 is a result of endogenous learning induced by the fast deployment of synfuel capacities during this period. This initial cost decrease triggers thereafter the expansion of the production reaching over 100 Mtoe of production (for both fuels) in 2050..

Figure 10. Synfuels global overnight investment cost and production



Source: JRC-POLES model

The global production of synfuels (gaseous and liquid) reaches about 90 Mtoe by 2050 as also shown in Figure 10. These global projections are based on the *Global CETO 2°C scenario 2024* which showcases a future where concerted efforts to limit global temperature increases to 2°C yield transformative impacts on the production and economic viability of clean energy technologies. The report acknowledges historical fluctuations in renewable technology costs, sourced from IRENA data up to 2022/23, but shows more stable cost descent from 2025 onwards. Notably, the 2024 iteration of this scenario distinguishes itself from its 2023 predecessor by integrating advanced modelling of endogenous learning and more detailed representations of technologies such as Direct Air Capture (DAC), hydrogen transport technologies, and batteries in transport. These enhancements have led to substantial scenario differences regarding the deployment and cost development of DAC, synfuels, Carbon Capture and Storage (CCS) power technologies, wind power, and ocean power. The chart thus projects a future where increased production and technological learning drive down the costs of synfuels, making them a more economically viable option within the low-carbon transition envisaged in the *Global CETO 2°C scenario 2024*.

2.4 Public RD&I Funding and Investments

RFNBO available technologies have been mainly funded by Horizon 2020 projects (data extracted from TIM/CORDIS), and the current Horizon Europe programme is dedicating specific calls to such technologies. Innovation Fund will also support the development of the sector, but mainly focusing on the upstream processes of H_2 production and CO_2 capture and utilization.

Horizon 2020 funded 33 projects concerning RFNBO other than pure electrolytic hydrogen (Table 14). All the projects used innovative technologies and were RIAs, with max TRL 5 at the end of the project. The total EU funding received by the projects totalled 114 M€.

Table 14. Horizon 2020 and Horizon Europe projects on RFNBO.

Project Acronym	**Project Title**	**Feedstock**	**Technology**	**End-product**	**EU Contribution kilo €**
SUN-to-LIQUID	SUNlight-to-LIQUID: Integrated solar-thermochemical synthesis of liquid hydrocarbon fuels	Sunlight, CO_2	CSP, FT	Synthetic jet fuel	4,451 €
FReSME	From residual gasses to methanol	CO_2 from steel	Sorption-enhanced water–gas shift (SEWGS) technology + water electrolysis + catalytic conversion	methanol	11,407 €
eForFuel	Fuels from electricity: de novo metabolic conversion of electrochemically produced format into hydrocarbons	CO_2	Electrobioreactor	Propane and isobutene	4,117 €
KEROGREEN	Production of Sustainable aircraft grade Kerosene from water and air powered by Renewable Electricity, through the splitting of CO_2, syngas formation and Fischer-Tropsch synthesis	CO_2	plasma driven dissociation of air captured CO_2, solid oxide membrane oxygen separation, FT	biojet	4,951€
CO_2Fokus	CO_2 utilisation focused on market relevant dimethyl ether production, via 3D printed reactor - and solid oxide cell-based technologies	CO_2	CO_2 hydrogenation involving both catalytic chemical and electrochemical conversion	DME	3,994€
eCOCO_2	Direct electrocatalytic conversion of CO_2 into chemical energy carriers in a co-ionic membrane reactor	CO_2	electrochemical: multifunctional catalyst integrated in a co-ionic electrochemical cell	synthetic jet fuel	3,949€
C2Fuel	Carbon Captured Fuel and Energy Carriers for an Intensified Steel Off-Gases based Electricity Generation in a Smarter Industrial Ecosystem	CO_2 from steel	electrochemical, several routes	biodiesel, formic acid	3,999 €
COZMOS	Efficient CO_2 conversion over multisite Zeolite-Metal nanocatalysts to fuels and Olefins	CO_2 from steel and refinery	electrochemical: multisite Zeolite-Metal nano catalysts	propane, propene	3,997 €
SELECTCO_2	Selective Electrochemical Reduction of CO_2 to High Value Chemicals	CO_2	Selective Electrochemical Reduction of CO_2 to High Value Chemicals	carbon monoxide, ethanol or ethylene	3,772€
TAKE-OFF	Production of synthetic renewable aviation fuel from CO_2 and H_2	CO_2	conversion of CO_2 and H_2 to SAF via ethylene as intermediate	Aviation fuel	4,998 €
ECOFUEL	Renewable Electricity-based, cyclic and economic production of Fuel	CO_2	electrochemical conversion of CO_2 to transport fuels via light alkenes	transport fuels	4,858 €
METHASOL	International cooperation for selective conversion of CO_2 into METHAnol under SOLar light	CO_2	CO_2 reduction via artificial photosynthesis with	methanol	3,999€

Project Acronym	**Project Title**	**Feedstock**	**Technology**	**End-product**	**EU Contribution** **kilo €**
			corresponding photocatalysts		
NEFERTITI	Innovative photocatalysts integrated in flow photoreactor systems for direct CO_2 and H_2O conversion into solar fuels	CO_2, H_2O	photocatalysis for CO_2 and H_2O conversion to alcohols	Ethanol, longer chain alcohols	3,844 €
TELEGRAM	TOWARD EFFICIENT ELECTROCHEMICAL GREEN AMMONIA CYCLE	Air, water and renewable energy	Electrochemical ammonia synthesis and direct ammonia fuel cell	NH3 as energy carrier	3,468€
LAURELIN	Selective CO_2 conversion to renewable methanol through innovative heterogeneous catalyst systems optimized for advanced hydrogenation technologies (microwave, plasma and magnetic induction).	CO_2 and H_2	disruptive multifunctional catalyst systems for CO_2 hydrogenation	Renewable methanol	4,448 €
4AIRCRAFT	Air Carbon Recycling for Aviation Fuel Technology	CO_2/H_2	Novel multi catalyst reactor technology that combines electro-, chemo-, and biocatalysts to provide a net-neutral carbon-based fuel for aviation	Jet fuel (C8-C16)	2,239€
ORACLE	Novel routes and catalysts for synthesis of ammonia as alternative renewable fuel	N_2/H_2O	plasma-aided electro catalytic as well as electrified thermal catalysis	NH3	2,846 €
UP-TO-ME	Unmanned-Power-to-Methanol-production	CO_2 from biogas and H_2O	3D printed methanol synthesis reactor	renewable methanol	2,997 €
E-TANDEM	Hybrid tandem catalytic conversion process towards higher oxygenate e-fuels	CO_2 and H_2O	electro catalysis/solid thermocatalysis	oxygenate e-fuels	3,334€
SOREC2	SOlar Energy to power CO_2 REduction towards C2 chemicals for energy storage	CO_2, H_2O, sunlight	Photo electrochemistry technology (PEC)	ethanol or ethylene	3,084 €
DARE2X	Decentralised Ammonia production from Renewable Energy utilising novel sorption-enhanced plasma-catalytic Power-to-X technology	Air and H_2O	Water electrolysis + non-thermal plasma (sorption-enhanced plasma catalytic technology)	Ammonia	2,952
DESIRED	Direct co-processing of CO_2 and water to sustainable multicarbon energy products in novel photocatalytic reactor	CO_2, H_2O, sunlight	e hybrid photo-electrocatalysts	C2+ solar fuels, methanol and methane	3,058€
FreeHydroCells	Freestanding energy-to-Hydrogen fuel by water splitting using Earth-abundant materials in a novel, eco-friendly, sustainable and scalable photoelectrochemical Cell system	H_2O, sunlight	solar-to-chemical energy conversion (photoelectrochemical system)	H_2	3,748€

Project Acronym	**Project Title**	**Feedstock**	**Technology**	**End-product**	**EU Contribution** **kilo €**
MOF2H$_2$	Metal Organic Frameworks for Hydrogen production by photocatalytic overall water splitting	H$_2$O, sunlight	MOF-based photocatalysis for sun-driven H$_2$ production	H$_2$	2,998€
ECO$_2$fuel	Large-scale low-temperature electrochemical CO$_2$ conversion to sustainable liquid fuels	CO$_2$, water, electricity	Innovative electrocatalytic CO$_2$ at 80 °C and 15 bar	Liquid fuels	16,620 €
FLEXnCONFU	FLExibilize combined cycle power plant through power-to-X solutions using non-CONventional FUels	CO$_2$, water, electricity	1MW scale power-to-hydrogen-to-power system or ammonia to be in turn locally re-used in the same power plant to balance the load	Hydrogen, ammonia	9,887€
MefCO$_2$	Synthesis of methanol from captured carbon dioxide using surplus electricity	CO$_2$, water, electricity	methanol production with high CO$_2$ concentration-streams and H$_2$ as an input	Methanol	8,622 €
MegaSyn	Megawatt scale co-electrolysis as syngas generation for e-fuels synthesis	CO$_2$, water, electricity	First demonstration of mega-watt scale syngas production by co-electrolysis (SOECs) to e-fuels.	Liquid fuels	4,999€
SUN-to-LIQUID II	SUNlight-to-LIQUID: Integrated solar-thermochemical synthesis of liquid hydrocarbon fuels	H$_2$O, CO$_2$ and solar energy	Concentrated solar radiation drives a thermochemical redox cycle, which inherently operates at high temperatures and utilizes the full solar spectrum	Liquid fuels	4,450€
ELCOREL	Electrochemical Conversion of Renewable Electricity into Fuels and Chemicals	CO$_2$, water, electricity	Electrochemical oxidation of water and electrochemical reduction of carbon dioxide based on the principles of quantum chemistry and innovative catalysts	Fuel and chemicals	3,616€
HELENIC-REF	Hybrid Electric Energy Integrated Cluster concerning Renewable Fuels	CO$_2$, water, heat	water thermolysis with innovative catalysts at temperatures below 300oC	Synthetic natural gas	2,578 €
Circlenergy	Production of renewable methanol from captured emissions and renewable energy sources, for its utilisation for clean fuel production and green consumer goods	CO$_2$, water, electricity	Innovative methanol production through CO$_2$ capture with ISCC certified technology	Methanol	1,827 €
COFLeaf	Fuel from sunlight: Covalent organic frameworks as integrated platforms for photocatalytic water splitting and CO$_2$ reduction	H$_2$O, CO$_2$ and solar energy	Artificial photosynthesis with polymeric photocatalysts based	methane or methanol	1,497 €

Project Acronym	**Project Title**	**Feedstock**	**Technology**	**End-product**	**EU Contribution** **kilo €**
			on covalent organic frameworks		

