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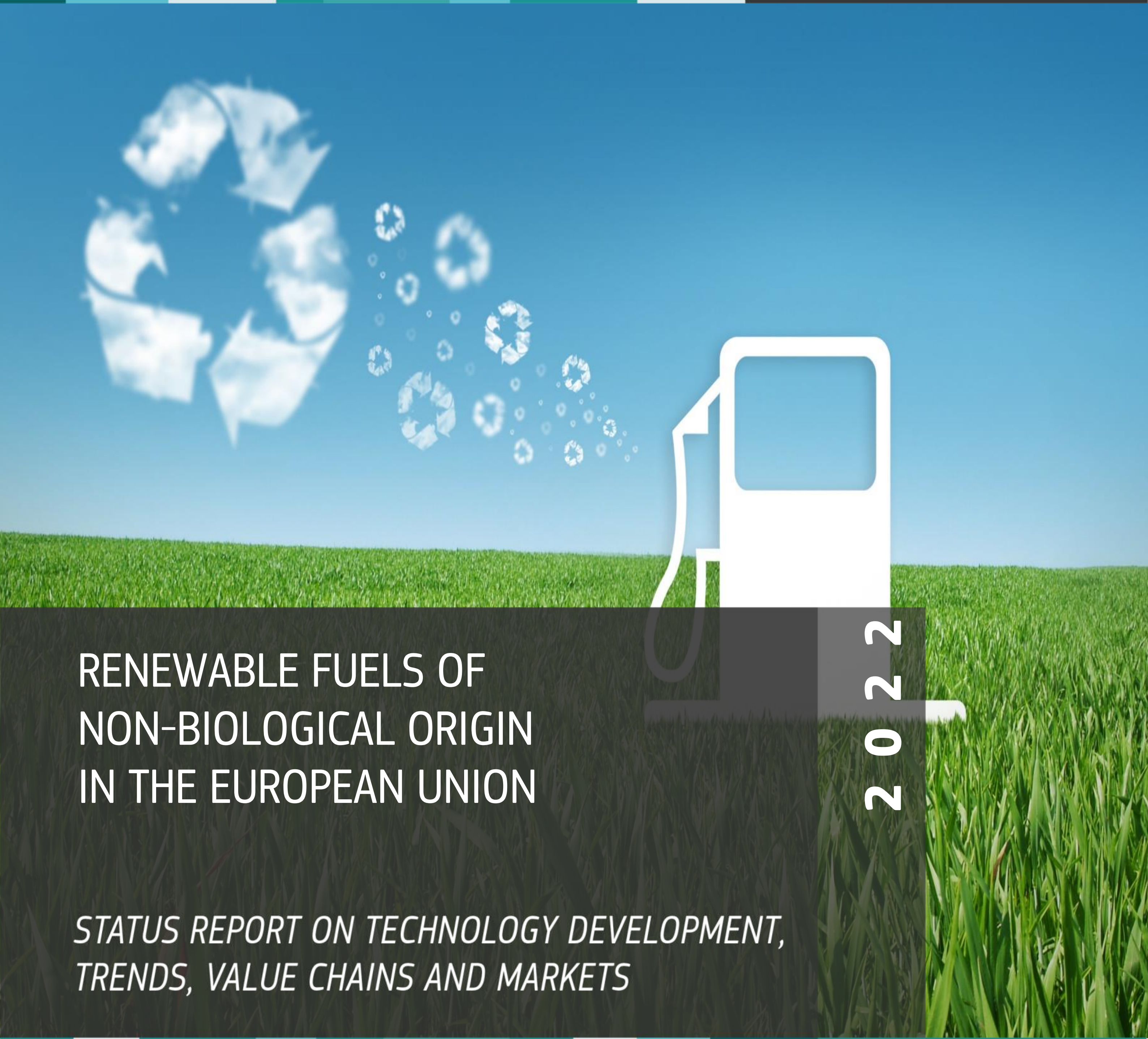

RENEWABLE FUELS OF NON-BIOLOGICAL ORIGIN IN THE EUROPEAN UNION

2022

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

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Contents

Abstract

This report investigates the current status and trend of Renewable Fuels of Non-Biological Origin (RFNBO), except hydrogen, which are needed to cover part of the EU's demand renewable fuels in the coming years. Most of the conversion technologies investigated here have been already tested at demonstration scale thanks to the financial support of EU-funded projects, and the current EU legislative framework under the recast of the Renewable Energy Directive (EU) 2018/2001 already set specific targets and delegated acts for their use. As first priority, solid hydrogen supply chains are needed, together with carbon capture technologies aimed to build Carbon Capture and Utilization (CCU) systems. Fuels that may be produced starting from H2 and CO2 or N2 are hydrocarbons, alcohols and ammonia. The use of RFNBO is crucial in the transition towards full decarbonisation on account of their ability to be used in the existing fuel infrastructures. As a result, a large number of funding programmes are available today. Moreover, EU leads the sector in terms of patents, companies and demonstration activities. As well as describing the current overall situation, this report identifies the major challenges and the opportunities for a rapid market uptake of such fuels.

Foreword

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

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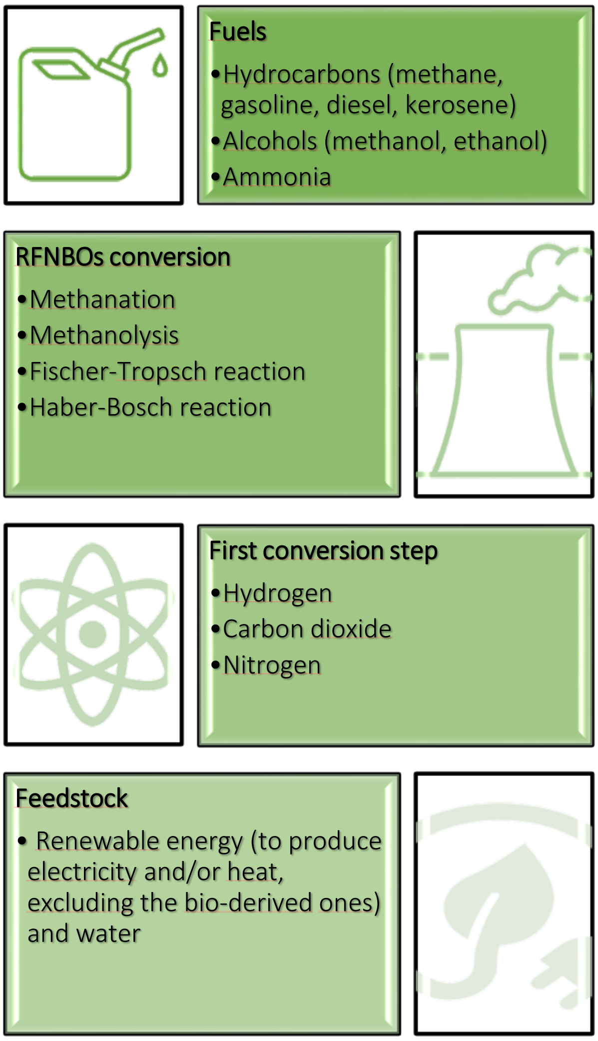
Executive Summary

Renewable Fuels of Non-Biological Origin (RFNBO) consists in either:

- pure hydrogen derived from water and renewable energy (except biomass sources) in the form of heat or electricity, or
- in liquid and gaseous fuels derived from hydrogen combined with CO2 from fossil sources such as flue gases, from DAC (Direct Air Capture) technologies or from other non-renewable and natural sources, or
- liquid and gaseous fuels derived from hydrogen combined with nitrogen captured from air in the case of ammonia production.

However, since CO2 and N2 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 CCU/CCS, i.e. the synthesis reactions that lead to methane, drop-in liquid fuels as gasoline, kerosene or diesel, and other fuels/chemicals as alcohols and ammonia.

Figure 1. Production pathway of RFNBO starting from renewable energy sources.



Source: JRC analysis

Specifically, this study is based on a TRL, energy and environmental assessment of the conversion pathways already available from fossil refining and chemical industries, with a short 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-CO2 splitting are investigated too, but they are still limited to small scale demo activities.

RFNBO consisting in hydrocarbons produced from synthesis processes are mainly paraffins, hence drop-in fuels to be used in the current fuel infrastructures and vehicles. An extensive technology review showed that such technologies would be ready for the market uptake, but the upstream processes of green H2 production and CO2 capture still need to be developed at large scale for commercial production (so the current TRL according to the Horizon 2020 guidelines is about 6-7, i.e. pilot scale). Some conversion technologies as Fisher-Tropsch synthesis, Haber-Bosch process and others are at high TRL as they were developed over the years to operate with fossil-based feedstocks. Energy and environmental assessments are evaluated considering the most recent findings from peer-reviewed papers, technical reports and JECv5 Well-to-Tank assessment. At EU level, the main criterion used to classify a fuel as RFNBO, is if its production complies with the 70% GHG emissions saving threshold calculated according to the methodology defined in a dedicated delegated act. In the case So for hydrogen, if the electricity used for electrolysis is fully renewable (as defined in the upcoming delegated act based on the additionally principle), the carbon footprint of electricity is zero according to RED II, so the carbon intensity of hydrogen results to zero.

The analysis of the past and current available public and private funding mainly focuses on EU Horizon 2020 programme, where specific projects descriptions are provided (focusing on TRL and scale of production). Several demo-activities have shown that the current technologies are ready to be scaled up. For this next step the Innovation Fund can potentially 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, integrating data from other recent technical report. 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 the 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 active international collaboration networks.

The analysis of the available patents is included the CETO' report on "advanced biofuels", since most of synthesis process can be fed also by biogenic carbon sources deriving from biomass. The present classification of CETO reports makes hard to address a process in a fuel category based on its origin, so a different type of analysis would be needed.

Market assessment is only briefly evaluated since there is still no trade of RFNBO, hence the present analysis is limited to investigate the main initiatives developed form the main associations of the sector.

Finally, the conclusions address opportunities to further develop the sector, indicators to monitor the trends, and current limiting factors to the market uptake of RFNBO.

Table 1. SWOT analysis for RFNBO

Strengths:	**Weaknesses:**
• several technologies are available and getting close to commercial deployment; • energy storage solution/grid balancing and opportunities to use the surplus of renewable electricity; • contribution to energy diversification and energy security; • use of existing fuel distribution infrastructure with no additional investment needed; • only available 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, as well as robust power connections and grid infrastructure; • several technologies are not yet demonstrated • high conversion and efficiency losses associated with the production and use of RFNBOs 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; • reliance of variable renewable electricity (solar and wind) that make intermittent production of RFNBOs very expensive; • dependency on upstream hydrogen production and carbon capture solutions, that are still limited.
Opportunities:	**Threats:**
• promoting higher share of solar and wind in the electricity mix to produce green hydrogen; • grid balancing; • contribution to energy diversification; • the reduction of dependency on fossil fuel imports; • contribution to the decarbonisation of hard to decarbonise sectors such as aviation, shipping and heavy road freight transport; • job opportunities along the supply chain, including skilled labour.	• lack of stable policy framework or long-term policy perspectives; • slow market uptake due to the insufficient incentives; • failure to reach cost competitiveness through technology improvement; • slow growth in renewable electricity capacity and lack of available, cheap renewable electricity; • insufficient development of the electricity grid infrastructure; • low availability of cheap hydrogen; • Risk of certifying renewability even if not generated with renewable energy electricity;

Source: JRC analysis

1 Introduction

1.1 Definition

The former definition of renewable fuels of non-biological origin (RFNBO) derives from the recast Renewable Energy Directive (The European Parliament, 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 CO2 deriving from fossil sources such as flue gases, from DAC technologies and from other non-renewable and natural sources, or N2 captured from air. The hydrogen used as a RFNBO in either fuel cells, or direct combustion engine dedicated vehicles, and its associated production pathways, will not be investigated in this report, which aims to consider it only as feedstock for further upgrading processes to produce hydrocarbons-, alcohols- and ammonia-based fuels. The other main input, i.e. CO2, is captured either from a concentrated source (e.g. flue gases from an industrial sites and other processes that would emit it into the atmosphere) or from the air (via direct air capture, DAC). Coming with zero energy content, CO2 and N2 needs energy from hydrogen or other renewable sources (except bio-derived ones) to split carbon from oxygen to produce carbon-based fuels.

