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RENEWABLE FUELS OF NON-BIOLOGICAL ORIGIN IN THE EUROPEAN UNION

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

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Contents

Abstract

This report investigates the status and trend of Renewable Fuels of Non-Biological Origin (RFNBO), except hydrogen, which are needed to cover part of the EU's demand for renewable fuels in the coming years. Most of the conversion technologies investigated have been already demonstrated at small-scale, and the current EU legislative framework under the recast of the Renewable Energy Directive (EU) 2018/2001 (Fit-for-55 package) set specific targets for their use. As first, well-established solid hydrogen supply chains are needed, together with carbon capture technologies for Carbon Capture and Use (CCU). Fuels that may be produced starting from H_2 and CO_2 or N_2 are hydrocarbons, alcohols and ammonia. The use of RFNBO is crucial in the transition period towards the electrification for their ability to be used in the existing fuel infrastructures, so many funding programmes is today available. Moreover, EU leads the sector in terms of patents, companies and demonstration activities. Finally, the report considers the major challenges and the opportunities for a rapid market uptake of such fuels.

Foreword on the Clean Energy Technology Observatory

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

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

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

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

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

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

More details are available on the CETO web pages

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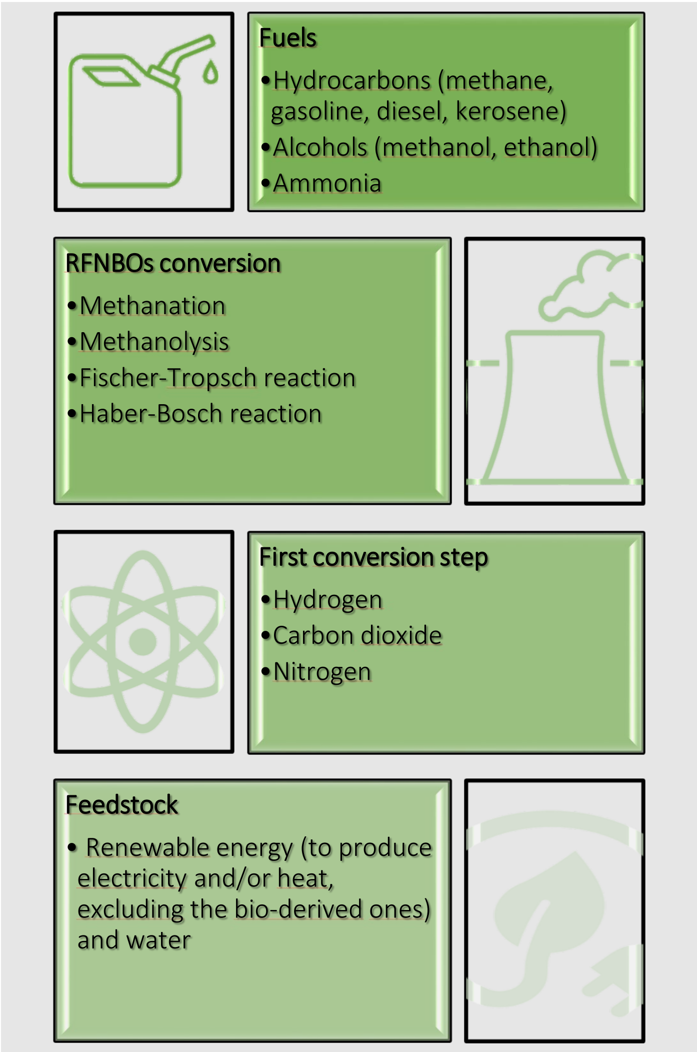
Executive Summary

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

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



Source: *JRC analysis*

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

RFNBO consisting in hydrocarbons produced from synthesis processes are mainly paraffin, hence drop-in fuels which can already be used in the existing fuel infrastructures and vehicles. An extensive technology review shows that such technologies would be ready for the market uptake, but the upstream processes of H_2 production and CO_2 capture still need to be developed at large scale for commercial production (so the overall current TRL of the whole conversion pathways is about 6-7, i.e. pilot scale projects). Some conversion technologies as Fischer-Tropsch synthesis, Haber-Bosch process and others are at high TRL as they were developed over the years to operate with fossil-based feedstock, and can relatively easily be retrofitted to process renewable feedstock. 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 for classifying a fuel as RFNBO, is if its production and sustainability criteria comply with the 70% GHG emissions saving threshold as specified by the delegated act of the Renewable Energy Directive EU (2018/2001, also called RED II), which provides the methodology for calculating life-cycle greenhouse gas emissions. In the case that the electricity used for the feedstock is fully renewable (as defined in the parallel delegated act on the eligibility of hydrogen, hydrogen-based fuels or other energy carriers as RFNBOs), the carbon footprint of electricity comes with no carbon emissions, and hence the carbon intensity is zero.

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

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

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

The analysis on patenting trend is included within the CETO' report on "advanced biofuels", since most of synthesis process used for RFNBOs production coincide with processes converting bio-based molecules into fuels, while the production of Hydrogen is investigated in CETO Water Electrolysis and *Hydrogen*. The present classification of CETO reports is based on fuel type or technology deployed, so there is no differentiation based on feedstock or energy origin, making some analyses outside the boundaries of each report.