Source: TIM/CORDIS elaboration

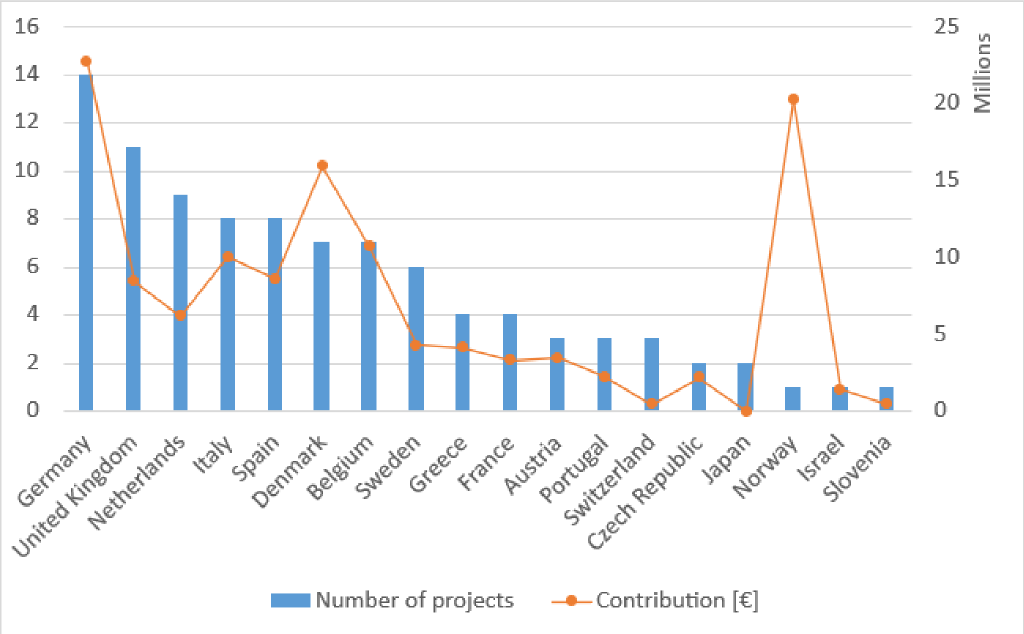
For feedstocks used for the RFNBO production, 26 projects have tested the CO_2 recovery, 5 projects have used water in combination with sunlight, and 2 projects air and water.

Concerning the technologies tested, in addition to the traditional hydrolysis and synthesis processes, there are also photo-electrochemical conversion, photo-catalysis, thermo-catalysis, sorption-enhanced water–gas shift, artificial photosynthesis.

The processes tested are delivering as output several different products: road, maritime and synthetic jet fuels; methanol; methane, propane and isobutene; ethanol; ethylene, ammonia. It is worth to mention that other small (e.g. MSCA) activities and hybrid projects (thus including bio-feedstock) also study and demonstrate similar applications, including RFNBO.

As shown in Figure 11, Germany, Denmark and Norway received higher contribution related to the number of projects financed.

Figure 11. Public R&D financing country level 2021



Source: JRC elaboration

The European Innovation Council EIC in the framework of Horizon Programme opens funding opportunities worth over €1.72 billion in 2024 for breakthrough innovators to scale up and create new markets. Such calls potentially include RFNBO production. The 2024 work programme is divided in three sections:

- EIC Pathfinder - for multi-disciplinary research teams, worth €256 million in 2024, to undertake visionary research with the potential to lead to technology breakthroughs, research teams can apply for up to €3 or €4 million in grants, the RNFBO activities could be financed under the umbrella of EIC challenge: "Solar-to-X" devices towards cement and concrete as a carbon sink".

- EIC Transition - funding to turn research results into innovation opportunities, worth €94 million in 2024. The calls will focus on results generated by EIC Pathfinder projects and European Research Council Proof of Concept projects, to mature the technologies and build a business case and market readiness for specific applications.
- EIC Accelerator - worth €675 million in 2024, for start-ups and SMEs to develop and scale up high impact innovations with the potential to create new markets or disrupt existing ones. the RNFBIO activities could be financed under the umbrella of EIC challenge: "Renewable energy sources and their whole value chain".

Finally, it worth mentioning that EC is funding mainly upstream processes for CCS/CCU and hydrogen production by means of the Innovation Fund. The Commission ran 3 large-scale calls and 3 small-scale calls between 2020 and 2023. (European Commission (EC), 2022). There are no specific projects based only on RFNBO production, but many hybrids processes which co-produce both synthetic bio- and non-biological fuels.

2.5 Private RD&I funding

Some data and companies investing in such technologies have been already reported in section 2.2. From the available information, there are still no large private funding aimed to produce e-fuels. However, a recent initiative coming from Hy2gen AG (i.e., the German green hydrogen investment platform) announced the successful completion of a €200 million investment round in February 2022. The capital will be used for the construction of facilities in several geographical areas including Europe, producing green hydrogen-based fuels – or "e-fuels" – for maritime and ground transport, aviation and industrial applications. The investment, which is the largest private green hydrogen-focused capital raise to date, is led by Hy24 with Mirova, CDPQ and strategic investor, Technip Energies (HY2GEN, 2022). More recent data on recent private funding initiatives are reported in the observatories of EBA (European Biogas Association (EBA), 2024) and Transport and Environment (Transport & Environment, 2024a, 2024b).

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

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

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

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

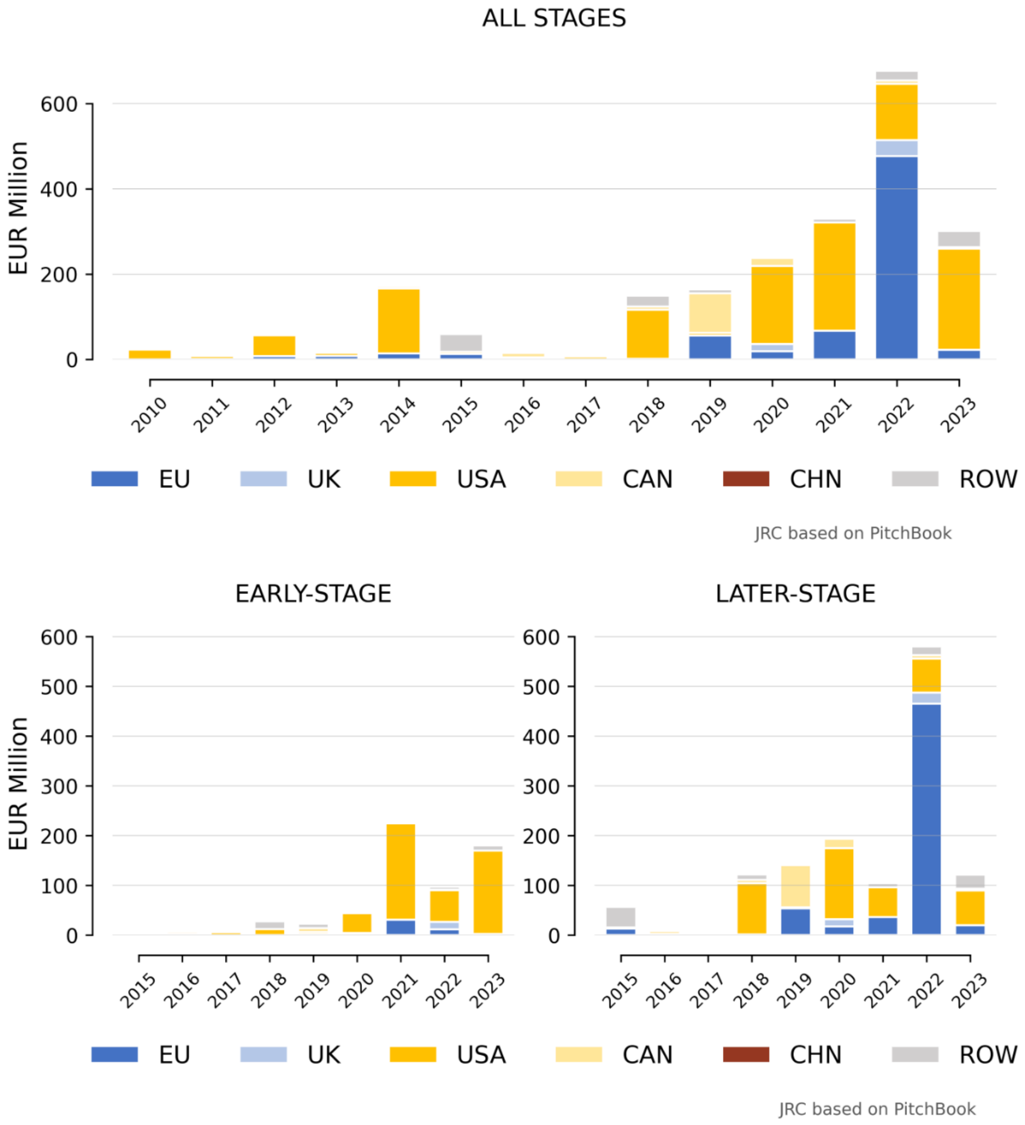
The lists of companies include two distinct populations: VC and corporate companies. Corporate companies are a selection of companies with a relevant patenting activity among the subsidiaries of top R&D investors from the EU Industrial R&D investment Scoreboard.

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

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

Global Venture Capital VC and PE investments in RFNBO firms started to take off in 2018, display a sharp increase in 2021-22 (x 5 as compared to 2020) and exceeded EUR 600 million in 2022. For 2023, however, the value has decreased to the levels of 2021, particularly due to the European contribution which had been largely disbursed in the previous year. Figure 12 recaps such findings here below.

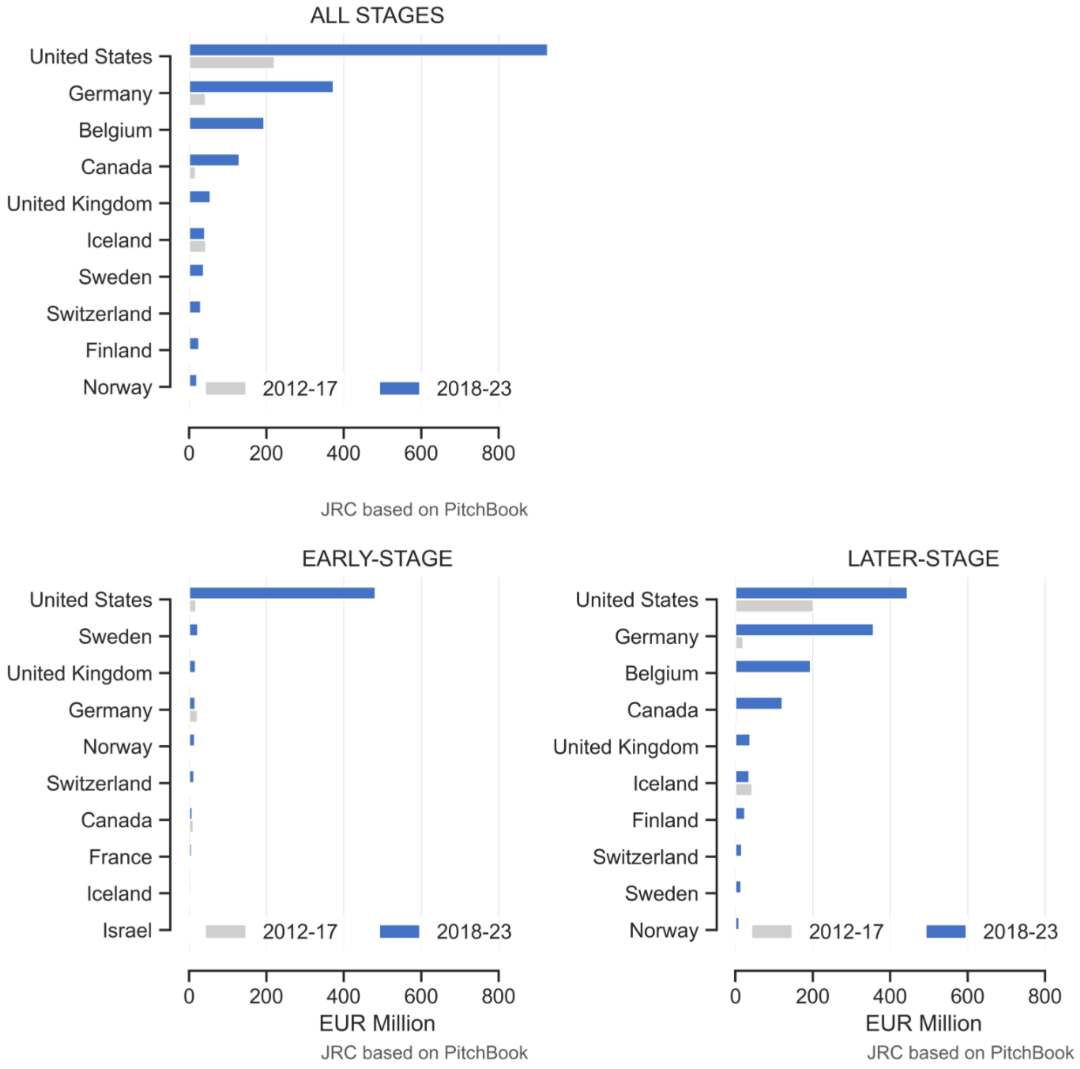
Figure 12. RFNBO VC/PE investment by region