Within the category of renewable fuels of non-biological origin, there are both electro-fuels, or simply e-fuels (also named power-to-liquids, power-to-gas, or power-fuels) when hydrogen comes from electrolysis powered by renewables (Malins, 2017), solar-derived fuels, or simply solar fuels, when hydrogen uses the sunlight as energy source to split hydrogen from water, other fuels derived from renewable heat, and fuels from microbes through synthetic biology, cyano - bacteria or chemical catalysis. Together with advanced biofuels, RFNBO consist in a ready alternative to fossil liquids fuels for the market being fully drop-in (Panoutsou *et al.*, 2021), so they do not require dedicated infrastructures for distribution and storage (Yugo and Soler, 2019), even only no standards as regards their composition and blending walls have been developed so far. Summarizing, this report describes and analyses the conversion pathways producing RFNBO starting from the main process inputs, i.e. hydrogen and CO2, whose conversion technologies will be reported in other CETO reports. This report also integrates the findings reported in the previous LCEO (O'Connell *et al.*, 2019) report investigating this topic.

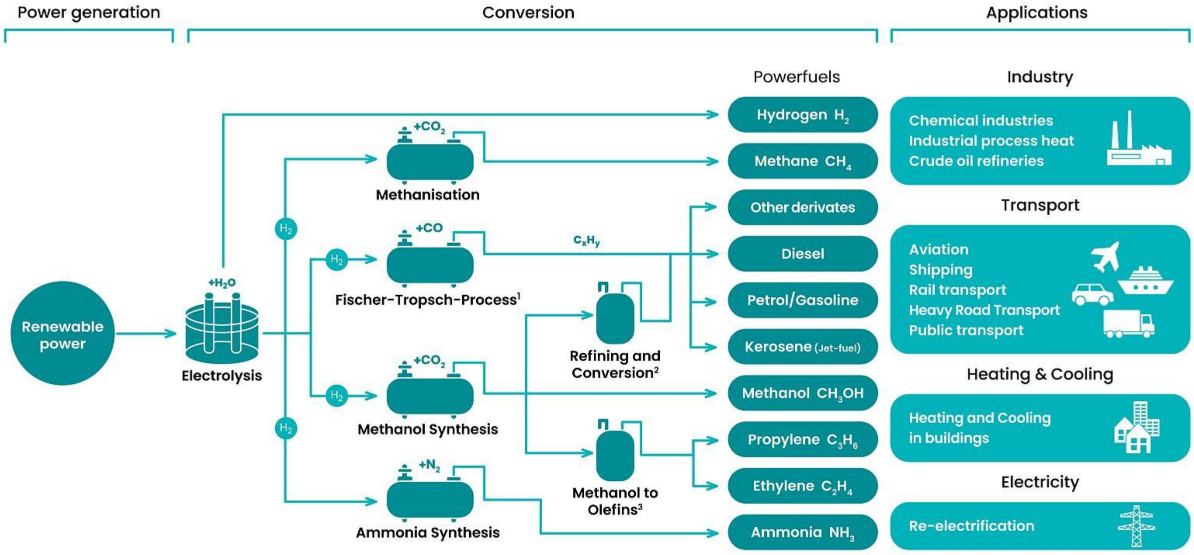
1.2 Technologies and fuels

The growing European transport fuel demand as well as the stricter requirements in terms of environmental impact and sustainability are driving the fuel market to alternative conversion pathways using renewable feedstock in addition to the bio-sources. In parallel to the growing development of hydrogen sector and carbon capture technologies, the production of RFNBO is an opportunity to produce drop-in fuels starting from the supply chains of renewable hydrogen and capturing CO2/N2. Although the energy efficiency of the production of RFNBO is lower than pure hydrogen (Lindstad *et al.*, 2021), they offer the opportunity to be an immediate alternative to fossil fuels. Moreover, for some sectors as aviation, where electrification is harder than for road transports, such fuels can play a crucial role in the coming years (Scheelhaase, Maertens and Grimme, 2019).

Despite the relatively limited number of RFNBO plants available today, the main conversion technologies can be summarized in two main categories, i.e. power-to-gas and power-to-liquid. In most cases, hydrogen derives from electricity and RFNBO are placed in cascade to H2 production, but these pathways can be also supplied by hydrogen coming from other renewable sources. Depending on the synthesis reactions used within the conversion pathways, the output fuels could be methane for natural gas vehicles and/or directly injected into the natural gas grids; synthetic drop-in liquid fuels for gasoline, kerosene or diesel (including also other hydrocarbons, depending on the marked demand); other fuels/chemicals as alcohols (e.g. methanol, ethanol and their isomers); ammonia. Hydrocarbons produced from synthesis processes are mainly paraffin, which lead to cleaner combustion than their counterparts containing also an aromatic fraction (Styring, Dowson and Tozer, 2021). Thus, they can potentially meet more stringent limits than the current commercial blends (Transport & Environment, 2021), making of their use a solution to meet both environmental targets in terms of GHGs emissions and pollutants reduction. It is worth to mention also that e-fuels technologies also produce chemical and energy carrier as methanol and ammonia that could be of high interest for biodiesel production and other applications. Today biodiesel is mainly produced using fossil-derived methanol that significantly affects its carbon footprint (Sebos, 2022), so adding a full renewable contribution along its supply chain will contribute in large part to reduce the biodiesel carbon footprint. Moreover, methanol could be also used as blending components for maritime fuels (Svanberg *et al.*, 2018). Figure 2 shows the main conversion pathways considering the most common e-fuels conversion pathways downstream to water electrolysis.

Other pathways to produce RFNBO are possible but still at early stages of developments, such as direct solar fuel synthesis and bio-hybrid processes. However, it is worth mentioning that some conversion processes can be also used in biomass conversion processes, e.g. Fischer-Tropsch synthesis from wood gasification, which is a mature technology already available at commercial level (Gruber *et al.*, 2021). The current EU facilities producing e-fuels are still at demo-scale in a TRL classification around 6 (Prussi *et al.*, 2020; BEST and IEA Bioenergy Task 39, 2022), although 220 projects in 20 different countries have been identified, with France and Germany as the leading countries. Both countries plan to install around 500 MW of capacity by 2025 (Wulf, Zapp and Schreiber, 2020).

Figure 2. Production pathways of various power-to-liquid fuels (*Powerfuels – Global Alliance Powerfuels*, 2022).



❶ Includes: Fischer-Tropsch synthesis, hydrocracking, isomerization and distillation.

❷ Includes: DME/OME synthesis, olefin synthesis, oligomerisation and hydrotrating.

❸ Methanol-to-olefins process.

Source: Global Alliance Powerfuels

1.3 Current EU legislative framework

In the last years, the European legislation started the promotion of renewable fuels of non-biological origin production, mainly focusing on hydrogen, with the aim at developing new initiatives and projects towards the production of clean, renewable fuels. Hydrogen is considered as one of the main pillars of the Europe's decarbonisation strategy for the next years, offering an alternative solution for transports, industrial applications or to produce other fuels. However, without a reliable system and infrastructures dedicated to hydrogen generation, new initiatives towards e-fuels production are still limited, so it is of primary importance to first boost the upstream energy generation by means of renewables.

According to the European Green Deal (EGD) (European Commission (EC), 2019), issued by the European Commission in December 2019, hydrogen is today considered one of the main energy vectors towards the EU carbon neutrality by 2050. However, some techno-economic, sustainability and legislative barriers still exist, so the European Commission promoted the sector with the communication "A hydrogen strategy for a climate-neutral Europe" (European Commission (EC), 2020), which recently updated its targets to more ambitious achievements by means of the RePowerEU' plan (European Commission (EC), 2022b). In addition, the "Next Generation EU" recovery fund (European Commission (EC), 2022a) to support the MSs after the Covid crisis, is stimulating the production of new clean production technologies, including hydrogen to boost its market uptake. Other Important steps towards the promotion of clean hydrogen are contained in a new initiative derived from the manifesto for the development of a European "Hydrogen Technologies and Systems" value chain, signed by

22 EU MS and Norway. This new initiative is committed to promoting Important Projects of Common European Interest (IPCEIs) in the hydrogen sector. The Strategic Forum on IPCEIs identified in its report six strategic value chains that include hydrogen technologies and systems entitled to be supported (European Commission (EC), 2014).

In parallel, the Renewable Energy Directive recast (EU 2018/2001) or REDII (The European Parliament, 2018) sets the framework towards targets and sustainability criteria for alternative renewable transport fuels, including RFNBO that can be produced using additional renewable energy production, hence respecting the criteria of additionality (see 1.4) to ensure that e-fuels can contribute to the GHG emissions reduction. Otherwise, if grid electricity is used, a reliable methodology (under development by the Commission through a dedicated delegated act) needs to be used to properly assess the real carbon footprint of such fuels. For this scope, REDII states that renewable fuels of non-biological origin can't count as fully renewable if produced from fossil-derived electricity. Moreover, a second delegated act will set up the methodology to calculate the GHGs emissions assessment for RCFs and RFNBO (the drafts of such DAs are today under open consultation for the stakeholders).

Recently the REDII has been updated towards the EDG targets by means of the Fit-for-55 package (The European Commission (EC), 2021), which introduced a new target of 2.6% (on energy basis) for the share of renewable fuels of non-biological origin by 2030 in the renewable energy share for transport. This revision also includes large modifications such as the main 14% target for renewable energy in transport (as set by RED II) has been replaced by a new 13% GHG intensity reduction target for 2030. Moreover, the revision excludes the use of multipliers, thus resulting in real target that guarantees equal volumes of renewable fuels replacing fossil fuels. The only multiplier maintained is based on a figure of 1.2x for advanced biofuels and RFNBO in aviation and maritime sectors. The energy from renewable fuels as RFNBO and the bio-derived one, can only be counted towards the GHGs emissions reduction targets if they pass specific reduction thresholds: these requirements are 50-65% for biofuels, depending on date of facility construction, and 70% for RFNBO & RCFs. Finally, RCFs, RFNBO and advanced biofuels can also contribute to the targets imposed by ReFuel EU (The European Parliament, 2021b) and FuelEU Maritime (The European Parliament, 2021a), which set a target of 63% of SAFs and -75% as GHGs reduction intensity respectively, by 2050.

1.4 Certification schemes

Renewable hydrogen deriving from renewable electricity needs harmonized, coherent, and consistent certification schemes which deliver GoO (Guarantee of Origin) that can be recognized and used at a global level. Such certification schemes could allow us to use a single methodology to calculate the greenhouse gas (GHG) emissions and life cycle assessment (LCA) of hydrogen. Today many ongoing initiatives are working for this scope (e.g. IPHE task force, CertifHy, Hydrogen Europe, etc.) and are committed to carry out international rules to develop globally common standards, rules to ensure the guarantee of origin, LCA guidelines for transparency and accountability when producing hydrogen and hydrogen-derived fuels. At EU level, EC is developing the specific guidelines on which voluntary schemes will be qualified to certify RFNBO according to the REDII regulation.