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

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

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

Strengths:	**Weaknesses:**
• several technologies (HB and FT) are already available and can be easily retrofitted to work with renewable hydrogen; • contribution to energy diversification and energy security; • use of existing fuel infrastructure with no additional investment needed;	• large additional renewable electricity capacity and generation needed and robust power connections and grid infrastructure; • several technologies are not yet demonstrated for the unavailability of hydrogen/CO_2 supply; • high conversion and efficiency losses associated with the production and use of

• 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;	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 • variable renewable electricity supply (solar and wind) that make intermittent production of electricity necessitating other sources; • dependency on upstream hydrogen production and carbon capture solutions, that are still limited.
Opportunities: • better use of solar and wind electricity production • energy storage solution/grid balancing and way to use the surplus of renewable electricity; • contribution to energy diversification and energy security; • contribution to decarbonisation of hard to electrify sectors and 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.	**Threats:** • lack of stable policy framework, lack of long-term policy perspectives and change in policy directions; • 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-enough hydrogen; • Risk of certifying renewability even if not generated with renewable energy electricity;

Source: *JRC analysis*

1 Introduction

1.1 Scope and context

Renewable fuels of non-biological origin (RFNBO) have been defined for the first time in the recast Renewable Energy Directive (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 CO_2 deriving from fossil sources such as flue gases, from DAC technologies and from other non-renewable and natural sources, or N_2 captured from air. Such category includes synthetic hydrocarbons-, alcohols- and ammonia-based fuels. Together with advanced biofuels, RFNBOs consist in a viable alternative to fossil liquids fuels for the market being fully drop-in (Panoutsou *et al.*, 2021), so they do not require dedicated infrastructures for distribution and storage (Yugo and Soler, 2019). However, today there are still no standards as regards their composition and blending limits into commercial fuel blend.

The present report describes and analyses the conversion pathways producing RFNBO starting from the main process inputs, i.e. hydrogen and CO_2 (captured by CCU), whose conversion pathways will be reported in other CETO reports.

1.2 EU legislative framework

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 RFNBOs.

On 13th February 2023 the Commission has adopted two Delegated Acts (DAs), as required under Article 27(3) of the Renewable Energy Directive (2018/2001), defining the rules to produce RFNBO. Such documents integrated EU regulatory framework for hydrogen and set a new framework to develop supporting schemes and State aids to develop the hydrogen sector.

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

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

The revision of the Renewable Energy Directive raises the EU's binding renewable target for 2030 to a minimum of 42.5%, up from the current 32% target and almost doubling the existing share of renewable energy in the EU. Negotiators also agreed that the EU would aim to reach 45% of renewables by 2030. The European Parliament approved the 42.5% target on 12 September 2023.

On transport, the provisional agreement gives the possibility for Member States to choose between:

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

The recast of REDII sets a binding combined sub-target of 5.5% for advanced biofuels (generally derived from non-food-based feedstock) and renewable fuels of non-biological origin (mostly renewable hydrogen and hydrogen-based synthetic fuels) in the share of renewable energies supplied to the transport sector.

Within this target, there is a minimum requirement of 1% of RFNBOs in the share of renewable energies supplied to the transport sector in 2030.

The provisional agreement provides that industry would increase their use of renewable energy annually by 1.6%. They agreed that 42% of the hydrogen used in industry should come from renewable fuels of non-biological origin (RFNBOs) by 2030 and 60% by 2035.

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

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

RFNBO and advanced biofuels can also contribute to the targets imposed by ReFuel EU (The European Parliament, 2021a) and FuelEU Maritime (The European Parliament, 2021b), which set a target of 63% of SAFs (in terms of energy) and -75% as GHGs reduction intensity (compared to the fossil fuels supply) respectively, by 2050.

Finally, it is worth mentioning that on 28th March, the EU adopted the Regulation (EU) 2023/851 for CO_2 emission performance standards for cars and vans which potentially depicted a new scenario for RFNBO and advanced biofuels beyond 2035, making them a decarbonisation solution only for those sectors where electrification is challenging, as aviation and maritime.

1.3 Methodology and Data Sources

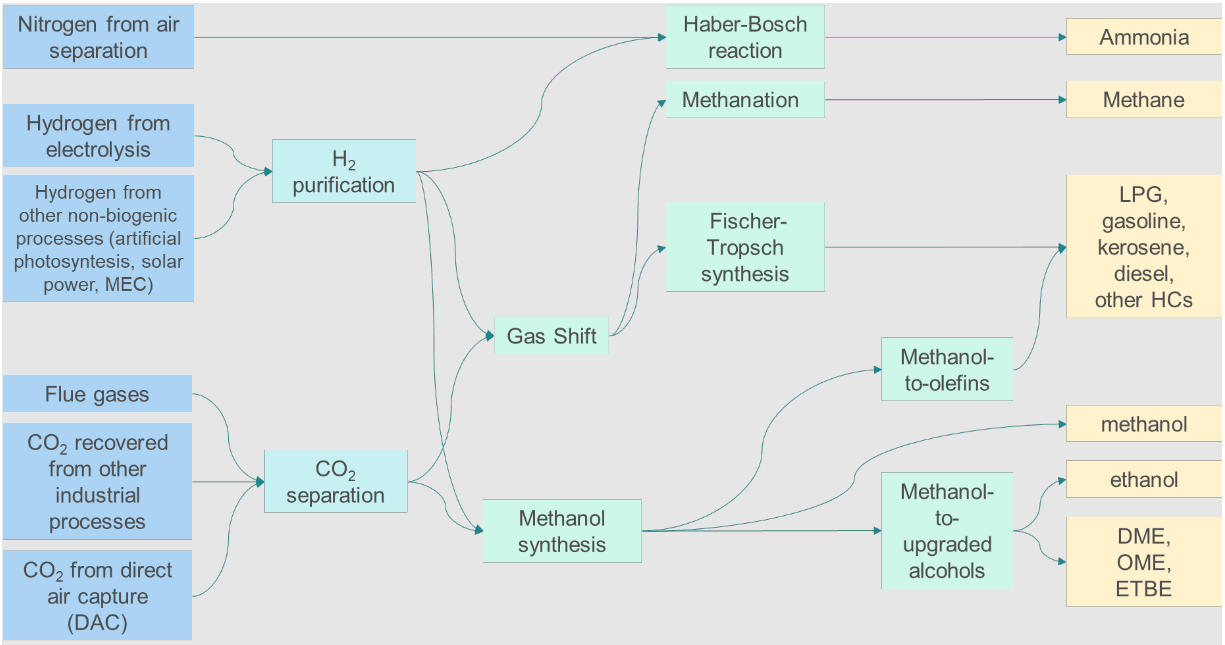
This document summarizes the state-of-the-art, ongoing and future initiatives that regard RFNBO production, using hydrogen from renewable energy and non-biological CO_2 (or N_2) captured from industrial off-gases, flue gases and DAC technologies. Its main information sources consist in scientific publications, knowledge gained through the JRC's own work on this topic, material from international institutions (IEA, IRENA, etc.), and also related previous CETO and 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 (H_2020) programme and the new Horizon Europe 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. Full value chains analyses cannot be performed so far, since RFNBO market penetration is still far from the commercial activities. However, some highlights from recent studies providing forecasts towards 2030 and beyond, have been reported and discussed.