Source: JRC elaboration

Over the period 2018-23, global VC and PE investments amount to EUR 1.8 billion, which represents a nine–fold increase as compared to a previous 2012-17 period of very low investment levels. The EU hosts 35 % of active venture capital companies' investment over the 2017-22 period. Germany (2nd) hosts half of EU ventures and follows the US (1st), which hosts 40% of active VC companies. Figure 13 reports such findings here below.

Figure 13. VC/PE investment in top 10 beneficiary countries, by period for all deals (top), early-stage deals (bottom left) and later-stage deals (bottom right)



ALL STAGES

EARLY-STAGE

LATER-STAGE

Source: JRC elaboration

VC investments in RFNBO firms are however driven by a limited number of ventures that account for the main part of investments over the 2017-22 period.

Over the 2017-22 period, the EU accounted for 17.6 % of global early stage investments. This amounts to EUR 67.5 million and essentially consist of grant funding (70 %). The US led the early stage investment race with companies such a as Prometheus and Infinium that together accounted for 46 % of global early stage investments.

In the same period, the EU accounted for 52 % of global later stage investment (amounting to EUR 351.2 million). This was essentially due to a large deal realised in 2022 by the German company Sunfire (DE, syngas electrolysis solutions), which by itself accounted for 35 % of global later stage investments. The US and Canada ranked next, supported by investments realised since 2019 in Lanzajet (US), Carbon Engineering (CA) and others.

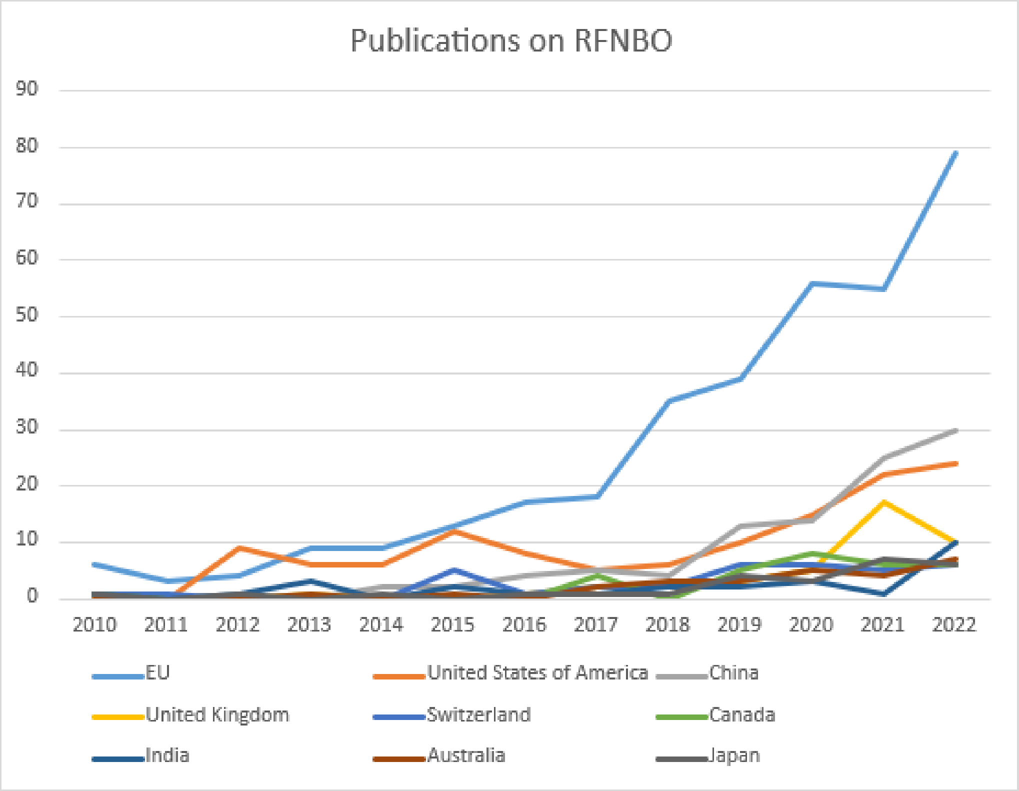
2.6 Patenting trends

The patents of RFNBO overlap significantly with those analysed in the "advanced biofuels" CETO report (Hurtig *et al.*, 2023), since most processes are in common, or are the same as those used for bio-derived processing technologies (e.g. FT-process). This means that the process does not change if biogenic carbon (in the form of CO_2/CO) is used as feedstock. The same consideration holds for novel patents deriving from hydrogen and carbon capture-related production.

2.7 Scientific publication trends

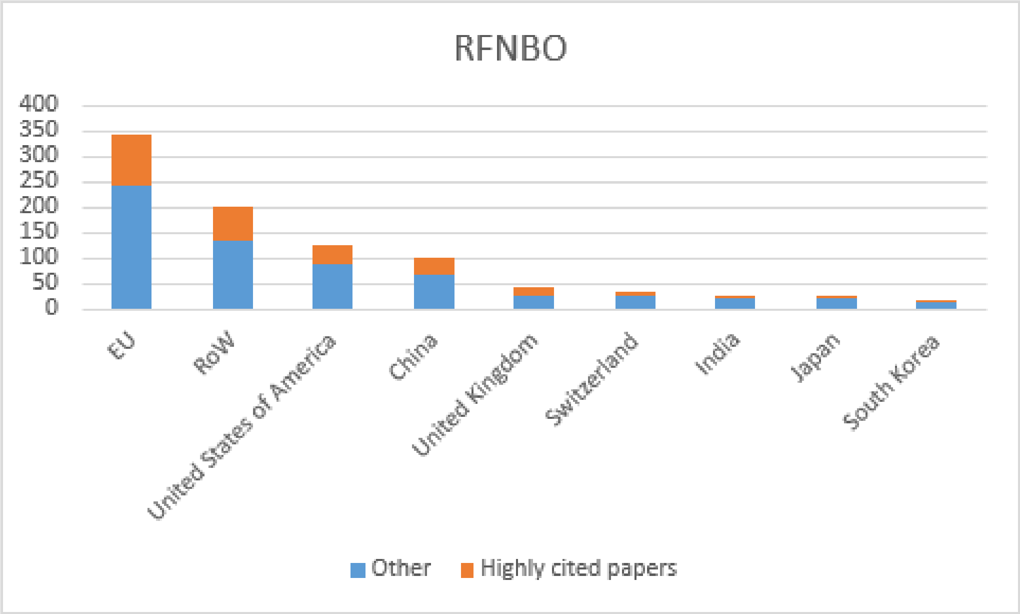
At global level, the publications on RFNBO gained momentum from 2017 onward, with the EU leading the ranking and quadruplicating from 20 to 80 publications per year, as shown in Figure 14. Concerning the share of EU publications among the top 10% most cited articles in the field, the EU had 99 highly cited publication with a share of 36% among the top 10% most cited in the field, as reported in Figure 15. At the EU level Germany leads the publication in the field with almost 120 publication and a share of 27% of highly cited articles, as shown in Figure 16.