Some institutions such as the ISCC PLUS have made already possible a preliminary certification scheme (*ISCC website: Certification of energy sector*, 2022) where the general rule is to respect the GHG emissions targets using renewable electricity. The EU legislative framework focuses on the additionality principle, which ensures that an expected increase in demand for electricity in the transport sector is met with additional renewable energy generation capacity. The main pillars are:

- additional renewable generation units dedicated for this scope;
- a 'temporal and geographic correlation' between electricity generation and RFNBO production, with a parallel development of digital, certified systems;
- accounting for the carbon intensity of the grid power used;
- avoid double counting of RFNBO, so to distinguish the renewable electricity consumed during RFNBO production from that one counted towards overall member states' renewables targets.

1.5 Summary of the methodology and data sources

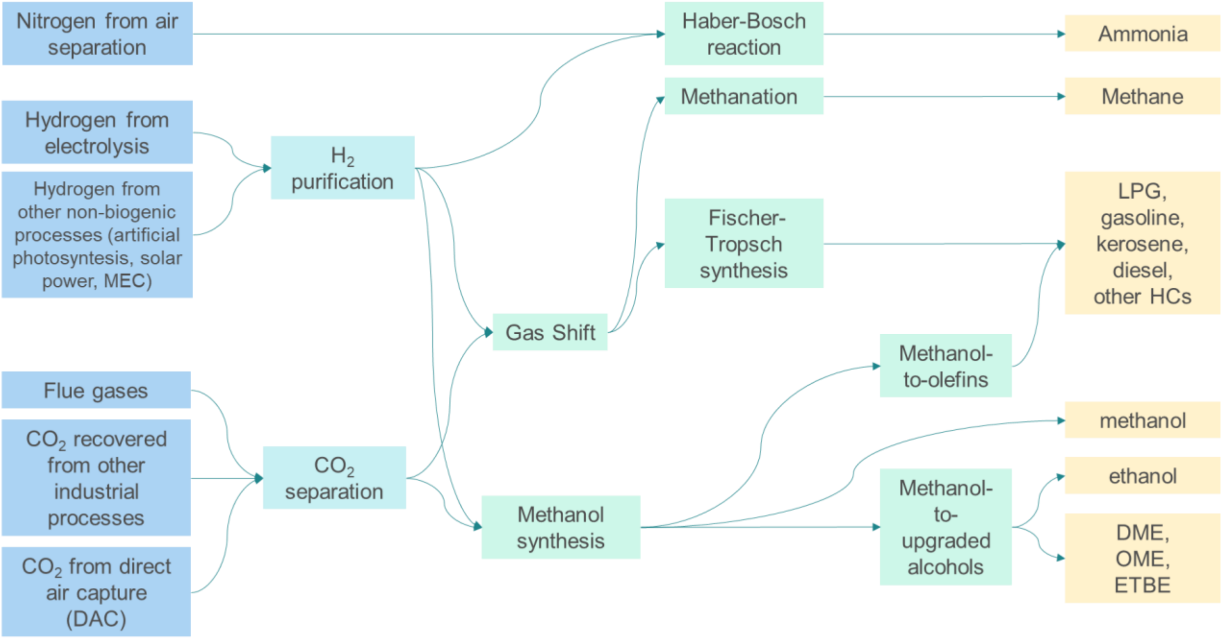
This document summarizes the state-of-the-art, ongoing and future initiatives that regard RFNBO production (including artificial photosynthesis), using hydrogen from renewable energy and non-biological CO2 (or N2) captured from industrial off-gases, flue gases and DAC technologies. Its main information sources consist in scientific publications, knowledge gained through the JRC's own work on this topic, material from international institutions (IEA, IRENA, etc.), and also related previous LCEO 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 a feedstock provider 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) programme. Further analysis, to describe objectives and main achievements was conducted, in order 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.

2 Technology State of the art and future developments and trends (For each technology)

2.1 Technology readiness level (TRL)

The supply chain of RFNBO as electrofuels (e-fuels), Power-to-Gas (PtG) and Power-to-Liquid (PtL) is generally associated to several conversion steps starting from renewable electricity and non-biological carbon or nitrogen sources (generally CO2 or N2). 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 CO2 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. The present report focuses on the second stage of conversion, assuming both hydrogen and CO2/N2 as feedstock for the production of hydrocarbons, ammonia or alcohol fuels. The production of carbon-based fuels starts with a gas shift reaction aimed followed by other specific reactions depending on the fuels required. In the case of production of methanol, CO2 and H2 can be reacted directly through the methanol synthesis, while for other products such as methane and FT hydrocarbons, a reverse water gas shift reaction is needed to convert CO2 to CO, prior to the catalytic synthesis process where the products are formed.

Figure 3. Elaboration of the investigated pathways.



Source: JRC analysis

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 recent assessment of IEA (AMF Annex 58 and IEA Bioenergy Task 41, 2020) and LBST, the average TRL of RFNBO conversion pathways is around 6-7, but some technologies may have also high values when included in established fossil-based supply chains (for example the chemical industry producing ammonia and alcohols).

2.1.1 Hydrogen production

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. For a specific overview on hydrogen production, please consult the CETO report (Dolci *et al.*, 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 Electrolyzer Cells - MCEC) (Dincer and Acar, 2015). Electrolyzers 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. The production by means of alkaline electrolyzers 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 electrolyzers. The high temperature processes are still under development, but they have the potential to achieve very high conversion rates.

Electrolyzers installations are generally powered by few 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 allowed larger electrolyzers capacity > 100 MW. According to IEA (IEA, 2021b), today AEL have 63-70% of efficiency, higher than PEMEL, with reduced CAPEX but larger starting-up times.

2.1.1.2 Artificial photosynthesis

The 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 multijunction semiconductor for the light-reaction side, where water changes 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 CO2 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 CO2 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). Finally, another process of interest is the photobiological 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). To sum up, the current TRL of this technology is about 3-4 (Walczak, Hutchins and Dornfeld, 2014).

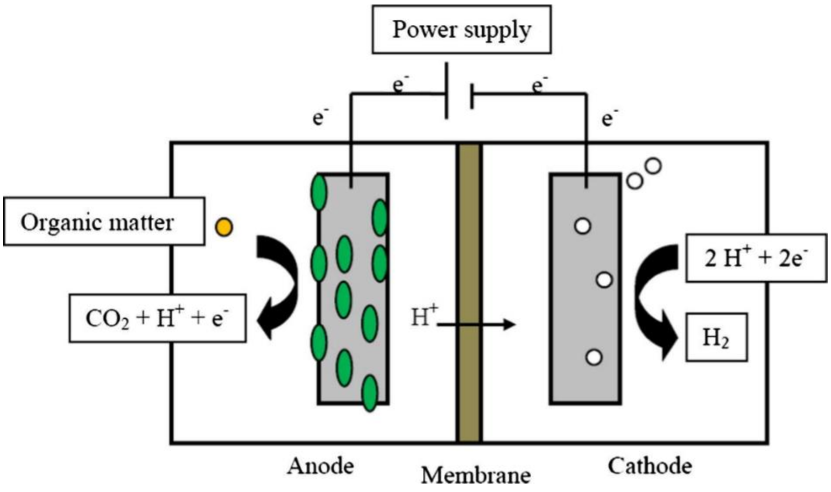
2.1.1.3 Solar power derived hydrogen

The thermolysis process can be used efficiently to produce hydrogen using solar–thermal energy. 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. 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). To sum up, 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 CO2, 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 4. 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 CO2, and CO2 captured directly from the air (Madejski *et al.*, 2022). Carbon capture and utilization (CCU) is considered an important CO2 mitigation strategy to support and complement carbon capture and storage (CCS) objectives for the abatement and sequestration of CO2. It represents various pathways that use CO2 as a feedstock in process systems or otherwise for the generation of value-added commodities (Dange *et al.*, 2021). The main technologies include post-combustion CO2 capture (using membranes, absorption or adsorption systems) or DAC (Direct Air Capture). However, it is worth noting that such technologies are already available at commercial level (resulting in high TRLs as shown here below), since their use has been already consolidated from other sectors. Additional information can be found in a specific CETO report on CCUS (Kapetaki *et al.*, 2022).

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	9	Mainly applied in natural gas and ethanol processes, this technology is responsible for CO2 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	6-7	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.
Chemical capture	4-6	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 Fuel synthesis: Power-to-Gas

This section reports the only process producing gaseous fuels from hydrogen and CO2. Here following a list of the most common synthesis-based conversion technology, i.e. the production of e-CH_4.

2.1.3.1 e-CH4 (methanation with renewable hydrogen and CO2)

Methanation is the easiest reaction to produce a hydrocarbon from hydrogen and CO, formerly CO2. The general reaction is reported here below:

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

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 electrolyzers 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 (Jarvis and Samsatli, 2018).

Indicator/measure		**Value**
Technical	TRL	8-9
	Typical operating temperature (°C)	250-550
	Typical operating pressure (bar)	1-100

	Typical overall CO_2 conversion (%)	100
	Plant lifetime	20
Economics	Fuel price (Euro/t_{fuel})	320
Environmental	Electricity usage (MWh/t_{fuel})	15.2
	Net CO_2 utilization (t/t_{fuel})	1.0

Source: Jarvis and Samsatli, 2018

Finally, other studies suggest that the production of e-methane can be economically competitive in 2030 if the electricity prices are low enough (30 EUR/MWh), and if CAPEX and OPEX decrease in price due to the development of the technology (Gorre, Ortloff and van Leeuwen, 2019; IEA, 2021a) . Thus, the methanation field is expanding with several projects planned to be in operation soon.

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 have been in operation in the EU. Including plants under construction, planned, and announced plants the capacity will reach more than 16 MW of CH4. In most of the plants the CO2 is derived from biogas upgrading or CO2 in biogas streams via direct methanation using the CO2 fraction of biogas. One plant uses direct air capture (DAC) of CO2.

2.1.4 Fuel synthesis: Power-to-Liquid

This section reports the processes producing liquid fuels from hydrogen and CO2/N2. 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 (depending on the initial sources, which can derive also from biomass or other organic matter converted by gasification in the form of CO and H2).

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

Ammonia is the simplest hydride of nitrogen (NH3), and is a colorless 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 specific energy 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).

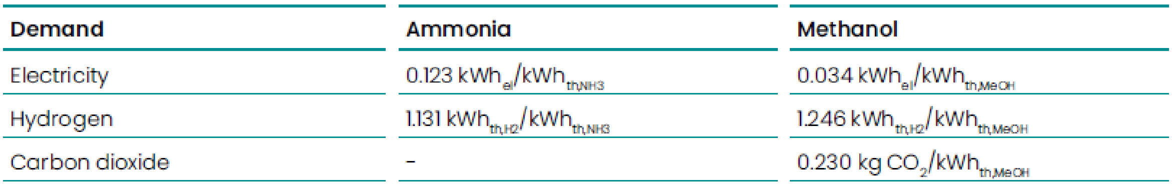
Ammonia has been formerly used as refrigerant since almost two centuries, and as a feedstock for nitrogen fertilizers for a century. NH3 can be also combusted in ICEs and turbines, leading to a higher fraction of NOx compared to carbon-based fuels (Salmon *et al.*, 2021), but recent developments in the combustion chambers design and oxygen distribution, allowed to reduce to very low level such emissions (Guteša Božo *et al.*, 2019; Elbaz *et al.*, 2022).

Ammonia can be also used as hydrogen carrier, both for large-scale transportation (e.g. into oceangoing tankers) and for distribution (e.g. industry or road vehicles). It is worth mentioning that many innovative applications in fuels cells are currently under development (Jeerh, Zhang and Tao, 2021).

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, 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 (Imhoff, Gkantonas and Mastorakos, 2021).