2 Technology status and development trends

2.1 Technology readiness level

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 CO_2 or N_2). According to their definition, RFNBO can also derive from hydrogen produced from other non-biological sources (still at very low TRL) as solar power, microbial electrolysis cells or artificial photosynthesis. On the other hand, the CO_2 recovery is also referred to Carbon Capture and Utilization (CCU) value chains, meaning that the recovered carbon is incorporated into either a fuel, or for other scopes. The present report focuses on the second stage of conversion, assuming both hydrogen and CO_2/N_2 as feedstock for the production of hydrocarbons, ammonia or alcohol fuels. The production of carbon-based fuels starts with a gas shift reaction followed by other specific reactions depending on the fuels required. In the case of production of methanol, CO_2 and H_2 can be reacted directly through the methanol synthesis, while for other products such as methane and Fischer-Tropsch (FT) hydrocarbons, a reverse water gas shift reaction is needed to convert CO_2 to CO, prior to the catalytic synthesis process where the products are formed, see investigated pathways in Figure 2.

Figure 2. Elaboration of the investigated pathways.



Source: JRC Elaboration

The TRL evaluation considers the processing steps afterwards the hydrogen production and CCUS processes (in which hydrogen assumes the role of intermediate energy carrier). According to recent assessment of IEA (AMF Annex 58 and IEA Bioenergy Task 41, 2020), 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.

2.1.1.1 Electrolysis

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

Electrolysers’ installations are going to be built above some MW in capacity, even considering that the current hydrogen demand is still limited. However, the increasing production of renewable electricity through wind and solar power allowed larger electrolysers capacity > 100 MW. According to IEA (IEA, 2021b).

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

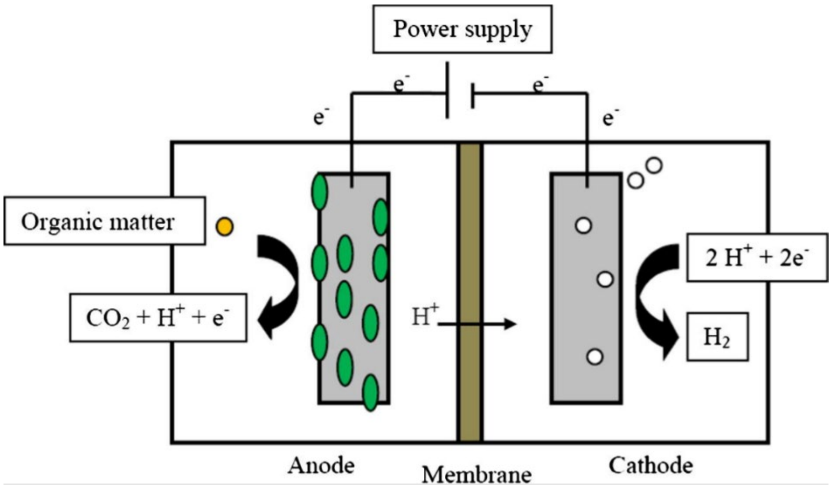
2.1.1.3 Solar power derived hydrogen

The thermolysis process can be used efficiently to produce hydrogen using solar−thermal energy. A complete analysis of this topic is provided in the CETO report on solar fuels (Taylor, 2022). 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 CO_2, electrons and protons. The bacteria transfer the electrons to the anode, and the protons are released to the solution. Therefore, the electrons flow through a wire to a cathode and combine with the free protons in solution. In order to produce hydrogen at the cathode due to protons and electrons exchange, MEC reactors require an externally supplied voltage ($\geqslant$0.2 V) under a biologically assisted condition (pH = 7, Temperature about 30 °C, and 101320 Pa) (Boretti, 2021). This is done by the input of a voltage via a power supply. However, MECs require relatively low energy input (0.2–0.8 V) compared to typical water electrolysis (1.23–1.8 V). Schematic diagram of two-chamber MEC is reported here below.

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



Source: Kadier er et al, 2014

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

2.1.2 Carbon capture

The production of e-fuels requires CO_2 (except for ammonia), which can be obtained from various sources such as combustion gases (from both bio- or fossil- fuels), industrial processes (e.g. off gases), biogenic CO_2, and CO_2 captured directly from the air (Madejski et al., 2022). Carbon capture and utilisation (CCU) is considered an important CO_2 mitigation strategy to support and complement carbon capture and storage (CCS) objectives for the abatement and sequestration of CO_2. It represents various pathways that use CO_2 as a feedstock in process systems or otherwise for the generation of value-added commodities (Dange et al., 2021). The main technologies include post-combustion CO_2 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. More detailed analysis on this topic can be found on CETO CCUS report (Kapeteki, 2022)

Table 2. TRL analysis for adsorption, absorption, membrane separation and chemical capture technologies (IEA, 2022; Vaz, Rodrigues de Souza and Lobo Baeta, 2022).