Figure 14. RFNBO publications



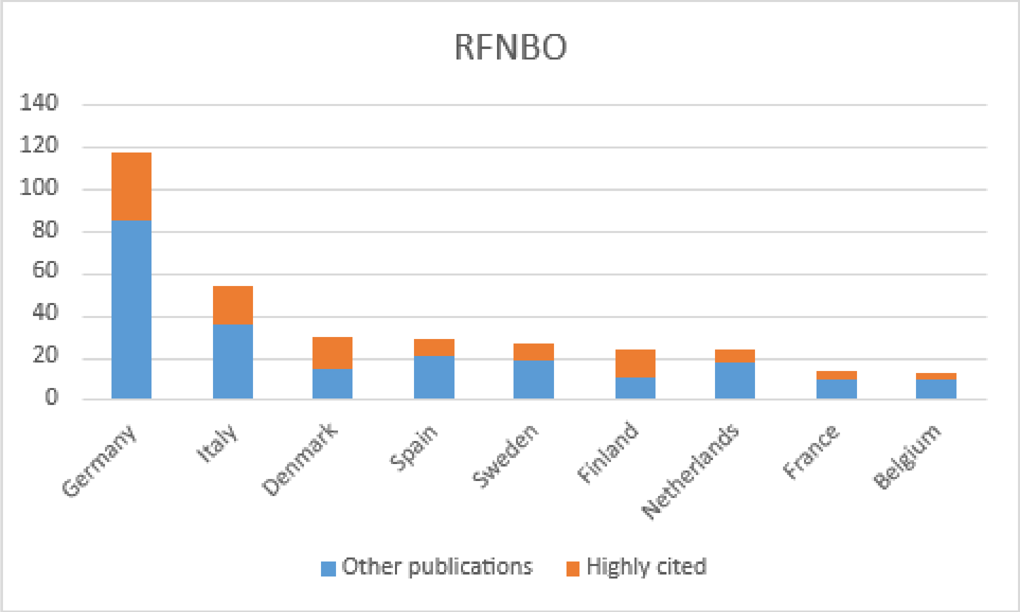
Source: JRC elaboration

Figure 15. RFNBO global publications of highly cited papers 2010-2022



Source: JRC elaboration

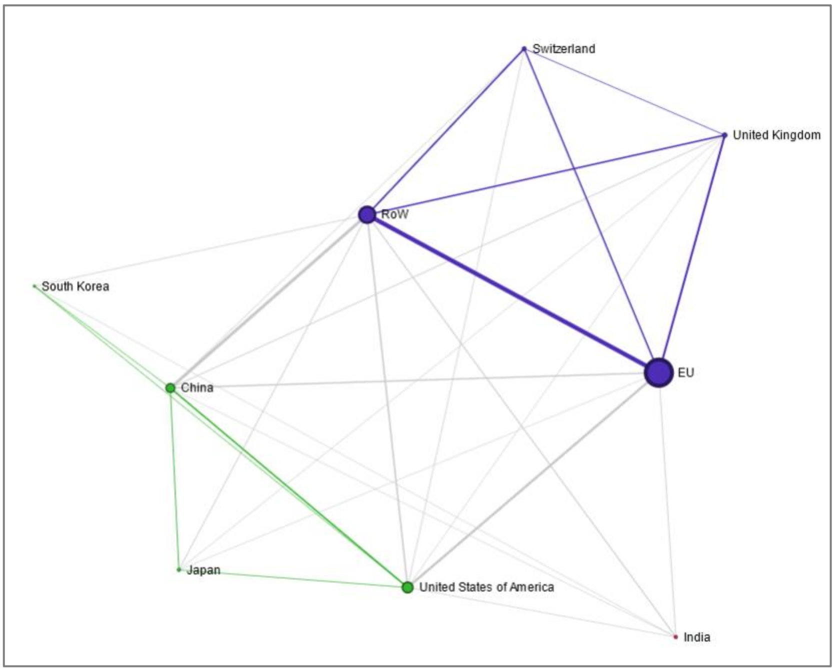
Figure 16. RFNBO EU countries publications with share of highly cited papers 2010-2022



Source: JRC elaboration

The publication cluster shows a particular relation between the EU and the RoW with a connection with UK and Switzerland as well, as shown in Figure 17.

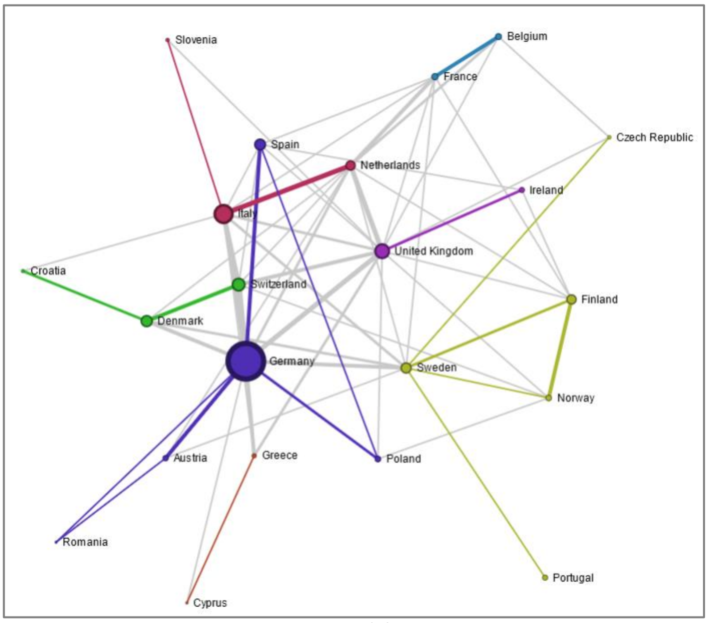
Figure 17. RFNBO global publication cluster 2010-2022



Source: JRC elaboration

The cluster at the EU level evidences links between Germany with Spain and Poland, and Italy with Netherlands.

Figure 18. RFNBO European publication cluster 2010-2022



Source: JRC elaboration

2.8 Sustainability/resilience

Today the biggest barriers to RFNBO industry development are the lack of hydrogen supply for this scope, and the upcoming phasing out of internal combustion engines for passenger cars towards the full electrification of the sector. Another major issue is related to the high cost of e-fuels, driven by the high cost of investment and high cost of electricity. Even if some Member States as Germany and Italy recently expressed their opposition (ICCT, 2022) to the EU regulation on "CO_2 emission performance standards for cars and vans" (European Parliament and the Council of the European Union, 2023d), the possibility to create new economic businesses for this sector has not been attractive so far (except for transport sectors as aviation, which may be of high interest for the mid-term scenario). This barrier could be somewhat mitigated through the specific supporting schemes focusing on RFNBO supply for the hard-to-abate sectors (aviation and maritime) which would be weaker given the unavailability of alternatives, i.e. direct electrification solutions.

However, RFNBO for road transport has garnered new considerable interest after the release of the Draghi report in September 2024 (Draghi, 2024), which proposes that EU competitiveness should follow a technologically neutral approach and should take stock of market and technological developments. The analysis underscored the importance of adopting sustainable alternative fuels (such as RFNBO and biofuels) as a critical measure for the decarbonization of the whole transport sector, thereby leaving the final decision to each MS to choose their preferred way to reduce GHG emissions. For such scenario, sustainability of e-fuels needs to meet the requirements set in the RED II and its delegated acts on hydrogen (see section 1.2), and the new requirements that the EC will publish by the end of 2025 in a report setting out the methodology for the assessment and the consistent data reporting of the full life-cycle CO_2 emissions of passenger cars and light commercial vehicles that are placed on the EU market (European Parliament and the Council of the European Union, 2023d).

For the coming years, the support to e-fuels technologies could lead to creating stable business models and competitive cost levels to the counterfactual alternatives as fossil fuels. However, once the hydrogen market is developed and resilient energy- and fuel-supply frame established, the industry can develop rapidly since such technologies have the ability to scale up production quickly to meet the potential demand. Also regulatory barriers such as chain of custody for electricity/H_2/CO_2 source and planning arrangements will be already solved (since today they regard mostly electricity/H_2/CO_2 management and trading). Today the sector still relies on economic support from demonstration projects which are helping to break down cost barriers, promote standards and develop the first value chains (easier to scale up than biofuels).

3 Conclusions

Renewable fuels of non-biological origin (RFNBO), are synthetic, gaseous or liquid fuels derived from renewable energy and renewable hydrogen, CO_2 or N_2, and can play an important role for ensuring security of energy supply and the decarbonization of transport services that cannot be electrified (maritime, aviation and road transports as heavy-duty vehicles). For this scope, the Renewable Energy Directive (EU) 2023/2413 has specific production targets for RFNBO by 2030, and both Fuel EU Maritime and REFuel EU Aviation set further targets towards 2050. RFNBO have also an important role to supply renewable chemicals and fertilizers to reduce GHG emissions of industry and agricultural activities.

The technologies for the production of RFNBO have advanced significantly in recent years, with Europe at the leading edge, driven by strong policy support and industrial capabilities. However, RFNBO production depends on several technologies along the whole value chain that include hydrogen production, carbon capture (or nitrogen separation) and fuel synthesis. Large-scale deployment remains still limited, primarily due to high costs, high energy requirements and the need for robust infrastructure. Advancements in electrolysis, carbon capture technology and renewable energy generation could quickly ramp up the RFNBO production, but upstream processes of hydrogen production and carbon capture still need to be developed at large scale for commercial production to reduce the production costs.

Significant challenges remain. Achieving cost competitiveness with fossil fuels, overcoming certain technological barriers and building the required infrastructure are substantial challenges that must be addressed. Significant investment and innovation are needed to scale-up the technologies for widespread commercial use and cost-competitiveness. A combination of policy incentives, technological advancements, and scaling efforts will be critical for RFNBOs to reach their full market potential.

On the other hand, the opportunities offered by RFNBO are the creation of new value chains based on renewable hydrogen supply and carbon capture, the use of the existing fuel infrastructures for fuel distribution and use (since liquid and gaseous RFNBOs are mostly drop-in fuels, except alcohols), and the possibility to integrate bio-based value chains for CO_2 recovery.

The production of RFNBO will depend on the availability of excess renewable electricity and its price when available. The high energy-intensive nature of RFNBO production means that scaling the technology will require massive investments in renewable energy. Other challenges for RFNBO market uptake include all the techno-economic aspects related to the limited capacity of the renewable electricity distribution grid to integrate renewable electricity generation. Moreoover, the slow-growing carbon capture solutions for providing (or capture) CO_2 (fossil-based CO_2 limited from 2041) or N_2, the constraints in coupling such systems in providing stable operation, other competing markets (e.g. fertilizers) and the environmental aspects (level of GHG emissions savings) are still aspects to address.

The potential market for RFNBOs is substantial, driven by the need for sustainable energy solutions, in particular in sectors where alternatives are limited, such as hard-to-abate transports and heavy industry. The scenarios outlined by JRC's POTEnCIA and POLES energy system models show a rapid increase in the production of RFNBO in the EU starting from 2025, which could become a significant source of low-carbon fuel for the hard-to-abate transport sectors, such as aviation and maritime.

Overcoming cost and infrastructure barriers will be crucial for RFNBOs to meet their potential, but with continued technological advances and policy support, RFNBO are positioned to play a key role in Europe's decarbonization strategy across various hard-to-abate sectors. Although the full RFNBO value chain is not yet fully developed, Europe has the foundational industries and expertise to create a robust supply chain for RFNBO.

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List of abbreviations and definitions

AEL	Alkaline Electrolysis
CCS/CCU/CCSU	Carbon Capture and Storage, Utilization
DAC	Direct Air Capture
DME	DiMethyl Ether
FT	Fischer-Tropsch
HB	Haber-Bosch
HDVs	Heavy Duty Vehicles
LNG	Liquefied Natural Gas
MCEC/MEC	Molten Carbonate Electrolyser Cells
MEC	Microbial Electrolysis Cell
OME	OxyMethylene Ether
PEMEL/PMEL	Polymer Electrolyte Membrane Electrolysis
POLES-JRC	Prospective Outlook on Long term Energy Systems
POTEnCIA	Policy Oriented Tool for Energy and Climate Change Impact Assessment
PtG	Power-to-Gas
PtL	Power-to-Liquid
PtX	Power-to-Fuel
PV	PhotoVoltaic
RED	Renewable Energy Directive
RFNBO	Renewable Fuel of Non-Biological Origin
SMR	Steam Methane Reforming
SNG	Synthetic Natural Gas
SOEL/SOC	Solid Oxide Electrolysis/Cells
TRL	Technology Readiness Level
VC	Ventur Capital
WEEE	Waste Electrical and Electronic Equipment Directive