As regards ammonia production, it generally derives from hydrogen via the Haber-Bosch (HB) ammonia synthesis. The world's first ammonia plant was commissioned in 1913 by BASF in Oppau, Germany (Rouwenhorst, Travis and Lefferts, 2022). Today's modern plants still retain the same basic configuration, 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. 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 CO2 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 the electrolyzer 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 4. Electricity and hydrogen demand in the production of ammonia and methanol (Ram *et al.*, 2020).



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

2.1.4.2 *e-methanol via methanolysis*

Methanol is the simplest alcohol (CH_3OH), liquid at ambient temperature and atmospheric pressure, but with a high volatility. Differently than ethanol, it is toxic for human health. It can be produced in different ways, both from fossil sources as well as from (Pirola, Bozzano and Manenti, 2018; IRENA and Methanol Institute, 2021). Moreover, hydrogen can be converted to methanol via synthesis directly with CO2, without requirement of reverse water gas shift (as for methane), according to the methanolysis as follows:

CO2+3H2 => CH3OH + H2O

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 liters of methanol contain about the same energy contained in one liter 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 ambient conditions). 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, an international organization (ISO) is currently developing a standard for methyl/ethyl alcohols as a marine fuel under the reference ISO/AWI 6583 (ref). 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, the 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)) 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 H2 and CO2 supply and economy (Weindorf et al., 2019; Yugo and Soler, 2019).

Table 5. Main technical specifications and KPIs for the hydrogenation to methanol (Jarvis and Samsatli, 2018).

Indicator/measure		**Value**
Technical	TRL	6-7
	Typical operating temperature (°C)	225
	Typical operating pressure (bar)	50
	Typical overall CO_2 conversion (%)	93.85
	Plant lifetime	20
Economic	Fuel price (Euro/t_{fuel})	360
Environmental	Electricity usage (MWh/t_{fuel})	0.4
	Net CO_2 utilization (t/t_{fuel})	1.3
	Total water use (t/t_{fuel})	26.4

Source: Jarvis and Samsatli, 2018

2.1.4.3 e-diesel and e-gasoline via Fischer-Tropsch route

F-T synthesis is a technology that has a long history of production of gasoline and diesel from coal. Recently 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.

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 H2 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: $nCO + (2n + 1)H2 \rightleftharpoons CnH2n+2 + nH2O \qquad \Delta H = n(-146.0)\ kJ\ mol-1$

Olefins: $nCO + (2n)H2 \rightleftharpoons CnH2n + nH2O$

Alcohols: $nCO + (2n)H2 \rightleftharpoons CnH2n+1\ OH + (n - 1)H2O$

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 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 CO2-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 CO2 to CO have been operated successfully and further larger-scale plants have been announced (BEST and IEA Bioenergy Task 39, 2022). For the near 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 liters of water, 82–99 MJ of renewable electricity and 2.9–3.6 kg of CO2.

An upcoming CONCAWE report is going to update these figures (report under publication: not to be disclosed before the official release), hence: 11.7 g of hydrogen, 88 g of CO2 and 0.0441 MJ of electricity produce 23.2 g of e-Diesel (i.e. 1 MJ) and 0.2139 MJ of heat.

Table 6. Main KPIs for the Fischer-Tropsch' reaction for liquid fuels production (Jarvis and Samsatli, 2018).

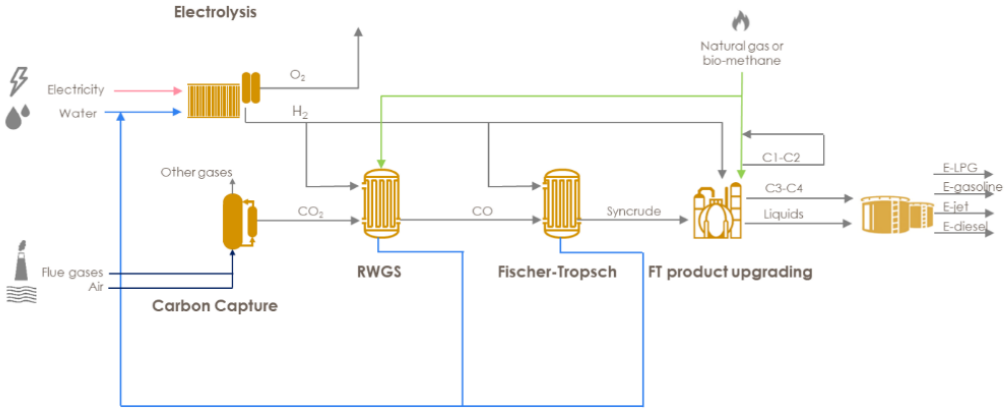
Indicator/measure		**Value**
Technical	TRL	5-9
	Typical operating temperature (°C)	200-350
	Typical operating pressure (bar)	20-40
	Typical overall CO_2 conversion (%)	51.5
	Plant lifetime	20
Economic	Fuel price (Euro/t_{fuel})	1375
Environmental	Electricity usage (MWh/t_{fuel})	6.8
	Net CO_2 utilization (t/t_{fuel})	2.6

Source: Jarvis and Samsatli, 2018

Finally, 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 REDII categories. For instance, biomass gasification leads to advance biofuels, non-organic wastes gasification/pyrolysis or the recovery of industrial off-gases lead to RCFs, and the generic CO2, 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 building a demo plant producing FT-synthesis liquid hydrocarbons supplied by CO2 from DAC and hydrogen from SOEC, that will start production in 2024 and will be gradually scaled to produce 25 million litres within 2026 (*Norsk e-Fuel website: tecnology description*, 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).

Figure 5. FT-fuels production from electricity and carbon capture (Alfonso García de las Heras, 2021).



Source: Heras (Concawe), 2018

2.1.4.4 e-diesel 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 CH3OH => CH3-O-CH3 + H2O

Olefin synthesis: CH3-O-CH3 => (CH2)2 + 2 H2O

Oligomerization: 0.5 n (CH2)2 => CnH2n

Hydrogenation: CnH2n + H2 =>CnH2n+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). The production pathway for the PtL methanol pathway is reported in the figure below.

As regards the TRL, LBST reported that this process has TRL 6 when supplied by high temperature electrolyzers, while 8-9 when supplied by low temperature, traditional electrolyzers (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 liters of gasoline per day) based on natural gas reforming (Dieterich *et al.*, 2020).

2.1.4.5 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 CO2 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 CO2 (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 (CH3O(CH2O)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.

2.1.4.6 Renewable jet fuel via ATJ (Alcohol to Jet fuel, i.e. Lanzatech process)

As last pathways, it is worth to mention that also novel, alternative processes converting CO2 to CO, to form syngas, that together with e-hydrogen can lead to fuels, alcohols or other compounds. Many companies are studying such innovative processes even if they are at early stage of development. Recently, Topsoe developed eCOs™ process (i.e. electrolytic Carbon Monoxide solution), where through a solid oxide electrolysis cell (SOEC), CO_2 is reduced to CO through the electrochemical process of electrolysis (Haldor Topsoe, 2022). Moreover, carbon transformation company Twelve and biotechnology company LanzaTech recently developed a process converting CO2 emissions into ethanol as a part of an ongoing research and development partnership (Green Car Congress website, 2022b, 2022c). Here the conversion pathway exploits Twelve's carbon transformation technology (a new class of CO2-reducing catalysts and a novel device that splits CO2 with just water and renewable electricity as inputs), and subsequently using 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 CO2 emissions.

The process can then 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 the fuel requirements for the alternative jet fuels (Geleynse *et al.*, 2018). As of the close of the project, ATJ produced from ethanol using the LanzaTech-PNNL hybrid process (Green Car Congress website, 2022a), 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).

There are also many other initiatives ongoing which may be of high interest in the near future as regards the e-fuels production (Küngas, 2020; Saravanan *et al.*, 2021).

2.2 Installed energy Capacity, Generation/Production

E-fuels facility are still at demo-scale, as demonstrated in the previous sections. Only few plants are currently operated at EU level, and the overall production is about few tons of fuels per year used for demonstration activities (BEST and IEA Bioenergy Task 39, 2022).

Table 7. RFNBO plants available today in EU.

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	SNG 1 m3/h	4-5	SNG	2015
Commercial synthetic kerosene facility	Synkero	Netherlands	E-Fuels Biomass Hybrids	50,000 t/y		sustainable aviation fuels SAF	2027
Jupiter 1000	GRTgaz	France	Water electrolysis (alkaline and PEM), methanation, CO2 capture from flue gas	CH4 25 Nm³ /h	3-4	H2 and CH4	2019
Store&Go-Falkenhagen	Uniper	Germany	Alkaline water electrolysis, catalytic methanation, direct air capture of CO2	CH4 57 Nm³ /h	3-4	CH4 and H2	2019
STORE&GO Falkenhagen	STORE&GO	Germany	Isothermic catalytic honeycomb technology	1,400 cubic meters of SNG / day	3-4	H2 and CH4	2019
GEORGE OLAH RENEWABLE METHANOL PLANT	Carbon recicling International	Iceland	alkaline water electrolysis, methanol synthesis from H2 and CO2, CO2 capture from a geothermal power plant	4000 t/year	8	Methanol	2012
FReSMe project	Swerim	Sweden	Electrolysis	50 kg/h of methanol	6	methanol	2021
ALIGN-CCUS	A consortium of 31 companies	Germany	Methanol synthesis from H2 and CO2	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 water gas shift (RWGS), F-T synthesis	180 l/day	3-4	bio-oil	2014
GreenPower2 Jet	Airbus, BP Lingen, BP Air, Dow, DLR, Hoyer Logistik, Easyjet, DHL	Germany	50 MW Electrolyzer	JET Fuel quantity N.A.	7-8	Hydrogen, Jet fuel	2024

Source: BEST, IEA T39 (2022)

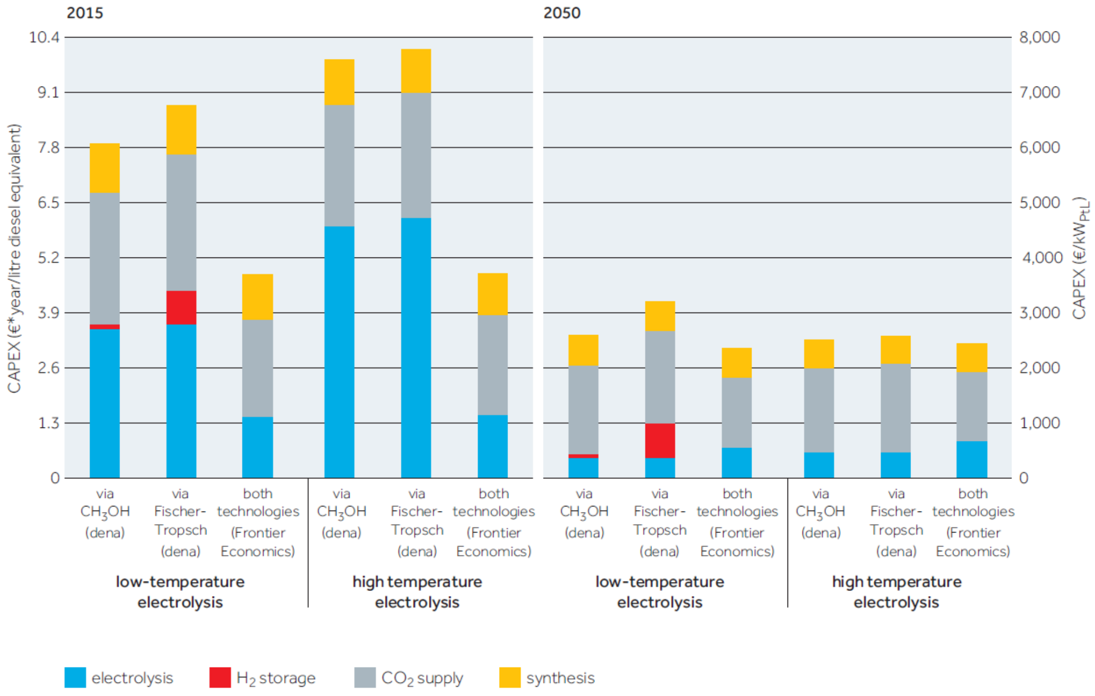
The largest Power-to-Methanol facility is the CRI's 'George Olah' Renewable Methanol Plant in Iceland, with a capacity of 4 000 tonnes per year. In addition, there are several pilot initiatives to produce methane and FT-fuels based on hydrogen from electrolysis at a scale of 1-5 MW electrolyzer capacity.