Category	TRL	Notes
Adsorption	7-9	Mainly applied in natural gas and ethanol processes, this technology is responsible for CO_2 capturing in large plants and has great application perspectives. Its advances are mainly due to the simple operation attributed to it.
Absorption	9	It is the most advanced technology. This is due to the research time and consequently its application in small and large power generation, fuel transformation and industrial production plants.
Membrane separation	6-9	Relatively new but promising technology and considered to be the most effective separation technology among the existing ones. Its advances depend on the type of gas emission source and its application. Currently,

		part of its applications is in the demonstration phase, and another part in the development phase, few are commercially available (from gas processing technology).
Chemical capture	3-6	The capture involving chemical reactions, are presented in that TRL for its time and research intensity. As it is relatively new, its level is justified by the need for large pilot scale tests.

Source: IEA, 2022; Vas et al, 2022

2.1.3 Fuel synthesis: Power-to-Gas

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

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

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

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

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

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

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

	supposed to be supplied by an internal turbine)
Net CO_2 utilization (t/t_{fuel})	3

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

In late 2022, (Concawe, 2022) proposed a full techno-economic assessment of e-fuels, including synthetic methane, which the most relevant data are reported in Table 4.

Table 4. Technical parameters methanation using renewable Hydrogen

<table>
<tr><td colspan="5">Cradle-to-grave GHG emission</td></tr>
<tr><td>Years</td><td>2020</td><td>2030</td><td colspan="2">2050</td></tr>
<tr><td>gCO_2eq/MJ</td><td>11.9</td><td>10.9</td><td colspan="2">11.1</td></tr>
<tr><td colspan="5">Production input and output</td></tr>
<tr><td>Input</td><td>H_2</td><td>CO_2</td><td>Power</td><td>Heat</td></tr>
<tr><td>Amount</td><td>0.50 kg/kg fuel</td><td>Up to 3.00 kg/kg fuel</td><td>1.15 MJ/kg fuel</td><td>10.8 MJ/kg fuel</td></tr>
<tr><td>Output</td><td>Methane</td><td>Water</td><td colspan="2">CO_2 (emission)</td></tr>
<tr><td>Amount</td><td>1.00 kg</td><td>2.25 kg/kg fuel</td><td colspan="2">0.25 kg/kg fuel</td></tr>
<tr><td colspan="5">Synthesis production plant input and output</td></tr>
<tr><td colspan="5">Note: Methanation plant with a capacity of 1368 MW based on the LHV</td></tr>
<tr><td>Input</td><td>H_2</td><td>CO_2</td><td colspan="2">Electricity</td></tr>
<tr><td>Amount</td><td>1.198 MJ/MJCH4, LHV</td><td>0.06 MJ/MJCH4, LHV</td><td colspan="2">0.0229 MJ/MJCH4, LHV</td></tr>
<tr><td>Output</td><td colspan="2">Methane</td><td colspan="2">Heat (250-300°C)</td></tr>
<tr><td>Amount</td><td colspan="2">1.000 MJ</td><td colspan="2">0.0720 MJ/MJCH4, LHV</td></tr>
</table>

Source: Concawe 2022

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 CO_2 is derived from biogas upgrading or CO_2 in biogas streams via direct methanation using the CO_2 fraction from biogas. One plant uses direct air capture (DAC) of CO_2.

2.1.4 Fuel synthesis: Power-to-Liquid

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

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

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

Ammonia may 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 CO_2 emissions are produced as a result of the HB process, and zero-emission ammonia production is possible if the used electricity is essentially carbon-free. Steam for the electrolyser is generated by recovering heat from the ammonia synthesis to boost the overall integrated-process efficiency. Higher efficiency, combined with a prospect of lower CAPEX, could improve the economics of the process, though the technology is presently in the development phase and is therefore limited to small scales.

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

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

Source: (Ram et al., 2020)

In late 2022, (Concawe, 2022) proposed a full techno-economic assessment of e-fuels, including synthetic ammonia, which the most relevant data are reported in Table 6.

Table 6. Technical parameters e-ammonia production

Production input and output			
Input	H_2	N_2	Power
Amount	0.178 kg/kg NH3	0.822 kg/kg NH3	2.16 MJ/kg NH3
Output	Ammonia		Heat
Amount	1.00 kg		2.18 MJ/kg NH3
Craddle-to-grave GHG emission			
Years	2020	2030	2050
gCO_2eq/MJ	11.6	11.4	9.3

Source: *Concawe 2022*

2.1.4.2 e-methanol via methanolysis

Methanol is the simplest alcohol (CH3OH), liquid at ambient temperature and atmospheric pressure, but with a high volatility. Differently than ethanol, it is dangerous for human health even in small quantities. 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 CO_2, without requirement of reverse water gas shift (as for methane), according to the methanolysis as follows:

$CO_2 + 3\ H_2 \Rightarrow CH3\ OH + H_2O$

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

Summarizing, 2 litres of methanol contain about the same energy contained in one litre of gasoline, making its use as fuel more challenging than gasoline or diesel. Its density corresponds to the density of most other liquid fuels, but with a lower boiling point at 64.7°C (at atmospheric pressure conditions). 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 EN_228 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 (ISO, 2023). However, the low density and the poor miscibility into the commercial fuel blends, make its use more suitable for other applications. For this scope, e-fuels technologies should not be intended only to produce e-fuels, but also chemicals that could be of high interest for industry. For instance, 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 H_2 and CO_2 supply and economy (Weindorf et al., 2019; Yugo and Soler, 2019).

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

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

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

In late 2022, (Concawe, 2022) proposed a full techno-economic assessment of e-fuels, including e-methanol, which the most relevant data are reported in Table 8.