WTT	Well-To-Tank

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Annexes

Annex 1 Sustainability Assessment Framework

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. 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 occurred depending 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 Nicolae *et al.*, 2019). In EU, the overarching legislation setting the LCA rules of the sector is the RED II, which provides the methodology for assessing greenhouse gas emissions savings from renewable liquid and gaseous transport fuels of non-biological origin and from recycled carbon fuels. Captured and used CO_2 can receive a credit for avoided emissions if it had not already received other credits before. To ensure that renewable fuels of non-biological origin contribute to greenhouse gas reduction, the electricity used should be of renewable origin. For this scope, another, parallel delegated act on hydrogen sets the guidelines for temporal and geographical correlations between the electricity production and the fuel production. The delegated act also provides updated input data as the carbon intensity of raw materials, reagents, fossil-fuels, etc. At international level, ISO developed integrating rules for hydrogen into their LCA standards (International Organization for Standardization, 2023), and a special task force is still working to improve such guidelines (International Organization for Standardization, 2024).
GHG emissions	According to RED II, the greenhouse gas emissions savings from the use of renewable liquid and gaseous transport fuels of non-biological origin shall be at least 70 % from 1 January 2021 compared to the fossil fuel comparator (94 gCO_2e/MJ). During 2023, the Commission published a specific delegated act setting a specific methodology to calculate the GHG emissions for RFNBO, therefore the carbon intensity of such fuels (in terms of actual values) can be calculated by the stakeholders. To certify such fuels for trade and legislation targets, the EC recently pre-approved specific voluntary schemes covering the certification of the whole supply chain (European

Commission website, 2024). Some calculations of the GHG emissions has been performed by the JRC (WTT v5) (Prussi *et al.*, 2020) for a large number of for renewable fuels of non biological origin pathways. However, it is worth to mention that JECv5 methodology differs from the RED II methodology in some aspects described in the report. The GHG emissions for a selection of pathways is presented in the next:

GHG footprint for RFNBO [g CO_{2eq}/MJ]

Syndiesel from renewable electricity, CO_2 from flue gas: 0.8 - 0.9 g CO_2eq/MJ

Syndiesel from renewable electricity via FT route, CO_2 from flue gas: 0.76 - 0.78 g CO_2eq/MJ

Syndiesel from renewable electricity via FT route, CO_2 from biogas upgrading: 0.8 - 0.8 g CO_2eq/MJ

Syndiesel from renewable electricity via FT route, CO_2 from air via TSA: 0.8 - 0.8 g CO_2eq/MJ

MeOH from renewable electricity, CO_2 from flue gas: 1.78 - 1.82 g CO_2eq/MJ

DME from renewable electricity, CO_2 from flue gas: 1.7 g CO_2eq/MJ

OME from renewable electricity, CO_2 from flue gas: 1.85 g CO_2eq/MJ

SNG from renewable electricity and CO_2 from flue gas: 1.7 - 3.0 g CO_2eq/MJ

SynLNG from renewable electricity, CO_2 from biogas upgrading: 6.7 - 6.7 g CO_2eq/MJ

Another recent paper from the JRC authors also provides other figures as regards e-fuels produced with DACs (Rocio Gonzales, 2023). Recently, Concawe proposed new calculations using the JEC methodology observing an average reduction of the carbon intensity of e-fuels (Soler *et al.*, 2024). Specifically, while JEC WTW study assumes that hydrogen liquefaction is powered by grid electricity, Concawe considers renewable energy only, while grid power is still utilized for processes such as compression and dispensing. Additionally, the JEC WTW study assumes hydrogen is transported at a pressure of 35 MPa, contrary to the 50 MPa considered by Concawe, influencing the volume of hydrogen transportable, along with its related GHG emissions and associated expenses.

In terms of energy utilization, the JEC figures for hydrogen liquefaction and methane compression/dispensing are elevated compared to Concawe (for instance, 0.30 vs 0.24 MJe/MJ_{H2} for hydrogen liquefaction). Such variances can be attributed to the assumptions done in the Concawe' study assuming potential advancements in technology by the year 2050.

Concerning CO_2 sources, the JEC WTW study relies on CO_2 from flue gases, while Concawe relies on steam methane reforming (SMR) pre-combustion processes as main source. Furthermore, while the JEC WTW study uses solid oxide electrolysis cells (SOEC) for e-diesel synthesis, Concawe employs alkaline electrolysis. Lastly, Concawe does not incorporate the emissions associated with oxygen production necessary for OMEx synthesis.

Energy balance	JRC performed the balance of the energy expended in different renewable fuels of non-biological origin pathways (WTT, v5)) (Prussi *et al.*, 2020), without accounting for the contributions related to plant construction, decommissioning and maintenance. The energy expended ratio is given for a selection of pathways is presented in the next: Energy [MJ/MJ final fuel] Syndiesel from renewable electricity, CO_2 from flue gas: 1.42 - 1.64 MJ/MJ Syndiesel from renewable electricity via FT route, CO_2 from flue gas: 1.55 - 1.55 MJ/MJ Syndiesel from renewable electricity via FT route, CO_2 from biogas upgrading: 1.13 - 1.13 MJ/MJ Syndiesel from renewable electricity via FT route, CO_2 from air via TSA: 1.78 - 1.89 MJ/MJ MeOH from renewable electricity, CO_2 from flue gas: 1.21 - 1.39 MJ/MJ DME from renewable electricity, CO_2 from flue gas: 1.30 - 1.49 MJ/MJ SNG from renewable electricity and CO_2 from flue gas: 0.95 - 1.09 MJ/MJ SynLNG from renewable electricity, CO_2 from biogas upgrading: 1.03 - 1.19 MJ/MJ
Ecosystem and biodiversity impact	RED II requires that the electricity used for the production of renewable fuels of non-biological origin should be of renewable origin, to ensure they contribute to greenhouse gas reduction. Potential impacts on ecosystem and biodiversity can be also related to the infrastructures of the renewable electricity plants, which should be located in dedicated areas at low impact.
Water use	Water consumption is of high interest in relation to the environmental sustainability of renewable fuels of non-biological origin. Hydrogen production via electrolysis generally requires an ecosystem rich in non-salted water (later discussed) which should not impact on the well-established industry, agriculture systems and local population. However, some processes might be developed to use saline water and thus avoiding the competition for water use. Water is needed for the production of renewable electricity (solar, wind, hydro, geothermal). A large proportion of life cycle water use is required for the manufacturing and construction of solar photovoltaic, wind power and geothermal facilities. Operational water for PV and wind is mainly used for cleaning purposes. Water consumption for hydropower production mostly relates to the water losses through evaporation in hydropower reservoirs that can be important, depending on the plant, location etc. Water consumption for renewable electricity generation varies between wide margins (Macknick *et al.*, 2012) (Meldrum, Heath and Macknick, 2013): Wind: 0.004 (0 – 0.04) m^3 / MWh Solar: 0.329 (0.042-0.893) m^3 / MWh Hydro: 17 (5-68) m^3 / MWh

	Geothermal flash technology: 0.05 (0.019 - 1.364) m^3 / MWh Where for hydropower it is considered the water discharged by the turbines, where in run-of-river plants this water is immediately available downstream. Water required in the other energy systems is that typically used for their construction, and no longer available (Mekonnen, Gerbens-Leenes and Hoekstra, 2015). Water is needed in the first steps of hydrogen production. Much less water is needed in the fuel synthesis steps downstream. The stoichiometric amount of water required to extract one kilogram of hydrogen via water electrolysis amounts to 8.92 litres. Experimental data show that Solid Oxide Cell (SOEC) and alkaline water (AEL) and Polymer Electrolyte Membrane electrolysers (PEM) require 9.1 l / kg hydrogen, 10 l / kg and 10.7 l / kg respectively. Some Direct Air Capture (DAC) plants can extract water from air during operation, producing water, estimated at 1 l water per kg of carbon dioxide captured or about 3.8 l water per kg of fuel produced (Altgelt *et al.*, 2021). The results show that the water consumed over the lifecycle of hydrogen production can be significantly higher than the water employed for electrolysis alone. On a LCA basis, the water consumption for hydrogen varies between 11.7 -19.8 l / kg H_2 (for SMR process) to 30.3 l/ kg H_2 for electrolysis (Altgelt *et al.*, 2021). Water consumption for renewable fuels of non-biological origin can vary widely (Altgelt *et al.*, 2021): e-diesel from wind electricity and DAC via FT: 0.3 - 3.6 l / kg e-diesel from PV electricity and DAC via FT: (-0.8) – 2.5 l / kg e-kerosene from wind electricity and DAC via FT: 5.0 – 8.0 l / kg e- kerosene from PV electricity and DAC via FT: 3.1 – 6.4 l / kg
Air quality	Air pollutants such as carbon monoxide, nitrogen oxides, hydrocarbons and particulate matter are major exhaust emissions from fossil fuels combustion in vehicles. Excessive exposure to these pollutants can have significant impact on human health. The combustion of renewable fuels of non-biological origin also produces emissions in the form of carbon monoxide, hydrocarbons and particulates. However, the emissions from renewable fuels of non-biological origin and their impact on air quality depend on the type of fuel, related to the wide variability of fuels that can be produced. Renewable fuels of non-biological origin in the form of drop-in fuels (i.e. e-diesel or e-gasoline) have the same chemical structure and thus the same air emissions like the fossil fuels. Oxygenated fuels (such as alcohols) produce lower nitrogen oxides and soot emissions than fossil fuels. Biodiesel combustion results in lower gaseous pollutants hydrocarbons, aromatic hydrocarbons, carbon, and sulphur emissions and slightly higher amounts of nitrogen oxides relative to petroleum diesel (US eia, 2022). In the case of ammonia, soot emissions are reduced significantly due to the lack of carbon in the fuel molecule, while the NO_x emissions increase significantly due to the fuel-bound nitrogen compared to the fossil fuel. Air emissions with impacts on air quality could also come from the production of PV panels or wind blades and accidental releases of toxic

	gases and particulates could affect occupational health. Air emissions with impacts on air quality might also appear at waste processing from decommissioning of the PV and wind plants. Accidental releases of toxic gases and vapours can be prevented by minimizing wastes produced during the processes through choosing safer technologies, processes and less toxic materials.
Land use	The production of renewable fuels of non-biological origin generally requires renewable electricity technologies (with the exemption of biomass electricity) and thus the land use impact is limited to the land use for various renewable electricity sources (PV, wind, hydro, geothermal) and the land use for fuel processing plants.
Soil health	The production of renewable fuels of non-biological origin are, by definition from renewable electricity (with the exemption of biomass electricity) and thus the impact on soil is limited to the area used for renewable electricity production. Soil health may be impacted by the wastewater resulted from the cleaning of the surface of the PV panels or from the waste processing and landfilling resulted from decommissioning PV or wind plants.
Hazardous materials	The production of renewable fuels of non-biological origin do not use hazardous materials for the manufacture of various plant components. There are some hazardous materials in the manufacturing process of the PV panels, chemicals and solvents used throughout the manufacturing processes of different PV technologies. Metals such as steel, copper, and aluminium account for most part of a wind turbine. There are various materials for the manufacture of wind turbine blades such as metals, fiberglass reinforced composite, carbon fibre reinforced polymers, natural fibre reinforced polymers or nanocomposites (Mishnaevsky *et al.*, 2017) that should be treated carefully during their transport, installation and dismission due to the large dimensions. Only small amounts of metals are used.
Economic	
Cost of energy	See 2.3 Technology Cost – Present and Potential Future Trends
Critical raw materials	Critical raw materials are needed for the production of PV and wind electricity. Solar cell manufacturing requires the use of silicon, silver, germanium, cadmium, tellurium, copper, indium, gallium and selenium. Critical raw materials such as neodymium and dysprosium are essential to the permanent magnets used in the generators of wind turbines. Certain catalysts are needed in relatively small quantities in the fuel synthesis to enhance the yield of desired product or promoting various reactions in fuel synthesis, gas shift reactions, cracking reactions, etc.
Resource efficiency and recycling	Resource efficiency is a major goal of the EU to develop a resource-efficient, low-carbon economy and to achieve sustainable growth and to decouple economic growth from resource and energy use. The most important aspects for the renewable fuels of non-biological origin relates to the treatment of end-of-life recycling of the PV panels and wind turbines. The majority of the components of a wind turbine are easy to recycle because they are made of