Oil companies has just started to look towards e-fuels. Today there is still no active commercial production of PtX technologies, but a significant growth is expected by 2030 to meet the Fit-for-55 targets for RFNBO production from REDII and ReFuelEU aviation targets (NESTE communication at the workshop "ReFuelEU Aviation – Ready for Take-Off?" organized by eFuel Alliance on Thursday 30 June, 2022).

2.3 Technology Cost – Present and Potential Future Trends

There is still no market behind e-fuels technologies, since they are collocated downstream to electrolyzer and carbon capture technologies. Cost of technology has been recently calculated by Concawe (Yugo and Soler, 2019), elaborating data from Frontier Economics (2018); LBST and DENA (2017).

Figure 6. CAPEX overview for RFNBO (Yugo and Soler, 2019)



Source: Yugo and Soler (Concawe), 2019

Main notes are:

- CO2 capture is based on DAC in both sources.
- 8,000 €/kWPtL (investment in 2015 according to DENA for a 70 Mt/year e-fuel plant) corresponds to ≈850 M€.
- Power generation CAPEX is not included in e-fuels plant investment. Depending on the level of deployment of e-fuels, additional power generation CAPEX could have an impact on electricity price.
- To express CAPEX in €*year/ litre of diesel equivalent, values considered are: e-diesel LHV: 44 MJ/kg and e-diesel density: 0.832 kg/litre
- Assumptions behind the calculation of the CAPEX regarding the inclusion of an RWGS reaction in a separate stage or in a co-electrolysis are not defined in the original sources.

2.4 Public R&I funding

E-fuels available technologies have been mainly funded by Horizon 2020 projects (data extracted from TIM/CORDIS), and the new Horizon Europe programme will dedicate specific calls to such technologies. Innovation Fund will also support the development of the sector, but mainly focusing on the upstream processes of H2 production and CO2 capture and utilization.

In the framework of Horizon 2020 there were 33 projects financed concerning RFNBO other than pure electrolytic hydrogen, all the projects are using innovative technologies and are RIAs, max TRL 5 at the end of the project, the total EU funding received by the projects totalled 114,429,066 Euro.

Table 8. Horizon 2020 projects on RFNBO.

Project Acronym	Project Title	Feedstock	Technology	End-product	EU Contribution
SUN-to-LIQUID	SUNlight-to-LIQUID: Integrated solar-thermochemical synthesis of liquid hydrocarbon fuels	Sunlight, CO2	CSP, FT	Synthetic jet fuel	4,450,618 €
FReSME	From residual gasses to methanol	CO2 from steel	Sorption-enhanced water–gas shift (SEWGS) technology + water electrolysis + catalytic conversion	methanol	11,406,725 €
eForFuel	Fuels from electricity: de novo metabolic conversion of electrochemically produced formate into hydrocarbons	CO2	Electrobioreactor	Propane and isobutene	4,117,207.50 €
KEROGREEN	Production of Sustainable aircraft grade Kerosene from water and air powered by Renewable Electricity, through the splitting of CO2, syngas formation and Fischer-Tropsch synthesis	CO2	plasma driven dissociation of air captured CO2, solid oxide membrane oxygen separation, FT	biojet	4,951,958.75 €
CO2Fokus	CO2 utilisation focused on market relevant dimethyl ether production, via 3D printed reactor - and solid oxide cell-based technologies	CO2	CO2 hydrogenation involving both catalytic chemical and electrochemical conversion	DME	3,994,950 €
eCOCO2	Direct electrocatalytic conversion of CO2 into chemical energy carriers in a co-ionic membrane reactor	CO2	electrochemical: multifunctional catalyst integrated in a co-ionic electrochemical cell	synthetic jet fuel	3,949,978.75 €
C2Fuel	Carbon Captured Fuel and Energy Carriers for an Intensified Steel Off-Gases based Electricity Generation in a Smarter Industrial Ecosystem	CO2 from steel	electrochemical, several routes	biodiesel, formic acid	3,999,840 €
COZMOS	Efficient CO2 conversion over multisite Zeolite-Metal nanocatalysts to fuels and OlefinS	CO2 from steel and refinery	electrochemical: multisite Zeolite-Metal nano catalysts	propane, propene	3,997,163.75 €
SELECTCO2	Selective Electrochemical Reduction of CO2 to High Value Chemicals	CO2	Selective Electrochemical Reduction of CO2 to High Value Chemicals	carbon monoxide, ethanol or ethylene	3,772,265 €
TAKE-OFF	Production of synthetic renewable aviation fuel from CO2 and H2	CO2	conversion of CO2 and H2 to SAF via ethylene as intermediate	Aviation fuel	4,998,788.25 €
ECOFUEL	Renewable Electricity-based, cyclic and economic production of Fuel	CO2	electrochemical conversion of CO2 to transport fuels via light alkenes	transport fuels	4,858,547.50 €
METHASOL	International cooperation for selective conversion of CO2 into METHAnol under SOLar light	CO2	CO2 reduction via artificial photosynthesis with	methanol	3,999,633.75 €

			corresponding photocatalysts		
NEFERTITI	Innovative photocatalysts integrated in flow photoreactor systems for direct CO2 and H2O conversion into solar fuels	CO2, H2O	photocatalysis for CO2 and H2O conversion to alcohols	Ethanol, longer chain alcohols	3,844,427.50 €
TELEGRAM	TOWARD EFFICIENT ELECTROCHEMICAL GREEN AMMONIA CYCLE	Air, water and renewable energy	Electrochemical ammonia synthesis and direct ammonia fuel cell	NH3 as energy carrier	3,468,021.25 €
LAURELIN	Selective CO2 conversion to renewable methanol through innovative heterogeneous catalyst systems optimized for advanced hydrogenation technologies (microwave, plasma and magnetic induction).	CO2 and H2	disruptive multifunctional catalyst systems for CO2 hydrogenation	Renewable methanol	4,448,838.75 €
4AIRCRAFT	Air Carbon Recycling for Aviation Fuel Technology	CO2/H2	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)	2,239,591.25 €
ORACLE	Novel routes and catalysts for synthesis of ammonia as alternative renewable fuel	N2/H2O	plasma-aided electrocatalytic as well as electrified thermal catalysis	NH3	2,846,078.75 €
UP-TO-ME	Unmanned-Power-to-Methanol-production	CO2 from biogas and H2O	3D printed methanol synthesis reactor	renewable methanol	2,997,500 €
E-TANDEM	Hybrid tandem catalytic conversion process towards higher oxygenate e-fuels	CO2 and H2O	electrocatalysis/solid thermocatalysis	oxygenate e-fuels	3,334,887 €
SOREC2	SOlar Energy to power CO2 REduction towards C2 chemicals for energy storage	CO2, H2O, sunlight	Photoelectrochemistry technology (PEC)	ethanol or ethylene	3,084,267 €
DARE2X	Decentralised Ammonia production from Renewable Energy utilising novel sorption-enhanced plasma-catalytic Power-to-X technology	Air and H2O	Water electrolysis + non-thermal plasma (sorption-enhaced plasma catalytic technology)	Ammonia	2,952,329
DESIRED	Direct co-processing of CO2 and water to sustainable multicarbon energy products in novel photocatalytic reactor	CO2, H2O, sunlight	e hybrid photo-electrocatalysts	C2+ solar fuels, methanol and methane	3,058,753 €
FreeHydroCells	Freestanding energy-to-Hydrogen fuel by water splitting using Earth-abundant materials in a novel, eco-friendly, sustainable and scalable photoelectrochemical Cell system	H2O, sunlight	solar-to-chemical energy conversion (photoelectrochemical system)	H2	3,748,301 €

MOF2H2	Metal Organic Frameworks for Hydrogen production by photocatalytic overall water splitting	H2O, sunlight	MOF-based photocatalysis for sun-driven H2 production	H2	2,998,723 €
ECO2fuel	Large-scale low-temperature electrochemical CO2 conversion to sustainable liquid fuels	CO2, water, electricity	Innovative electrocatalytic CO2 at 80 °C and 15 bar	Liquid fuels	16,620,616 €
FLEXnCONFU	FLExibilize combined cycle power plant through power-to-X solutions using non-CONventional FUels	CO2, 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	9,887,141.39 €
MefCO2	Synthesis of methanol from captured carbon dioxide using surplus electricity	CO2, water, electricity	methanol production with high CO2 concentration-streams and H2 as an input	Methanol	8,622,292.60 €
MegaSyn	Megawatt scale co-electrolysis as syngas generation for e-fuels synthesis	CO2, water, electricity	first demonstration of mega-watt scale syngas production by co-electrolysis (SOECs) to e-fuels.	Liquid fuels	4,999,449.39 €
SUN-to-LIQUID	SUNlight-to-LIQUID: Integrated solar-thermochemical synthesis of liquid hydrocarbon fuels	H2O, CO2 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	4,450,618 €
ELCOREL	Electrochemical Conversion of Renewable Electricity into Fuels and Chemicals	CO2, 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	3,616,665.12 €
HELENIC-REF	Hybrid Electric Energy Integrated Cluster concerning Renewable Fuels	CO2, water, heat	water thermolysis with innovative catalysts at temperatures below 300oC	Synthetic natural gas	2,578,386 €
Circlenergy	Production of renewable methanol from captured emissions and renewable energy sources, for its utilisation for clean fuel production and green consumer goods	CO2, water, electricity	Innovative methanol production through CO2 capture with ISCC certified technology	Methanol	1,827,380.63 €
COFLeaf	Fuel from sunlight: Covalent organic frameworks as integrated platforms for photocatalytic water splitting and CO2 reduction	H2O, CO2 and solar energy	Artificial photosynthesis with polymeric photocatalysts based on covalent organic frameworks	methane or methanol	1,497,125 €

Source: TIM/CORDIS elaboration

About the feedstock used for the RFNBO production, 26 projects have tested the CO2 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.

The European Innovation Council EIC in the framework of Horizon Programme opens funding opportunities worth over €1.7 billion in 2022 for breakthrough innovators to scale up and create new markets. The programme is divided in three sections:

- EIC Pathfinder - for multi-disciplinary research teams, worth €350 million, 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 RNFBIO activities could be financed under the umbrella of 2 challenges what are Carbon dioxide & nitrogen management and valorisation, mid-long term, systems-integrated energy storage.
- EIC Transition - funding to turn research results into innovation opportunities, worth €131 million. 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 for specific applications.
- EIC Accelerator - worth €1.16 billion, for start-ups and SMEs to develop and scale up high impact innovations with the potential to create new markets or disrupt existing ones. Almost €537 million is earmarked for breakthrough innovations for the technologies for Open Strategic Autonomy and technologies for 'Fit for 55'.

Finally, it worth mentioning that EC is funding mainly upstream processes foo CCS/CCU and hydrogen production by means of the Innovation Fund (now at the 3rd round of large-scale projects (European Commission (EC), 2022c). There 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 R&D funding

Some data and companies investing in such technologies have been already reported in 2.2. From the available information, today 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 on February 17th 2022, the successful completion of a €200 million investment round. 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).