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

Production input and output				
Input	H_2	CO_2	Power	Heat
Amount	0.193 kg/kg fuel	1.40 kg/kg fuel	1.07 MJ/kg fuel	1.72 MJ/kg fuel
Output	Methanol		Water	
Amount	1.00 kg		0.59 kg/kg fuel	
Synthesis production plant input and output				
Note: methanol synthesis plant including compressors and methanol purification with a capacity of 1368 MW based on the LHV				
Input	H_2	CO_2	Electricity	

Amount	1.161 MJ/MJCH3OH, LHV	0.0702 MJ/MJCH3OH, LHV	0.0499 MJ/MJCH3IH, LHV	
Output	Methanol		Heat (250-300°C)	
Amount	1.000 MJ		0.0720 MJ/MJCH3OH, LHV	
Craddle-to-grave GHG emission				
Years	2020	2030	2050	
gCO_2eq/MJ	10.8	10.6	11.6	

Source: Concawe 2022

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 H_2 to be processed into the FT-reactors. Generally, such gases must be cleaned by tars and other contaminants to produce a high purity syngas to run the desired reactions as follows (Basu, 2018):

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

Olefins: $nCO + (2n)H_2 \rightleftharpoons C_nH_{2n} + nH_2O$

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

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

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

According to CONCAWE report (Concawe, 2022) 11.7 g of hydrogen, 88 g of CO_2 and 0.0441 MJ of electricity are needed to produce 23.2 g of e-Diesel (i.e. 1 MJ) and 0.2139 MJ of heat.

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

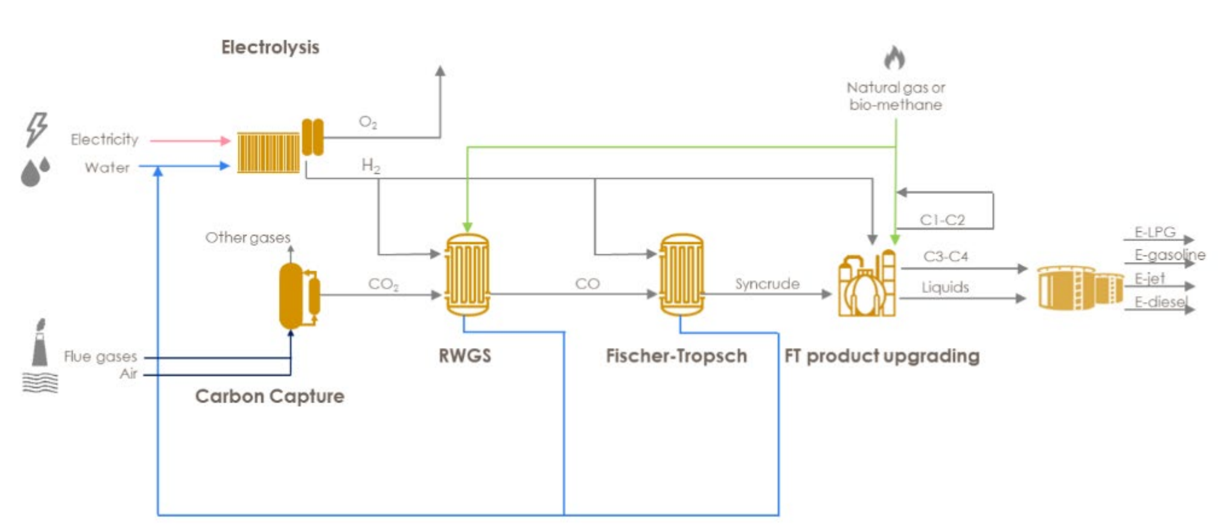
Indicator/measure		Value
Technical	TRL	5-9
	Typical operating temperature (°C)	200-350
	Typical operating pressure (bar)	20-40
	Typical overall CO_2 conversion (%)	51.5
	Plant lifetime (years)	20
Economic	Fuel price (Euro/t_{fuel})	1375
Environmental	Electricity usage (MWh/t_{fuel})	6.8
	Net CO_2 utilization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

Source: Jarvis and Samsatli, 2018

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 CO_2, derived by both bio- and fossil-source reacted with hydrogen from renewable electricity, leads to RFNBO. Moreover, if the overall feedstock is a mix between non-bio renewable hydrogen, bio- and non-bio renewable carbon, the final fuel share will belong to the different categories previously mentioned in a proportional fraction (on energy basis) depending on its origin.

It is worth to mention that Norsk e-Fuel is building a demo plant producing FT-synthesis liquid hydrocarbons supplied by CO_2 from DAC and hydrogen from SOEC, that will start production in 2024 and will be gradually scaled to produce 25 million litres within 2026 (*Our Technology | Norsk e-Fuel*, 2022). Here the expected TRL is about 7-8, which is relevantly increased from the recent updated figures from LBST (TRL 6 for both low/high temperature electrolysis) (Weindorf *et al.*, 2019).

Figure 4. 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).

As regards the TRL, LBST reported that this process has TRL 6 when supplied by high temperature electrolysers, while 8-9 when supplied by low temperature, traditional electrolysers (Weindorf *et al.*, 2019). First plants started producing hydrocarbons from fossil-derived methanol (MGT reactor of ExxonMobil), but today this technology is used also for plants producing gasoline from wastes-derived methanol (e.g. Primus Green Energy, Canada

(Chakraborty, Singh and Maity, 2022) and from hydrogen and oxygen from electrolysis in a large-scale methanol-to-gasoline plant (2.5 million 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 CO_2 via two main routes. By Route 1 it can be synthesised through the formation of syngas in the reverse water gas shift reaction (RWGSR) where it is then converted to DME through direct or indirect synthesis. Route 2 involves the synthesis of DME directly from CO_2 (Styring, Dowson and Tozer, 2021). Both routes have been already investigated into the previous sections.

Differently, Oxymethylene ethers (OME) are more complex compounds of carbon, oxygen, and hydrogen (CH3O(CH_2O)nCH3). Due to their high oxygen concentration, they suppress pollutant formation in combustion.