	metallic parts. The wind turbine blades are the components that are difficult to deal with in line with principles of sustainability and circularity, because they are made of composite materials, as well as secondary materials like glues, paints and metals. Treatment of end-of-life PV modules must comply the Waste Electrical and Electronic Equipment Directive (WEEE) Directive. WEEE defines the minimum proper treatment for the end-of-life equipment and sets the legal rules and obligation for collecting and recycling photovoltaic panels in the EU, including setting minimum collection and recovery targets. Several components are separated and recovered. Several sustainability aspects are being addressed in the framework Eco-design quantifying the environmental performance of PV technologies.
Technology lock-in/innovation lock-out	There is no considerable risk of technology lock-in as the renewable fuels of non-biological origin will be able to use existing infrastructure, transport and distribution network and fuel stations. Currently, they offer the only available option nowadays for the decarbonisation of aviation and shipping sectors together with advanced biofuels.
Tech-specific permitting requirements	The rules for permitting are very complex and lengthy and represent important barriers for renewable energy deployment and include environmental and building permits. The duration, complexity and the steps for the permit-granting procedures greatly varies between the different renewable energy technologies and between Member States between 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. Economic operators producing renewable fuels on non-biological origin methodology shall provide evidence on the temporal and geographical correlation between the electricity production unit and the fuel production, as well as on the additionally of renewable electricity generation.
Sustainability certification schemes	Renewable liquid and gaseous transport fuels of non-biological origin are important to increase the share of renewable energy in sectors that are expected to rely on liquid fuels in the long term. To ensure that renewable fuels of non-biological origin contribute to greenhouse gas reduction, the electricity used for the fuel production should be of renewable origin. The Commission published a specific delegated act setting the rules for counting electricity as renewable. The methodology ensures that there is a temporal and geographical correlation between the electricity production unit and the fuel production. Given the enormous amount of additional renewable electricity generation needed, the production of renewable fuels of non-biological origin should incentivise the deployment of new renewable electricity generation capacity (principle of additionality). The economic operator has to provide evidence or data on the production of renewable liquid and gaseous transport fuel of non-biological origin and the electricity used, obtained in accordance with a voluntary national, or international schemes, setting standards for the production of biofuels, bioliquids or biomass fuels, or other fuels.

Social	
Health	Air pollutants from fuel combustion in vehicles, such as carbon monoxide, nitrogen oxides, hydrocarbons and particulate matter, are found to be major exhaust emissions. Excessive exposure to these pollutants can have significant impact on air quality and human health. Renewable fuels of non-biological origin in the form of drop-in fuels (i.e. e-diesel or e-gasoline) have the same chemical structure and thus the same air emissions and the same health impact as fossil fuels. Some fuels produce lower gaseous pollutants emissions of hydrocarbons, aromatic hydrocarbons, carbon monoxide and sulphur emissions and slightly higher amounts of nitrogen oxides relative to fossil fuels with corresponding health threats. Various air pollutants emissions could come from the production as well as from recycling of PV panels or wind blades from accidental releases of toxic gases and particulates with potential occupational health impacts.
Public acceptance	Public acceptance is essential for successful development and take up of renewable energies. Public acceptance for the production of renewable fuels of non-biological origin relates mostly to the photovoltaics or wind electricity generation. Photovoltaics and wind power production are generally accepted by the public as public awareness has increased the last years. Some concerns have been expressed in particular to some impacts on land use (in the case of the use of agricultural land), biodiversity and environmental impact (offshore wind impacts on marine ecosystems, impacts on migrating birds, etc.), aesthetical reasons, etc.
Education opportunities and needs	The need for further R&D for technological development of renewable fuels of non-biological origin also requires the need for education programs on new technologies that involved the production of renewable electricity (wind, solar, hydro, etc.) and fuel synthesis technologies and environmental sciences. 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.
Rural development impact	Renewable liquid and gaseous transport fuels of non-biological origin provides good opportunities for local and distributed renewable electricity production and fuel synthesis plants. This has significant positive impact on sustainable rural development, providing job opportunities along the supply chain, including skilled labour that can be a driver of industry development in rural areas. This provides new income-generating opportunities in rural areas, enhanced economic security of rural communities by supporting economic activities and economic growth.
Industrial transition impact	Renewable fuels of non-biological origin can contribute significantly on short term to the decarbonization of transport, energy diversification in the transport sector and energy security, while promoting innovation, growth and jobs and reducing the dependence on energy imports. Renewable fuels of non-biological origin can play a key role in the transition, acting as energy storage solution of the excess renewable electricity, balancing the electricity grid and producing renewable fuels for the decarbonisation of transport on

	short term. The production of renewable fuels of non-biological origin requires a carbon source that can be provided, on short term, from concentrated sources (flue gas from combustion plants, from alcohol fermentation, from biogas upgrading to biomethane, etc.) or through Direct Air Capture. Bioenergy with Carbon Capture and Utilisation (BECCU) for the production of renewable fuels of non-biological origin using biogenic carbon is a promising option for achieving carbon-neutrality.
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. Renewable fuels of non-biological origin can offer great opportunities for the use of solar and wind plants to produce fuels (energy) for transport in local communities. Renewable fuels of non-biological origin, together with advanced biofuels, 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	Renewable fuels of non-biological origin will rely mostly on the local solar and wind resources, contribute to reducing the need for imported fossil fuels and diversifying the energy supply, that would avoid creating import dependencies elsewhere and rely on short supply chains, as well as improve EU energy security and resilience. Renewable liquid and gaseous transport fuels of non-biological origin play an important role in the endeavour for a rapid clean energy transition and the reduction of its dependency on fossil fuel imports set in the REPowerEU initiative.
Food security	The most significant concerns for the use of biomass for bioenergy include the risks of increased competition between food and non-food uses of biomass. Renewable fuels of non-biological origin avoid the competition for food and feed and negative impacts on food security. Since food security, according to FAO and other authors (Brandão *et al.*, 2021), has multiple dimensions: availability, accessibility, stability and utilization, the production of the renewable fuels of non-biological origin contributes to enhanced economic conditions of rural communities, new job opportunities, increasing overall food availability, food accessibility and affordability.
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, most of them 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, legality of operations and payment of taxes. EU Regulation (EU) 2017/821 established the requirements for supply chain due diligence obligations for materials originating from conflict-affected and high-risk areas. Responsible consumption and production is addressed by the SDG 12 *Ensure sustainable consumption and production patterns* 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 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.

Annex 2 Energy System Models and Scenarios: POTEnCIA and POLES-JRC

AN 2.1 POTEnCIA Model

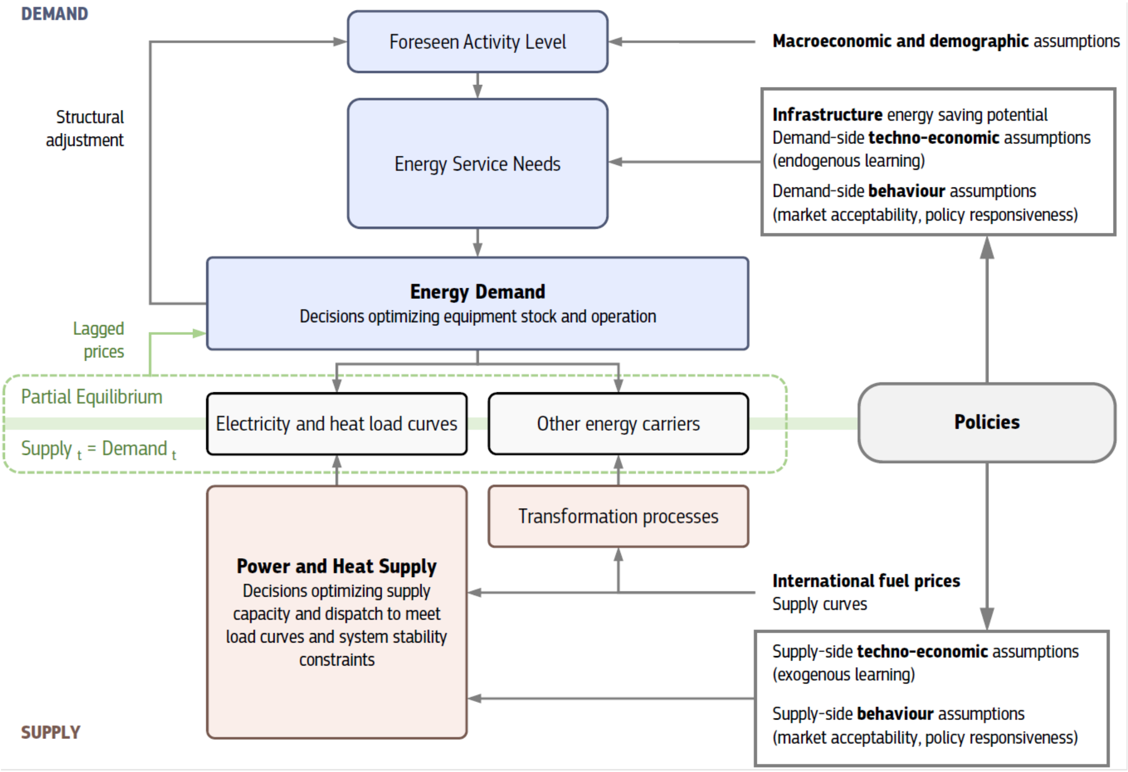
AN 2.1.1 Model Overview

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

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

The core modelling approach of POTEnCIA (**Figure 19**; detailed in Mantzos et al., 2017, 2019) focuses on the economically-driven operation of energy markets and corresponding supply-demand interactions, based on a recursive dynamic partial equilibrium method. As such, for each sector of energy supply and demand, this approach assumes a representative agent seeking to maximize its benefit or minimize its cost under constraints such as available technologies and fuels, behavioural preferences, and climate policies.