2.6 Patenting trends

The patents of RFNBO may have large overlapping with the patents analysed in the "advanced biofuels" CETO report, since most processes are in common, or the same ones, 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. Same considerations can be done for novel patents deriving from hydrogen and carbon capture-related production.

2.7 Bibliometric trends/Level of scientific publications

Bibliometric trends have been calculated by using Scopus' database, and selecting some specific keywords for the topic of interest. The research focused on three different category: initial feedstock, fuel type/category, processes and conversion technologies. In order to gather information for bibliometric trends and level of scientific publications for RFNBO, we selected the following keywords:

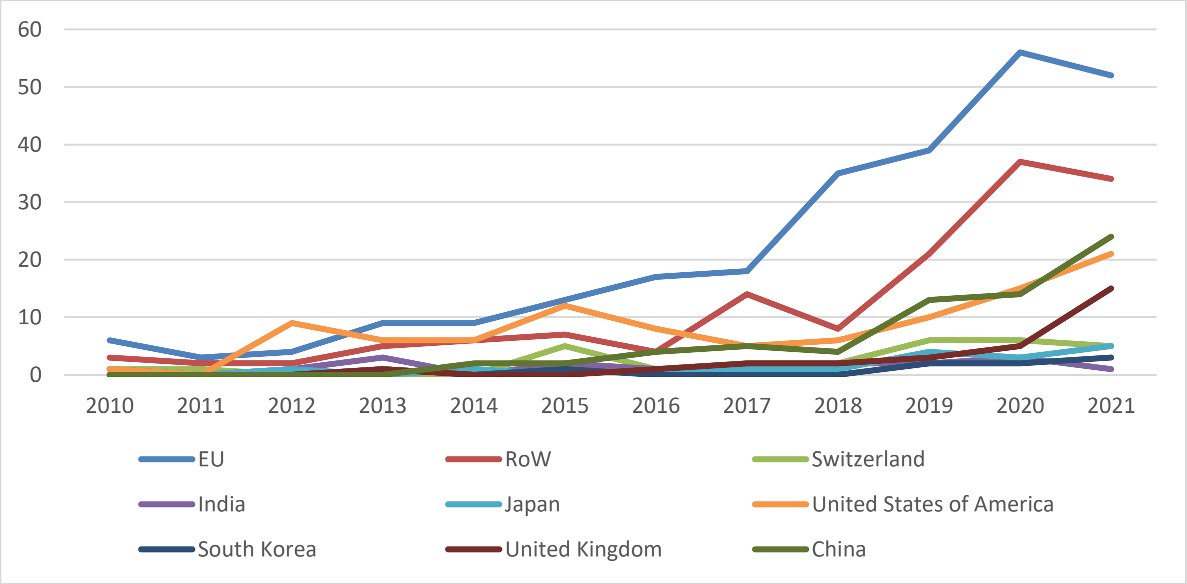
- Feedstock: renewable energy, green electricity, renewable electricity, renewables, green power, nitrogen, hydrogen, renewable hydrogen, CO2, carbon dioxide, flue gases, industrial gases, off gases.
- Fuel type and categories: drop-in, e-fuels, e-alcohol, e-diesel, e-gasoline, e-methane, hydrogen, e-jet, e-butanol, e-methanol, e-ethanol, e-ammonia, rfnbio.
- Processes and conversion technologies: gas shift, electrolysis, artificial photosynthesis, MEC, Haber Bosch, Fischer Tropsch, FT, methanation, reforming, direct air capture, DAC, gas upgrading, methanol synthesis, purification.

Time period is investigated from 2010 to 2022.

The output of the data provided have been summarized as:

i. Total articles in global regions:
According to the proposed categories, the total is: nr. 154 (feedstock); nr. 683 (fuel type); nr. 255 (processes).

Figure 7. Articles per year on RFNBO produced in global regions.

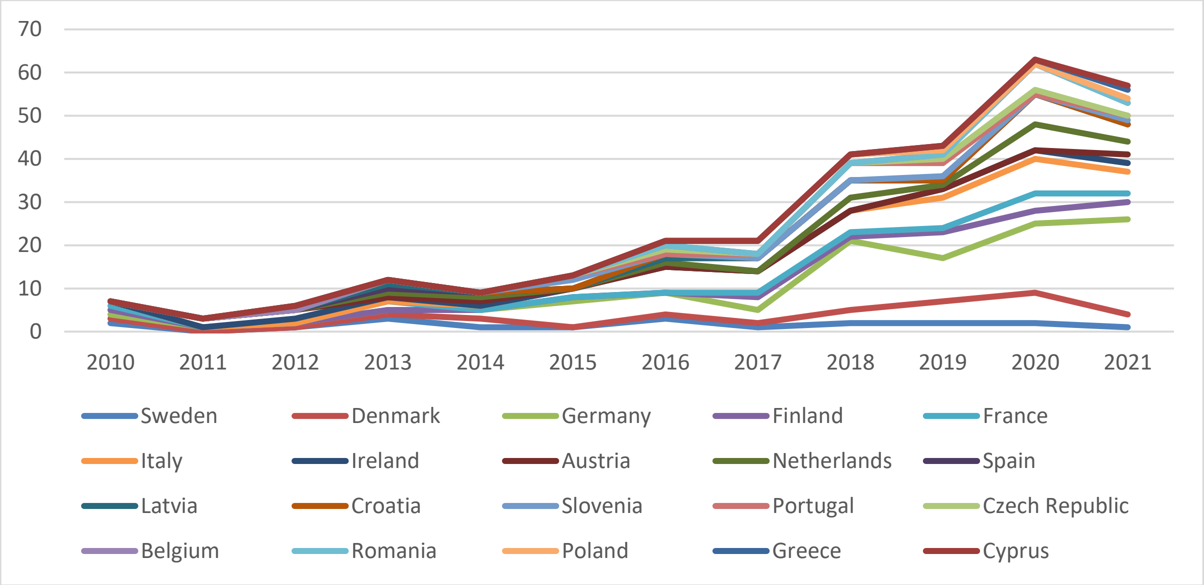


Source: JRC analysis

ii. Total articles in EU countries:

According to the proposed categories, the total is: nr. 74 (feedstock); nr. 300 (fuel type); nr. 119 (processes).

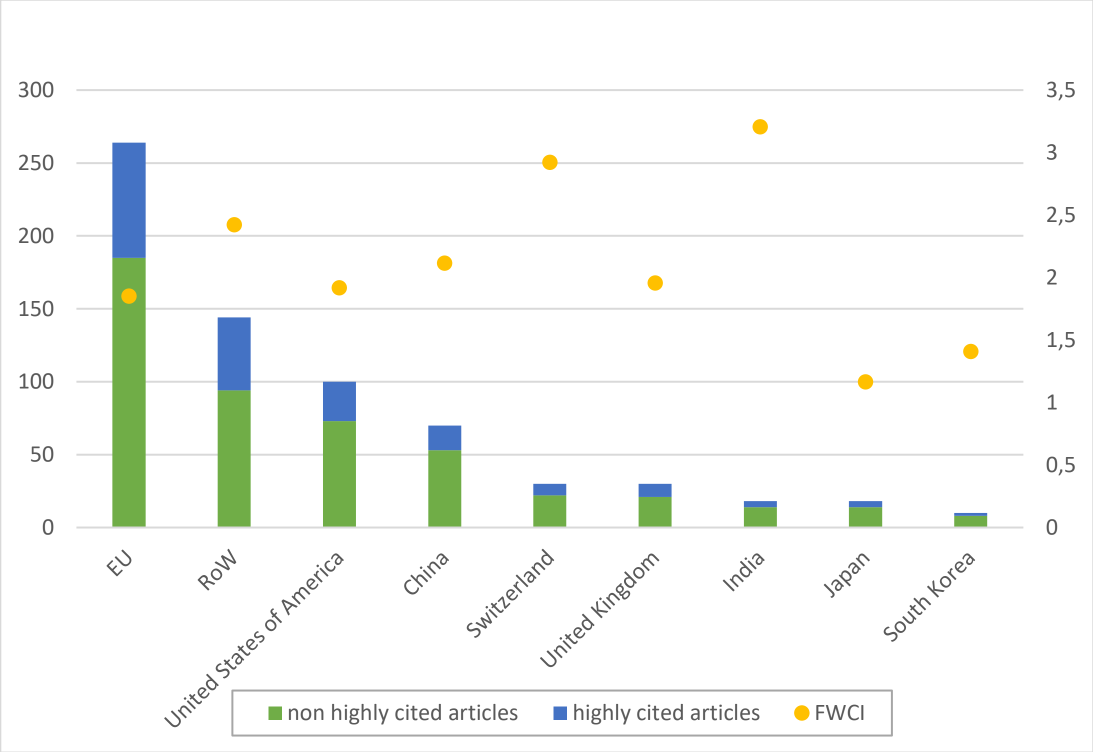
Figure 8. Articles per year on RFNBO produced in EU Countries.



Source: JRC analysis

iii. Number of High-cited articles and FWI per global region

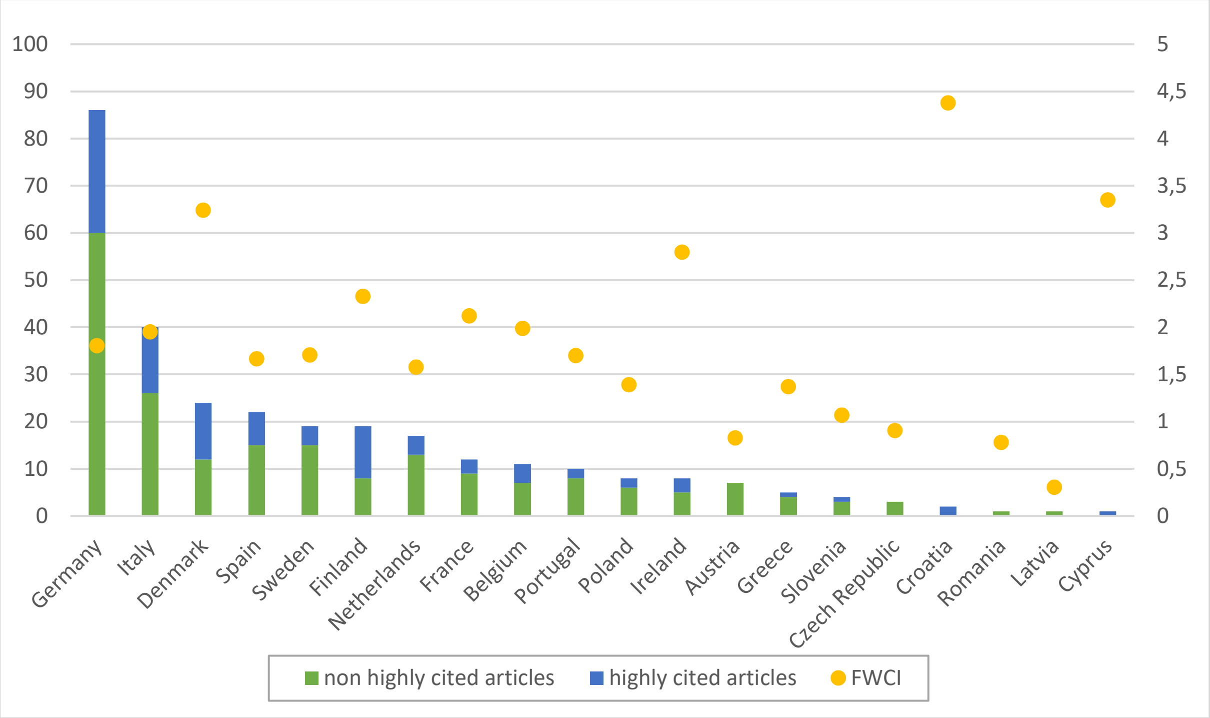
Figure 10. Number of High-cited articles and FWI per year on RFNBO produced in global regions.