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

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 CO_2 to CO, to form syngas that together with e-hydrogen can lead to fuels, alcohols or other compounds. Many companies are studying such innovative 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 CO_2 emissions into ethanol as a part of an ongoing research and development partnership (Green Car Congress, 2022; renewablesnow.com, 2022). Here the conversion pathway exploits Twelve's carbon transformation technology (a new class of CO_2-reducing catalysts and a novel device that splits CO_2 with just water and renewable electricity as inputs), and subsequently 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 CO_2 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, 2021), even if under ASTM review process, may be another option to add ethanol as a qualified ATJ feedstock for D7566 Annex A5 (Harmon *et al.*, 2017).

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).

In late 2022, (Concawe, 2022) proposed a full techno-economic assessment of e-fuels, including synthetic jet fuel, which the most relevant data are reported in Table 10.

Table 10. Technical parameters synthetic-Jet fuel production

Production input and output			
Source	E-Fuels (concawe.eu)		
Input	H_2	Methanol	Power
Amount	0.01 kg/kg fuel	2.32 kg/kg fuel	0.718 MJ/kg NH3
Output	Kerosene	Water	Heat
Amount	1.00 kg	1.31 kg/kg fuel	1.314 MJ/kg fuel
Craddle-to-grave GHG emission			
Source	E-Fuels (concawe.eu)		
Years	2020	2030	2050
gCO_2eq/MJ	12.4	12.2	12.9*

Source: Concawe 2022

In Table 11 are resumed the TRL level concerning the main RNFBO technologies, the TRL assigned to e-methane, e-gasoline, and e-ammonia is refered to the Sabatier , Fisher Tropsh and Haber Bosh reactions.

Table 11. Resume of TRL level of RNFBO Technologies

	TRL (Technology Readiness Level)								
Sub-Technology	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**
Artificial Photosynthesis									
Solar power derived hydrogen									
Microbial electrolysis cells									
E-Methane (Sabatier Reaction)									
E-Gasoline, E-diesel (Fisher Tropsh)									
E-Ammonia (Haber-Bosh)									

Source: JRC 2023

2.2 Installed Capacity and 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 12. RFNBO plants available and planned 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, CO_2 capture from flue gas	CH4 25 Nm³ /h	3-4	H_2 and CH4	2019
Store&Go-Falkenhagen	Uniper	Germany	Alkaline water electrolysis, catalytic methanation, direct air capture of CO_2	CH4 57 Nm³ /h	3-4	CH4 and H_2	2019
STORE&GO Falkenhagen	STORE&GO	Germany	Isothermic catalytic honeycomb technology	1,400 cubic meters of SNG / day	3-4	H_2 and CH4	2019
GEORGE OLAH RENEWABLE METHANOL PLANT	Carbon recicling International	Iceland	alkaline water electrolysis, methanol synthesis from H_2 and CO_2 , CO_2 capture from a geothermal power plant	4000 t/year	8	Methanol	2012
FReSMe project	Swerim	Sweden	Electrolysis	50 kg/h of methanol	6	methanol	2021
ALIGN-CCUS	A consortium of 31 companies	Germany	Methanol synthesis from H_2 and CO_2	50kg of DME per day	4-5	(DME), synthetic diesel substitute	2019
Sunfire PtL – Dresden	Sunfire PtL – Dresden	Germany	High temperature electrolysis with SOEC, DAC, reverse water gas shift (RWGS), F-T synthesis	180 l/day	3-4	bio-oil	2014

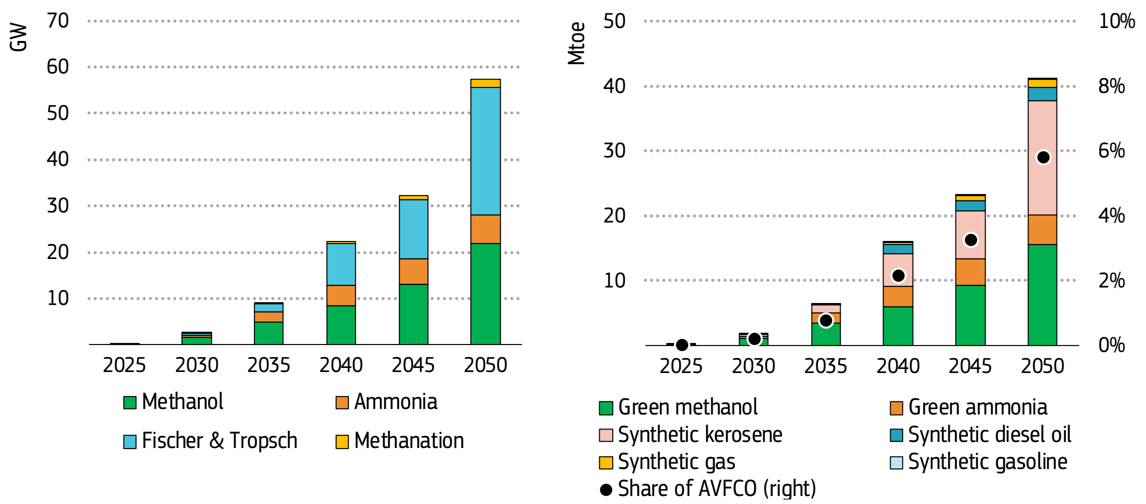
GreenPower2 Jet	Airbus, BP Lingen, BP Air, Dow, DLR, Hoyer Logistic, Easyjet, DHL	Germany	50 MW Electrolyser	JET Fuel quantity N.A.	7-8	Hydrogen, Jet fuel	2024

Source: (BEST and IEA Bioenergy Task 39, 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 electrolyser capacity.
Oil companies has just started to look towards e-fuels. Today there is still no active commercial production of RFNBOs technologies, but that is expected to scale up rapidly from the next decade encouraged by regulations such as ReFuelEU aviation and FuelEU maritime.