Figure 19. The POTEnCIA model at a glance



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

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

AN 2.1.2 POTEnCIA CETO 2024 Scenario

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

AN 2.2 POLES-JRC model

AN 2.2.1 Model Overview

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

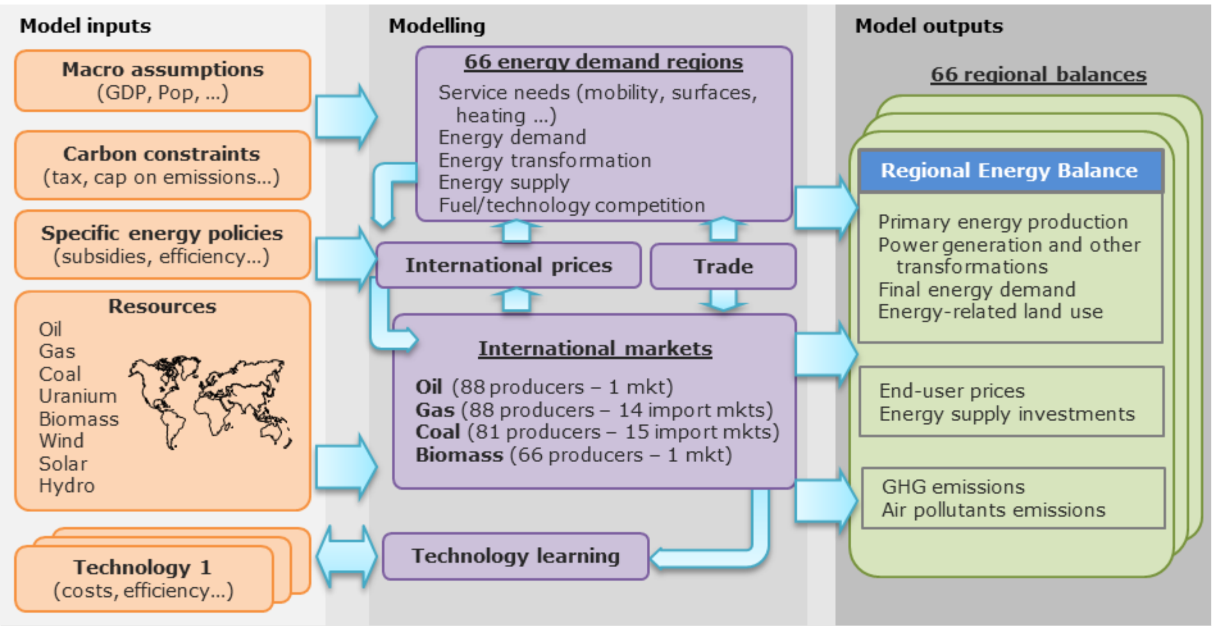
POLES-JRC covers the entire energy system, from primary supply (fossil fuels, renewables) to transformation (power, biofuels, hydrogen and hydrogen-derived fuels such as synfuels) and final sectoral demand (industry, buildings, transport). International markets and prices of energy fuels are calculated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

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

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

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

Figure 20. Schematic representation of the POLES-JRC model architecture.



Source: POLES-JRC model

AN 2.2.2 POLES-JRC Model description

Power system

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

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

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

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

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

Hydrogen

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

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

Bioenergy

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

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

Carbon Capture Utilization and Storage (CCUS)

POLES-JRC uses CCUS technologies in:

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

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

Endogenous technology learning

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

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

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

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

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

AN 2.2.3 Global CETO 2°C scenario 2024

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

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

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

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

The *Global CETO 2°C scenario 2024* differs fundamentally from the *Global CETO 2°C scenario 2023* used in the CETO technology reports in 2023 in various aspects[5]:

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

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

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

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

AN 2.3 Distinctions for the CETO 2024 Scenarios - POLES-JRC vs. POTEnCIA

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

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

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Annex 3 Installed capacity divided per sector

E-kerosene production potential in Europe in 2030

Project name	Project partners	Country	Location	Commissioning date	Production capacity in 2030 (t/y)	CO2 source
E-fuel 1	Nordic Electrofuel, BPT, Aker solutions, P2X-Europe, Sunclass airlines	Norway	Herøya	2026	6,000	PS, Bio
Accelerator		Norway		2027	20,000	
E-fuel 2		Norway		2029	120,000	
E-fuel 3		Norway		2030	114,000	
Sasol, DHL, HH2E		Germany	Eastern	2030	164,000	Bio
Alpha	Norsk e-Fuel, Sunfire, Climeworks, Paul Wurth, Axens, Norwegian, Gen2 Energy	Norway	Mosjoen	2026	32,000	Bio
Beta		Norway		2028	64,000	...
Gamma		Norway		2030	64,000	DAC
BioÖstrand	Biorefinery Östrand AB, St1, SCA	Sweden	Östrand	2029	100,000*	Bio
Hy X	Vattenfall, St1	Sweden	West Coast	2030	100,000*	Bio
SAF + Consortium, H2V		France	Marseille Fos	2029	80,000	PS, Bio
ReUze	Engie, Infinium, ArcelorMittal	France	Dunkirk	2028	71,000	PS, Bio

France KerEAUzen	Engie, Air France38	France	Le Havre	2028	68,000	PS, Bio
Endor	Arcadia e-fuels, Technip Energies, Haldor Topsoe S/A, Sasol Ltd, DCC/Shell Aviation Denmark A/S, Sunclass Airlines, BNP Paribas…	Denmark	Vordingborg	2026	68,000	Bio
Jangada	Hy2Gen, energy4future	Germany	Brandenburg	2028	64,000	Bio
Synkero	Sky NRG, KLM, Schiphol Group	The Netherlands	Amsterdam	2027	50,000	Bio
Hykero	XFuels, EDL, Airport Leipzig-Halle, Johnson Mattey, BP	Germany	Leipzig	2028	50,000	Bio
HySkies	Shell, Vattenfall, LanzaTech, SAS	Sweden	Forsmark	2027	50,000*	Bio
SkyFuelH2	Sasol ecoFT, Uniper	Sweden	Solleftea	2028	45,000*	Bio
IdunnH2, Icelandair		Iceland	Helguvik Harbour	2028	65,000	Bio
Dimensional Energy		Greece		n.a.	44,000	n.a.
BioTJet	Elyse Energy, Avril, Axens, Bionext, IFPEN	France	Bassin de Lacq	2027	38,000*	Bio
Take Kair	EDF, Holcim, IFPEN, Axens, Air France-KLM	France	Saint-Nazaire	2028	35,000	Bio
Smartenergy, REN, Lipor		Portugal	Porto	n.a.	35,000	Bio

Green Fuels for Denmark	Ørsted, Copenhagen Airports, DSV, DFDS, SAS, Topsoe, A.P. Moller - Maersk, Neste Shipping Oy, HOFOR , BIOFOS, CTR, VEKS	Denmark	Copenhagen	2029**	30,000**	Bio
Breogán Project	Greenalia - P2X Europe	Spain	Curtis-Teixeiro	2027	30,000	Bio
P2X-Portugal	P2X Europe - The Navigator, H&R Group, Mabanaft	Portugal	Figueira da Foz	2027	30,000	Bio
Concrete Chemicals	Sasol ecoFT, CEMEX, ENERTRAG	Germany	Berlin	2027	26,000	PS, Bio
INERATEC, Zenith Energy Terminals		The Netherlands	Port of Amsterdam	2027	26,000	PS, Bio
Hynovera	Hy2Gen, Technip Energies, Bionext, Axens, Airbus Helicopters	France	Meyreuil-Gardanne	2028	13,000*	Bio
TOTAL (estimated)					1,702,000	

Source: (Transport & Environment, 2024b)

Note : In cases where the total capacity for synthetic fuel production was identified without a clear breakdown of e-kerosene and associated by-products like e-naphtha, it was presumed that the average yield of e-kerosene would be around 75%. This is based on the ability to fine-tune the Fischer-Tropsch synthesis and subsequent refining processes to favor the production of e-kerosene primarily.

* electro-fuels with the generation of biofuels, referred to as "e-biofuels" projects, a default production ratio of 50% each was allocated, except when project planners specified a different distribution.

** the initiative known as Green Fuels for Denmark, which synthesizes both e-methanol and e-kerosene, is projected to achieve a combined production capacity of 60,000 kilotonnes by the year 2030, during its second phase (2b). It is projected that e-kerosene will account for half of this output, equating to 30,000 kilotonnes.

E-fuels for maritime production potential in Europe in 2030

Project Name	Project Leader	Country	Status	Date	Fuel Type	Volumes (Mtoe)
Green Fuels for Denmark	Ørsted	Denmark	Under discussion	2025	Green hydrogen	0.0086
BTL2030	VTT	Austria	Under discussion	2027	Biofuel	0.12596
North-C-Methanol	North CCU Hub	Belgium	Under discussion	2024	E-methanol	0.02091
ReIntegrate, Advent	European Energy and Port of Hanstholm	Denmark	Decided - FID	2024	E-methanol	0.0076
European Energy Kassø	European Energy	Denmark	Decided - FID	2024	E-methanol	0.01521
Vordinborg Biofuel	Vordingborg Havn	Denmark	Under discussion	2025	Biofuel	0.14259
European Energy Måde	European Energy	Denmark	Decided - FID	2024	Green hydrogen	0.00459
H2 Energy Esbjerg	H2 Energy Europe	Denmark	Under discussion	2027	Green hydrogen	0.2866
HØST	CIP	Denmark	Under discussion	2029	E-ammonia	0.26655
H2Driven	Dourogás	Portugal	Under discussion	2026	E-methanol	0.02377
Eco Bunkers	PRIO	Portugal	Operational	2006	Biofuel	0.1004
MadoquaPower2X	Madoqua Renewables, Power2X e Copenhagen Infrastructure Partners	Portugal	Under discussion	2028	E-ammonia	0.11995

Green H2 Atlantic	EDP, Galp, ENGIE, Bondalti, Martifer, Vestas Wind Systems A/S., McPhy and Efacec	Portugal	Under discussion	2025	Green hydrogen	0.02866
Green hydrogen Mobility Project	Fusion Fuel	Portugal	Under discussion	-	Green hydrogen	0.40814
Conseil1	Hy2Gen	Germany	Under discussion	2024	Green hydrogen	0.00089
Nautilus	Hy2Gen	Germany	Under discussion	2027	E-methanol	0.02852
Airpark Laage (hydrogen)	Apex Energy Teterow GmbH and East Energy Verwaltungs GmbH	Germany	Under discussion	2027	Green hydrogen	0.00086
H4Chem-EI	BASF	Germany	Decided - FID	-	Green hydrogen	0.02293
Zella-Mehlis	ZASt	Germany	Under discussion	2024	E-methanol	0.00333
The George Olah Renewable Methanol plant	CRI	Iceland	Operational	2012	E-methanol	0.0019
Advanced Methanol Rotterdam (AMR)	Gidara	Netherlands	Decided - FID	2025	Biofuel	0.04278
Advanced Methanol Amsterdam (AMA)	Gidara	Netherlands	Under discussion	2025	Biofuel	0.04159
Cromarty hydrogen Project	Storegda	United Kingdom	Under discussion	2026	Green hydrogen	0.00012
Finnfjord e-methanol plant	Carbon Recycling international (CRI),	Norway	Under discussion	2025	E-methanol	0.0019