Source: JRC analysis

iv. Number of High-cited articles and FWI per EU country

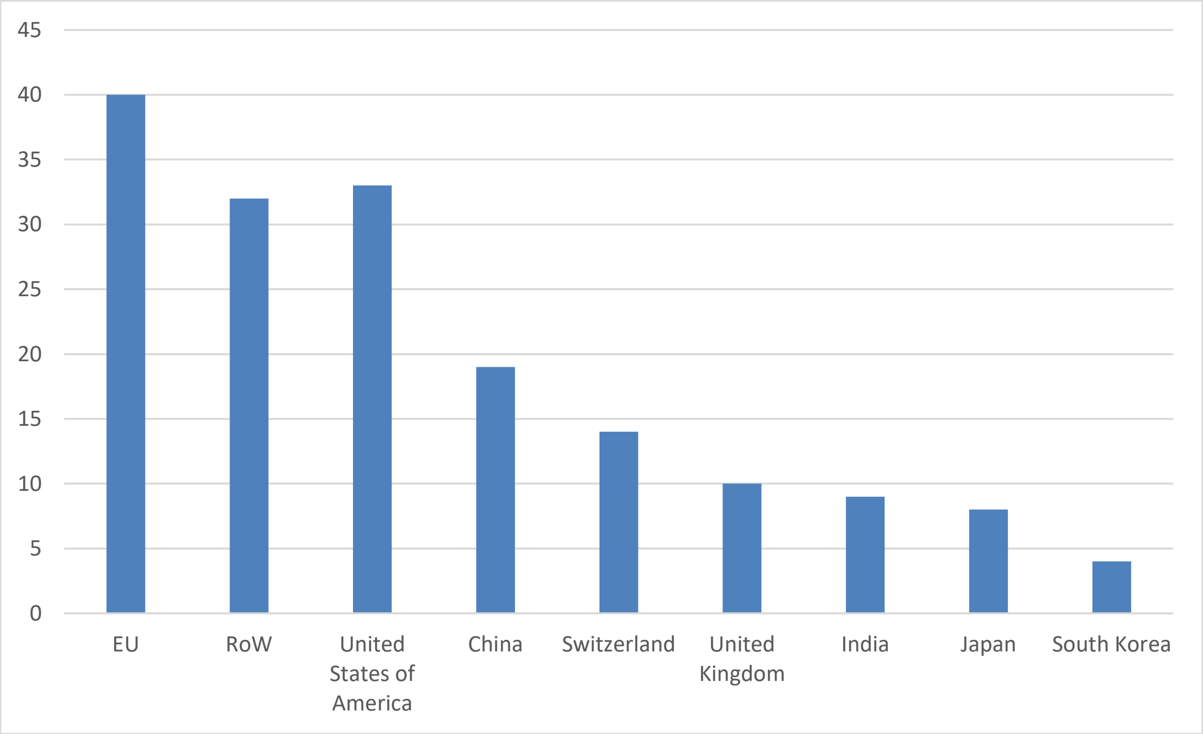
Figure 9. Number of High-cited articles and FWI per year on RFNBO produced in EU countries.



Source: JRC analysis

vii. h-index per global region

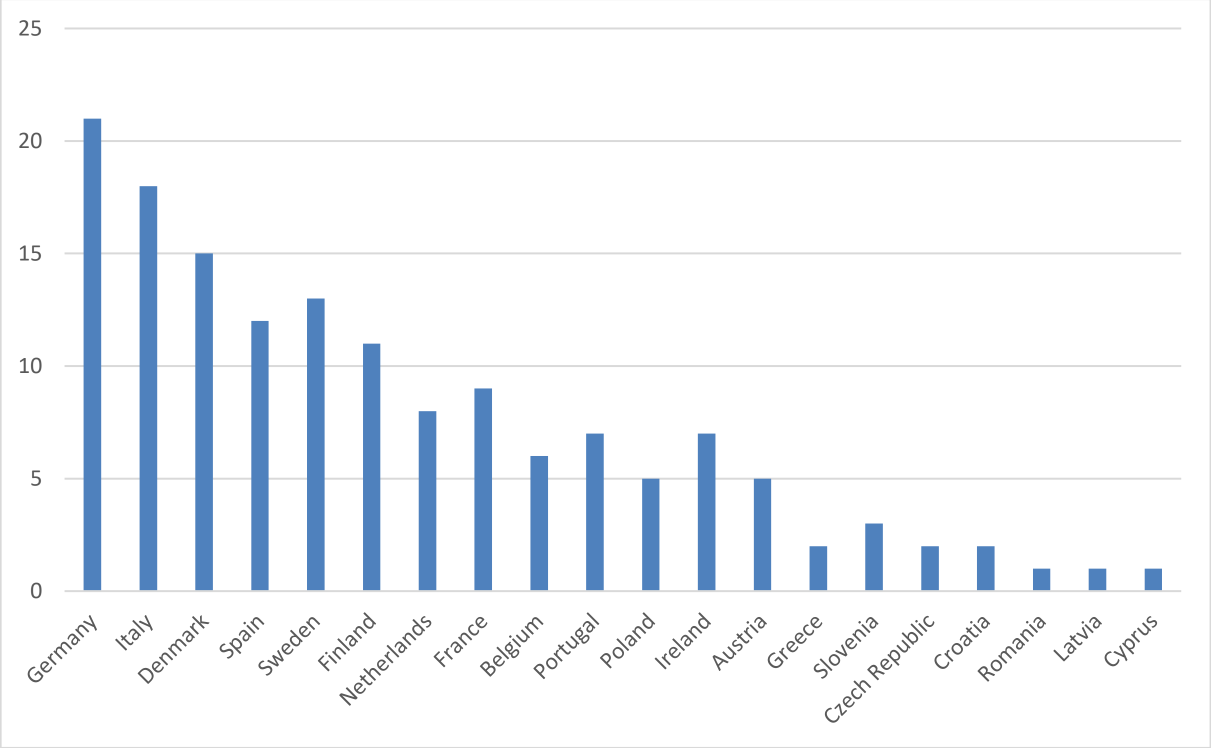
Figure 10. H-index of authors publishing articles on the topic of RFNBO in global regions.



Source: JRC analysis

viii. h-findex per EU member state

Figure 11. H-index of authors publishing articles on the topic of RFNBO in EU countries.



Source: JRC analysis

ix. collaborations at global level

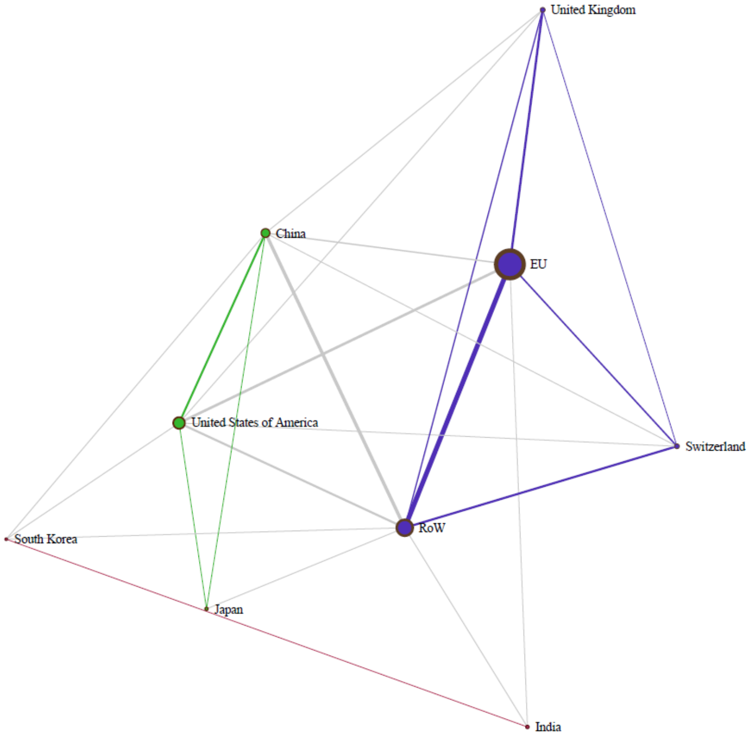
Data are reported as network graph, where:

(1) the size of the nodes represents the number of documents retrieved for a location;

(2) edges (lines between two nodes) are co-publications or co-occurrence in the same document(s), and edge thickness relative to number of documents in common;

(3) colours are communities of nodes that tend to appear more together than with the others.

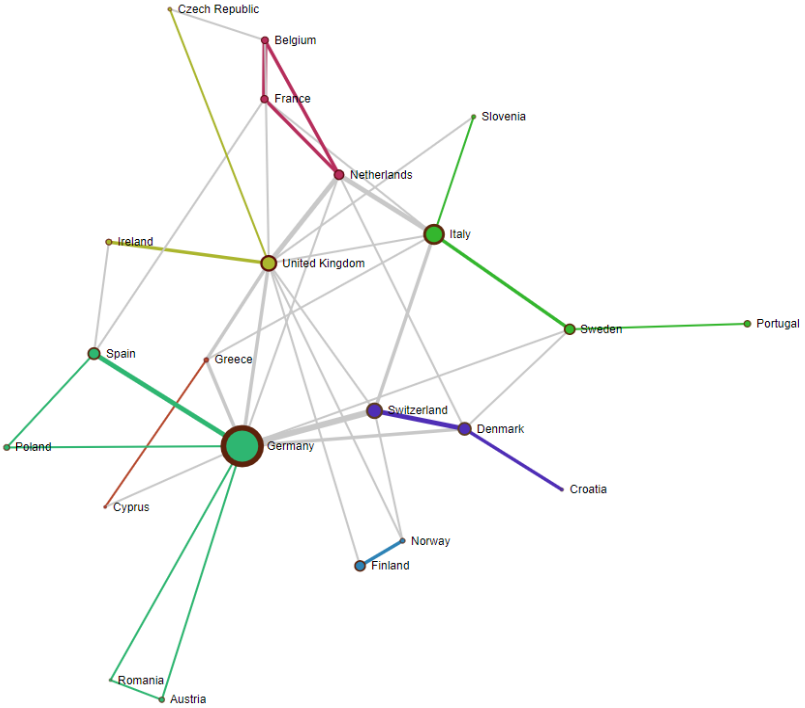
Figure 12. Interpretation of international collaboration in producing RFNBO articles



Source: JRC analysis

x. collaborations at European level (EU + EFTA + UK)

Figure 13. Interpretation of European collaboration in producing RFNBO articles



Source: JRC analysis

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

Data are missing here to extract specific R&I trends, since most technologies are still at early stage of development. However, it is expected a first, full assessment in the next years, since EU-funded H2020 projects already reached TRL 5+, while the upcoming Innovation Fund will provide funding for pre-commercial technologies that are entering deployment stage.

According to the current available data, most of the past and ongoing H2020 projects (investigated in 2.4) focus on innovative carbon capture solutions coupled with the synthesis process investigated in 2.1. Since hydrogen production is already a commercial technology, the challenge is to find solutions using less energy consumptions, innovative catalysts and incorporated processes doing multi-step reactions. It is expected a market uptake of the most promising solutions the time that hydrogen production will be consolidate at large scale.