Under the CETO Climate Neutrality Scenario, the POTEnCIA[1] model projects a sharp increase in RFNBO production in the EU (see Annex 3). The installed capacity of RFNBO synthesis processes in the EU scales up rapidly from 2035, achieving more than 20 GW in 2040 and almost 60 GW in 2030 (see Figure 5). Such uptake is mirrored by the RFNBos production, which exceeds 40 Mtoe in 2050 representing almost 6% of energy consumption in final energy, final non-energy and in international aviation and shipping

Figure 5. Installed capacity (left) and production (right) in the EU under the POTEnCIA CETO Climate Neutrality Scenario, 2025-2050



Source: POTEnCIA model

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

e-Methanol

Several PtX projects have been announced which will introduce e-methanol in the fuel market. Among these projects the Green Fuels for Denmark (GFDK) is a representative partnership of companies across the value chain for e-methanol. The project involves several Danish companies, from power generation, such as Orsted, to leading off-takers of the green fuel, such as the shipping companies Maersk and DFDS. The project also aims to use the e-methanol as an input for aviation fuel, producing e-kerosene. To secure the off-take of the aviation fuel, the project also counts with the partnership of SAS and Copenhagen Airport. The project aims to produce about 50,000 t/y of mainly e-methanol, being scalable to up to 250,000 t/y in the future. The project has been granted IPCEI status, being one of the projects subject to a total funding of DKK 850 million.

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

Similarly, the Port of Gothenburg project involves several companies across the value chain. This project is set by the Gothenburg Port Authority, Sweden, and counts with the collaboration of companies such as Stena Line, Orsted, DFDS, and Liquid Wind, in order to make it Europe's first e-methanol hub. The port will be fed with e-methanol produced by the project FlagshipONE, the first commercial-scale PtX facility, which will come into operation stage by 2025, producing circa 50,000 t/y of e-methanol. The port will introduce methanol bunkering services by the end of 2023, and expects that e-methanol to be introduced to the shipping sector will reduce shipping emissions in the port area by 70%.
Hynetherlands is another project involving a value chain of green hydrogen. The project is being developed in the Netherlands and involves deployment of renewable energy to produce green hydrogen, carbon capture and e-methanol production. The project plans to deliver e-methanol for the maritime sector as the first users, and later include the demand of chemical, plastic, steel, glass and other industries. Engie is the company driving the project, and it counts with the collaboration of OCI, a methanol producer, and EEW, a waste-to-energy company
Some of the main companies in the e-methanol value chain are listed below (this is an illustrative list):

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

e-Ammonia

Several projects worldwide have been announced for the production of e-ammonia. The IRENA report on Renewable Ammonia (2022) mapped a total of 54 existing and planned production plants, being both brownfield and greenfield investments. The largest ammonia companies in the world CF Industries and Yara have announced projects to revamp their existing production facilities to substitute their ammonia production fully or partially with e-ammonia, as well as to build new production facilities for the green chemical.
The 54 projects are expected to total a production of 15,000,000 tons per year by 2030, which would account for 6% of the total global ammonia production by then. By 2040, the announced projects are expected to deliver

up to 71,000,000 t/y globally. The largest of the European projects is the HØST PtX Esbjerg, to be developed in Esbjerg, Denmark. This project is being developed by Copenhagen Infrastructure Partners, Maersk, and DFDS, and is expected to have a production of 600,000 t/y. The project aims to produce the ammonia for both maritime fuel and fertilizer applications, yielding either 600,000 tons of bunkering fuel, or 1,5m tons of fertilizer. It has an estimated CAPEX is EUR 1.4 billion and is expected to start operating by 2028-2029. This project will create circa 100 to 150 permanent jobs. The largest announced project in the world so far is the Western Green Energy Hub to be developed by the Singapore-based company InterContinental Energy in Western Australia. The project will deploy 50 GW of renewable electricity, 30 GW from wind and 20 GW from solar, to generate 3,500,000 tons of green hydrogen per year, which will be converted to a production capacity of 20,000,000 t/y of e-ammonia.

Table 13. E-Ammonia supply and demand projections

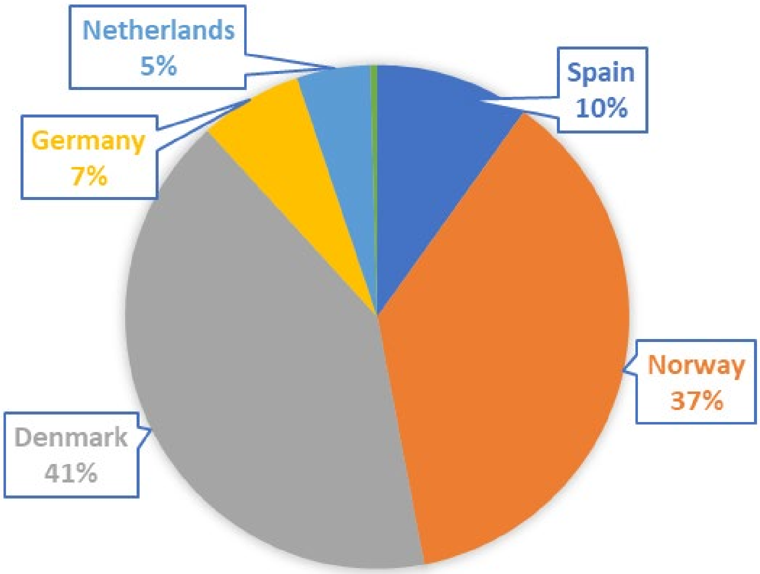
<table>
<tr><td colspan="4">Supply</td></tr>
<tr><td>Source</td><td colspan="3">(IRENA and AEA, 2022) Mega-project – Ammonia Energy Association</td></tr>
<tr><td colspan="2">Number of projects</td><td colspan="2">Expected production</td></tr>
<tr><td colspan="2">54</td><td colspan="2">~71- 90 million t/y by 2040 (1-2% in Europe)</td></tr>
<tr><td colspan="4">Demand</td></tr>
<tr><td>Source</td><td colspan="3">(Ram et al., 2020)</td></tr>
<tr><td>Year</td><td>2030</td><td>2040</td><td>2050</td></tr>
<tr><td>TWh</td><td>78</td><td>2,249</td><td>3,340</td></tr>
<tr><td colspan="2">Market share (of TWh demand among RFNBOs in 2050)</td><td colspan="2">7.8%</td></tr>
</table>

Source: (IRE*NA and AEA, 2022)*

Thirteen of the announced projects are to be developed in Europe, amounting to a total production of approximately 1,600,000 t/y (some of the projects do not yet have their production capacities disclosed). 36 projects have been announced outside of Europe, amounting to a total production of approximately 69,400,000 t/y. Of these projects, 16 are to be developed in Australia.