	Stratkraft ,Finnfjord					
FlagshipONE	Ørsted	Sweden	Decided - FID	2025	E-methanol	0.02377
Södra biomethanol plant	Andritz, Södra	Sweden	Operational	2019	Biofuel	0.00238
Glocal Green Innlandet AS	Glocal Green Innlandet	Norway	Under discussion	2025	Biofuel	0.03565
Hellesylt hydrogen Hub	Flakk Gruppen, Hexagon Composites, Hyon, TAFJORD, Fiskerstrand, Gexcon, SINTEF	Norway	Decided - FID	2024	Green hydrogen	0.00136
FlagshipTWO	Sundsvall Energi	Sweden	Under discussion	2024	E-methanol	0.0019
The Dava facility	Umeå Energi	Sweden	Under discussion	2026	E-methanol	0.0019
Synthetic methanol production plant	St1	Finland	Under discussion	2026	E-methanol	0.01188
Port of Aabenraa	Linde Gas A/S, Port of Aabenraa	Denmark	Under discussion	2025	Green hydrogen	0.0215
Orkney Green hydrogen/ammonia plant	Eneus Energy, Hammars Hill Energy	United Kingdom	Under discussion	-	E-ammonia	0.00433
Project Slagen terminal	ExxonMobil	Norway	Under discussion	2025	E-ammonia	0.04443
HyTech Hafen Rostock	RWE	Germany	Under discussion	2026	Green hydrogen	0.03332
Hegra (Heroya Green Ammonia)	Yara Clean Ammonia	Norway	Decided - FID	-	E-ammonia	0.1777

Hamina Fintoil biorefinery	Fintoil	Finland	Operational	2022	Biofuel	0.000078
Kokkola Renewable Ammonia	Hy2gen, Plug Power	Finland	Under discussion	2028	E-ammonia	0.33763
San Roque Ammonia	Cepsa, Yara	Spain	Under discussion	2027	E-ammonia	0.33319
EI-H2 - Aghada	Zenith Energy, EI-H2	Ireland	Under discussion	2028	E-ammonia	0.1666
Arendal	North Ammonia	Norway	Under discussion	2027	E-ammonia	0.04443
Flexens Kokkola	Flexens, KIP Infra	Finland	Under discussion	2027	E-ammonia	0.08885
Palos de la Frontera I	Fertiberia, Iberdrola, Cepsa	Spain	Under discussion	2025	E-ammonia	0.01022
Project Green Wolverine	Grupo Fertiberia	Sweden	Under discussion	2026	E-ammonia	0.23101
Haddock	Ørsted, Yara	Netherlands	Under discussion	2025	E-ammonia	0.03332
HyFuelUp	CoLAB BIOREF	Portugal	Operational	2022	Biofuel	0.00048
Project HyDeal España	ArcelorMittal, Enagás, Grupo Fertiberia and DH2 Energy	Spain	Decided - FID	2031	Green hydrogen	0.42992
Berlevåg Green ammonia value chain project	Varanger Kraft, Aker Clean hydrogen	Norway	Under discussion	2026	E-ammonia	0.04443
eM-Rhone	Elyse Energy	France	Under discussion	2028	E-methanol	0.0713
Veolia and Metsä Fibre	Veolia and Metsä Fibre	Norway	Under discussion	2024	Biofuel	0.01433

Green Ammonia plant	St1 Nordik OY	Norway	Under discussion	2029	E-ammonia	0.03554
Project Haldor	Haldor Topsoe, Aquamarine	Germany	Under discussion	2026	E-ammonia	0.04865
REDDAP v. Ramme	Skovgaard Energy, Topsoe	Denmark	Decided - FID	2024	E-ammonia	0.00076
BENORTH2 (ABoroa power plant)	Northega	Spain	Under discussion	2024	Green hydrogen	0.03439
Herrenhausen sewage works	Aspens	Germany	Under discussion	2024	Green hydrogen	0.00373
Vitale	pHYnix	Spain	Under discussion	2024	Green hydrogen	0.00416
hydrogen Hub Agder	Glencore Nikkelverk AS +++	Norway	Decided - FID	2025	Green hydrogen	0.02293
Bodø hydrogen	GreenH	Norway	Decided - FID	2026	Green hydrogen	0.0086
Holmaneset	Fortescue	Norway	Under discussion	2027	E-ammonia	0.1004
eM-Lacq	Elyse Energy	France	Under discussion	2028	E-methanol	0.09506
eM-Numancia	Elyse Energy	Spain	Under discussion	2028	E-methanol	0.02377
Hynovi	Vicat	France	Under discussion	2027	E-methanol	0.09506
Megaton	GreenGo Energy	Denmark	Under discussion	2030	Green hydrogen	2.86615
TOTAL (estimated)						7

Source: (Transport & Environment, 2024a)

Please note that most of projects producing biofuels also uses hydrogen as RFNBO, therefore the final fuel is a mix of RFNBO and advanced biofuels (if the feedstock meets the RED requirements). Specifically, in the table the "Volumes (Mtoe)" column represents the potential production volumes in million tonnes of oil equivalent, and the "Date" refers to the expected date of operationalisation or the status update. The "Status" indicates the current stage of the project, and "End Use" specifies whether shipping is included as a potential consumer of the produced e-fuel. The project leaders are listed as "Various partners" to indicate multiple partners involved, and specific details about each partner are not provided in the context.

Project name	Project partners	Country	Location	Commissioning date	Production capacity (GWh/year)	CO2 source
Renewable Gasfield	Energie Steiermark Technik GmbH, HyCentA Research GmbH, and others	Austria	Gabersdorf	2022	2	Biogas (AD)
Hybridkraftwerk Limeco	Limeco Swiss Power and others	Switzerland	Dietikon	2022	18	Biogas (AD)
Falkenhagen	Uniper Energy Storage GmbH and others	Germany	Falkenhagen	2018	5	Other biogenic
BioFARM/MicroPyros	Pietro Fiorentini, Hyter, BioKomp	Germany	Straubing	2023	0	Gasification
Pirmasens-Winzeln	PFI	Germany	Pirmasens-Winzeln	2015	5	Biogas (AD)
Schwandorf	Eucolino	Germany	Schwandorf	2012	1	Biogas (AD)
Flensburg	GICON GmbH and others	Germany	Flensburg	2025	18	Biogas (AD)
Werlte	Audi AG and others	Germany	Werlte	2013	16	Biogas (AD)
BioPower2Gas	Viessmann Werke GmbH & Co. KG and others	Germany	Allendorf	2016	28	Biogas (AD)
Mainz	Power-to-Gas-Anlage	Germany	Mainz	2018	32	Biogas (AD)
Energy Lab 2.0 am KIT	Karlsruhe Institute of Technology and others	Germany	Leopoldshafen	NA	1	Biogas (AD)

Nachhaltige Energieversorgung	Sunfire Forschungszentrum Jülich	Germany	Sassenburg	2020	NA	Biogas (AD)
KraftwerkLand project	Technical University of Ostwestfalen-Lippe	Germany	Dörentrup	2018	NA	Other biogenic
Turn2X	Karlsruher Institut für Technologie (KIT)	Germany	Brandenburg	2024	NA	NA
Infinity	Electrochaea GmbH	Germany	Pfaffenhofen an der Ilm	2020	752	Biogas (AD)
RB-HTWP / GICON GmbH	GICON GmbH and others	Germany	Cottbus	2022	0	Biogas (AD)
MissionGreen Fuel	Nature Energy and others	Denmark	Sønderborg	2024	9	Biogas (AD)
Glansager PtG	Nature Energy	Denmark	Glansager	2023	35	Biogas (AD)
BioCat	University of South Wales and others	Denmark	Rooslepa	2018	30	Biogas (AD)
CoSin Project	Arkolia Energies and others	France	Sabadell	2016	18	Biogas (AD)
Naturgy and Greene	Naturgy, Greene	Spain	Elche	2024	0	Other biogenic
Keravan Energia Bio-CHP	Q Power Oy	Finland	Kerava	2027	180	Other biogenic
Harjavalta P2X Solutions	Q Power	Finland	Harjavalta	2024	28	Fossil/industrial CO2
Lahti	Ren-Gas	Finland	Lahti	2027	360	Other biogenic
Kotka	Ren-Gas	Finland	Kotka	2026	200	Other biogenic
Mikkeli	Etelé-Savon Energia	Finland	Mikkeli	2027	200	Other biogenic

Pori	Ren-Gas	Finland	Pori	2027	382	Other biogenic
Kristinestad	Koppo Energy	Finland	Kristinestad	2026	949	Other biogenic
Riihimaki	Carbon2x	Finland	Riihimaki	2022	NA	Other biogenic
Vantaa Energia renewable methane	Vantaa Energy	Finland	Vantaa	2022	81	Other biogenic
Occi-Biome	Arkolia Energies and others	France	Ludiés	2025	67	Biogas (AD)
Biofactory Pau	CAPB Communauté d'agglo Pau Béarn Pyrénées and others	France	Lescar	2024	6.23	Biogas (AD)
MarHySol	Engie	France	Marmagne	2026	14	Biogas (AD)
STEP de Bonneuil	SIAH Croult et Petit Rosne	France	Bonneuil-en-France	2025	4	Biogas (AD)
STEP Perpignan	Terega	France	Perpignan	2023	5	Biogas (AD)
ENERGO	ENERGO S.p.A	France	Sempigny	2022	0	Biogas (AD)
METHA / GICON GmbH	GICON GmbH and others	France	Paris	2024	5	Biogas (AD)
Denobio-Enosis	Enosis	France	Lesquielles-Saint-Germain	2024	67	Biogas (AD)
Methan'Up	Urbeez and others	France	Le Havre	2024	10	Biogas (AD)
BIMOTEP - Enosis	Enosis	France	Epinal	2022	NA	Other biogenic
SOLIDIA - Enosis	Enosis and others	France	Toulouse	2018	NA	Biogas (AD)
SynBioS/MicroPyros	Pietro Fiorentini, Hyter, BioKomp	Italy	Corticella	2025	4.53	Gasification

Underground Sun Storage	RAG Austria, AXIOM and others	Austria	Gampern	2018	2.8	fossil / industrial CO2
Gaznat methanation project	TotalEnergies Lausanne (EPFL), Regensburg University of Applied Sciences (OTH Regensburg)	Switzerland	Aigle	2023	0.07	fossil / industrial CO2
Orbit II	Uniper Energy Storage GmbH, Climeworks AG, DBI GUT, DVGW, GWI, HSR Rapperswill, KIT	Germany	Pfaffenhofen	2022	0.03	other sources than biogas
Jupiter 1000	GRTgaz, ADEM, CEA, Atmostat, AGHUST, IChPW, Rafako, WTST Polska	France	Fos-sur-Mer	2024	2.29	fossil / industrial CO2
Harjavalta P2X Solutions	Q Power	Finland	Harjavalta	2024	28	fossil / industrial CO2
TAURON methanation	Tauron, CEA, Atmostat, AGHUST, IChPW, Rafako, WTST Polska	Poland	Zabrze	2025	21	fossil / industrial CO2
TOTAL (estimated)					3,587	

Source: (European Biogas Association (EBA), 2024)

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