3 Value chain Analysis

3.1 Environmental and Socio-economic Sustainability

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 (through a delegated act still under development). Captured and used CO2 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, the methodology also sets the guidelines for temporal and geographical correlations between the electricity production and the fuel production. The upcoming delegated act will also provide updated input data as the carbon intensity of raw materials, reagents, fossil-fuels, etc. **Sustainability criteria** RED II established the sustainability and greenhouse gas emissions saving criteria for biofuels, bioliquids and biomass fuels. The standard ISO 13065:2015 on Sustainability criteria for bioenergy provides a practical framework to facilitate the assessment of environmental, social and economic aspects and the evaluation and comparability of bioenergy production and products, supply chains and applications. ISO 13065 provides sustainability principles, criteria and measurable indicators to provide objective information for assessing sustainability. ISO 13065:2015 specifies principles, criteria and indicators for the bioenergy supply chain to facilitate assessment of environmental, social and economic aspects of sustainability.
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. The calculation 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. 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, CO2 from flue gas: 0.8 - 0.9 g CO2eq/MJ Syndiesel from renewable electricity via FT route, CO2 from flue gas: 0.76 - 0.78 g CO2eq/MJ Syndiesel from renewable electricity via FT route, CO2 from biogas upgrading: 0.8 - 0.8 g CO2eq/MJ Syndiesel from renewable electricity via FT route, CO2 from air via TSA: 0.8 - 0.8 g CO2eq/MJ MeOH from renewable electricity, CO2 from flue gas: 1.78 - 1.82 g CO2eq/MJ DME from renewable electricity, CO2 from flue gas: 1.7 - 1.7 g CO2eq/MJ SNG from renewable electricity and CO2 from flue gas: 1.7 - 3.0 g CO2eq/MJ SynLNG from renewable electricity, CO2 from biogas upgrading: 6.7 - 6.7 g CO2eq/MJ
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, CO2 from flue gas: 1.42 - 1.64 MJ/MJ Syndiesel from renewable electricity via FT route, CO2 from flue gas: 1.55 - 1.55 MJ/MJ Syndiesel from renewable electricity via FT route, CO2 from biogas upgrading: 1.13 - 1.13 MJ/MJ Syndiesel from renewable electricity via FT route, CO2 from air via TSA: 1.78 - 1.89 MJ/MJ MeOH from renewable electricity, CO2 from flue gas: 1.21 - 1.39 MJ/MJ DME from renewable electricity, CO2 from flue gas: 1.30 - 1.49 MJ/MJ SNG from renewable electricity and CO2 from flue gas: 0.95 - 1.09 MJ/MJ SynLNG from renewable electricity, CO2 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) m3 / MWh

Solar: 0.329 (0.042-0.893) m3 / MWh

Hydro: 17 (5-68) m3 / MWh

Geothermal flash technology: 0.05 (0.019 - 1.364) m3 / 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 electrolyzers (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 H2 (for SMR process) to 30.3 l/ kg H_2 for electrolysis.

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 (U.S. Energy Information Administration (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 (lead, cadmium, etc.), 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 had to develop a reliable methodology for setting the rules for counting electricity as renewable. The methodology has to ensure 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.

3.2 Role of EU Initiatives

Due to the absence of a real market behind RFNBO (except hydrogen) this section lists. some key-associations/initiatives aimed to promote the sector.

The eFuel Alliance is an interest group that promotes the industrial production of synthetic liquid fuels from renewable energy sources. It is open to all organizations includes companies, associations, consumer organizations as well as individuals

The Power-to-X Hub is implemented by the Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ) GmbH on behalf of the German Federal Ministry for Economic Affairs and Climate Action (BMWK). Financed by the International Climate Initiative (Internationale Klimaschutzinitiative, IKI), the PtX Hub is a contribution to the German National Hydrogen Strategy of 2020 and represents one of the four pillars of the BMUV's PtX action programme initiated in 2019.

The SUNRISE propose a sustainable alternative to the fossil-based, energy-intensive production of fuels and base chemicals, by sunlight, they aim to convert the raw materials such as carbon dioxide, water and nitrogen. The coordination and support action (CSA) has been successfully selected by the European Commission, funded with €1M for converting solar energy into fuels and commodity chemicals with high solar energy to product yield.

ENERGY-X will provide the disruptive new science and technology enabling efficient conversion of solar energy into chemical form and will combine this ambition with scale-up to industrially relevant scale by integrating with European industry. Three central chemical processes converting water, CO2 and base chemicals are the scientific targets. The approach is to aggregate fragmented knowledge and excellence throughout Europe creating the critical mass of scientific power to overcome the unresolved barriers for these chemical conversion technologies

ReFuelEU Aviation initiative. In the draft regulation, the Commission proposes obligations on fuel suppliers to distribute sustainable aviation fuels (SAF), with an increasing share of SAF (including synthetic aviation fuels, commonly known as e-fuels). The shares of SAF and synthetic aviation fuels are calculated on a volume basis; this differs from the accounting in the RED II, which is on an energy basis.

FuelEU Maritime regulation introduces GHG intensity reduction requirements for 2025 to 2050. Like ReFuel EU, FuelEU Maritime is a proposed regulation that would be directly binding on ship operators. It applies to all energy used on ships at EU ports of call and on voyages between EU ports of call, as well as half of the energy used on voyages between an EU port and a third country. In addition, the FuelEU Maritime proposal introduces an additional requirement that, starting in 2030, ships must use on-shore power for all energy needs when at berth.

Other associations are listed here below:

- https://sunriseaction.com/sunrise-initiative/
- https://www.fuelseurope.eu/
- https://www.energy-x.eu/about/
- https://www.concawe.eu/
- https://www.efuel-alliance.eu/
- https://www.methanol.org/
- https://ptx-hub.org/
- https://eranetbioenergy.net/
- https://www.fch.europa.eu/
- https://www.etipbioenergy.eu/
- https://www.dena.de/en/
- https://www.sunergy-initiative.eu/

4 EU position, resources efficiency and Global competitiveness

RFNBO production has no real market leader yet, since it relies on hydrogen and CCU/CCS market. So the material dependency EU for the production of renewable fuels of non-biological origin relates on the availability of some critical raw materials 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. (O'Connell *et al.*, 2019)

The most important recycling 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 that sets the legal rules and obligation for collecting and recycling PV panels in the EU, including setting minimum collection and recovery targets. Several PV module components are separated and recovered.

The production of renewable fuels of non-biological origin can play a key role on short-term for the decarbonization of the transport sector and at the same time for the increase of energy security and energy diversification. However, their production depends on the availability of renewable electricity or the excess of renewable electricity; the production of renewable fuels of non-biological origin can act as energy storage. Renewable fuels of non-biological origin provide short term solutions for all transport sectors, including the ones for which there are no other alternatives (aviation, maritime transport). Renewable fuels of non-biological origin allow the use of existing infrastructure (transport and distribution, storage and engines), while other solutions, such as the electrification of transport require long time to develop (charging points, urban grids, etc.). In addition, the production of renewable fuels of non-biological origin requires long time a huge increase of the low carbon electricity supply capacity. In particular, renewable fuels of non-biological origin can contribute on short term to the goals of the REPowerEU initiative that aims at reducing the EU dependence on imported fossil fuels and to the diversification of energy supply. The current high fuel prices can be an opportunity for renewable fuels of non-biological origin to achieve economic viability. The EU has a leading role on biofuel production today at global level (as shown in Chapter 2) and further development of the fuels can ensure EU technological leadership on new emerging technologies since their strict correlation with the one producing both RFNBOs and RCFs. The EU know-how on the sector may generate synergies with other countries producing renewable electricity technologies and hydrogen production, in particular during the transition period towards the transports electrification. A central role of EU in the hydrogen economy can also further promote the sector in the short-term period.

5 Conclusions

Renewable fuels of non-biological origin are synthetic, gaseous or liquid fuels derived from renewable energy and renewable hydrogen, CO2 or N2. They can play an important role for ensuring security of energy supply and the decarbonization of means of transport that are difficult to electrify (maritime, aviation) but also over the next decade in road transport. The production of renewable fuels of non-biological origin will depend on the availability of excess renewable electricity and its price. RFNBO production can be integrated within existing value chains producing H2 and recovering CO2 and N2, hence the development of such upstream processes can easily create expanded value chains, producing drop-in hydrocarbon fuels, alcohols or ammonia for the immediate market distribution. The availability of economical CO2 (concentrated in flue gases or from industrial process or from direct air capture) or N2, as well as the green hydrogen supply, are crucial to reduce the production costs. The present investigation showed that RFNBO conversion pathways are at early TRLs, and still need technology improvements, demonstration, de-risking and commercial validation in the future. So it is essential to provide adequate incentives for the support of the development of renewable fuels of non-biological origin for specific transport sectors (e.g. aviation, shipping and high duty vehicles as trucks) which are hard to electrify.

Summarizing, this report identified the major challenges as:

- availability of excess of renewable electricity, notwithstanding the expected overall higher demand due to the electrification of the economy;
- cost of renewable electricity and competition of various uses, e.g. for the use of hydrogen either as fuel, or for industrial processes, steel and fertiliser production;
- high costs of renewable fuels of non-biological origin in relation to conventional fossil fuels;
- low net energy conversion ratio of the renewable fuels of non-biological origin in comparison to direct use of electricity or hydrogen and energy consumption for providing (capture) CO2 or N2;
- the need for newly built renewable electricity plants dedicated for the production of RFNBO vis-a-vis the operation only when excess renewable electricity is available (part time) while cost-effectiveness requires 24h operation;
- the level of GHG emissions savings is strictly bounded to the energy sources used along a specific RFNBO supply chain and is only ensured if the electricity generation capacity is additional to other uses.

On the other hand, the opportunities offered by RFNBO are:

- the use of renewable electricity for the grid when demand is low, i.e. using such technologies to store energy and to decrease possible renewable electricity curtailment
- the use of the existing fuel infrastructures, since liquid and gaseous RFNBO are fully drop-in fuel (with the same composition of their fossil fuels counterpart);
- the possibility to integrate bio-based value chains with e-fuels production based on carbon from recycling CO2 and combining hydrogen production, to use the same technologies (e.g. Fischer-Tropsch reactors) to produce either advanced biofuels, or RFNBO (this also extend the conversion plant operation time);
- to store energy as liquid and gaseous fuels (i.e. seasonal long-term storage) instead in the form of hydrogen in places where renewables are abundant, but hydrogen storage would be challenging (e.g. deserts, off-shore infrastructures, …);
- promotion of new CCU technologies and solutions;
- to be used in fuel cells as energy carriers for hydrogen making easy to distribute, store and use hydrogen for energy generation and power propulsion with drop-in solutions.

Main indicators identified are:

- availability of low cost renewable electricity
- cost of renewable electricity and price of electricity in the energy stock market

- availability of concentrated CO2 (flue gases, industry)
- availability of renewable nitrogen
- mitigation of CO2 emissions, NOx emissions and N2O emissions
- contribution to reduce the fossil-fuels share
- contribution to decreasing imports in terms of €
- energy conversion efficiency from resource to final use
- costs of renewable fuels of non-biological origin relative to market prices
- cost of technologies deployed.

The report also identified key EU legislative proposals and strategies of interest to develop RFNBO, as:

- RePower EU
- Refuel EU Aviation
- Fuel EU Maritime
- EU Hydrogen Strategy
- RED II recast
- EU Energy System Integration Strategy

Finally, the current EU funding programmes which involve RFNBO are:

- Horizon Europe
- Horizon 2020 (still running projects)
- Innovation Fund
- Connecting Europe Facility
- INVESTEU
- Catalyst EU partnership

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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
LNG	Liquefied Natural Gas
MCEC/MEC	Molten Carbonate Electrolyzer Cells
MEC	Microbial Electrolysis Cell
OME	OxyMethylene Ether
PEMEL/PMEL	Polymer Electrolyte Membrane Electrolysis
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
WEEE	Waste Electrical and Electronic Equipment Directive
WTT	Well-To-Tank

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