Based on the announced projects so far, Denmark is expected to be the largest producer of e-ammonia in Europe, accounting for 655,000 t/y. One project has yet to disclose the expected production amount. Norway has the second highest production capacity announced, expecting to produce 590,000 t/y, and having two development projects yet to disclose their production capacity.

Figure 6. e-ammonia planned capacity in Europe



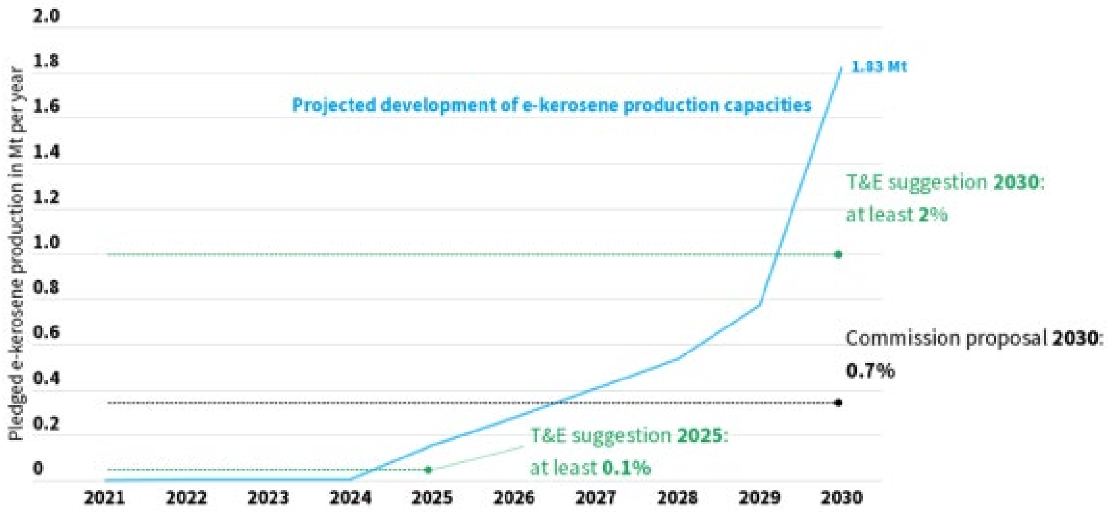
Source: (IRENA and AEA, 2022)

According to the reported projects in the Ammonia Energy Association's website, 20 e-ammonia projects have been announced. Based on these projects, the total global e-ammonia production capacity is expected to reach approximately 90,000,000 t/y by 2035. From the announced projects, approximately 1,105,000 t/y is expected to be produced from Europe, with Denmark being the largest producer, this accounts to a total of 1.2% of the global production by 2035.

e-Kerosene

The blending mandates agreed in the EU demands for an uptake of the fuel production to achieve those targets. Several companies have started on the production of the fuel. The European NGO Transport and Environment estimates (transportenvironment.org, 2022) that, by 2025, 0.16 Mt of e-kerosene will be produced in Europe (based on the proposed mandate, not the agreed). Furthermore, the organization mapped out that companies' pledges amount to a 1.83 Mt production by 2030, a supply higher than the Commission's then-proposed mandate.

Figure 7. e-kerosene planned capacity



Source: NGO Transport and Evironment (T&E, 2022)

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

The Green Fuels for Denmark project is a partnership between the energy and transport industries with Ørsted, DSV, Maersk, DFDS, Copenhagen Airports and Scandinavian Airlines. It will produce a slate of PtL products for the road, aviation and maritime sectors. The project plans to start production in 2025 with over 50 000 tons of PtL fuel from wind power. The European Commission recognized Green Fuels for Demark as an important project of common European interest (IPCEI), allowing the Danish government to support the project with public funding (DKK 850 million).

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

Luxembourg Airport has entered a consortium to produce PtL aviation fuel to meet the PtL blending target of the ReFuelEU Aviation policy proposal. The consortium partners include e-fuel producer Sunfire, DAC specialist Climeworks, and wind power company Norsk Vind. Production is planned for 2024 in Norway.

The SAF production capacity target by 2050, according to SAF producer's estimations, need 104-106 SAF plants to be built, requiring an estimated investment of circa €10.4-10.5 billion. Furthermore, it is estimated that this emerging market will create around 202,100 additional jobs and will have a decrease in external costs from air pollution by €1.5 billion by 2050.

e-Methane

According to the Global Alliance Powerfuels, e-methane will account for almost 20% of the e-fuels final energy demand by 2050, having a total of 8,590 TWhth of final energy demand. E-methane could be applied in the areas of transportation, power generation, and industrial heating. As a fuel, use of e-methane is being explored in the maritime sector, as it is suitable for dual-engine vessels running in LNG. A few projects have started exploring this solution. Synthetic methane is also being widely considered, especially in gas-dependent regions, as a new source of gas supply, for power generation and heating. Several initiatives have started projecting and demonstrating the application of e-methane to the gas grid, as a form of broadening its gas-sourcing and decarbonizing the heating sector.

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

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

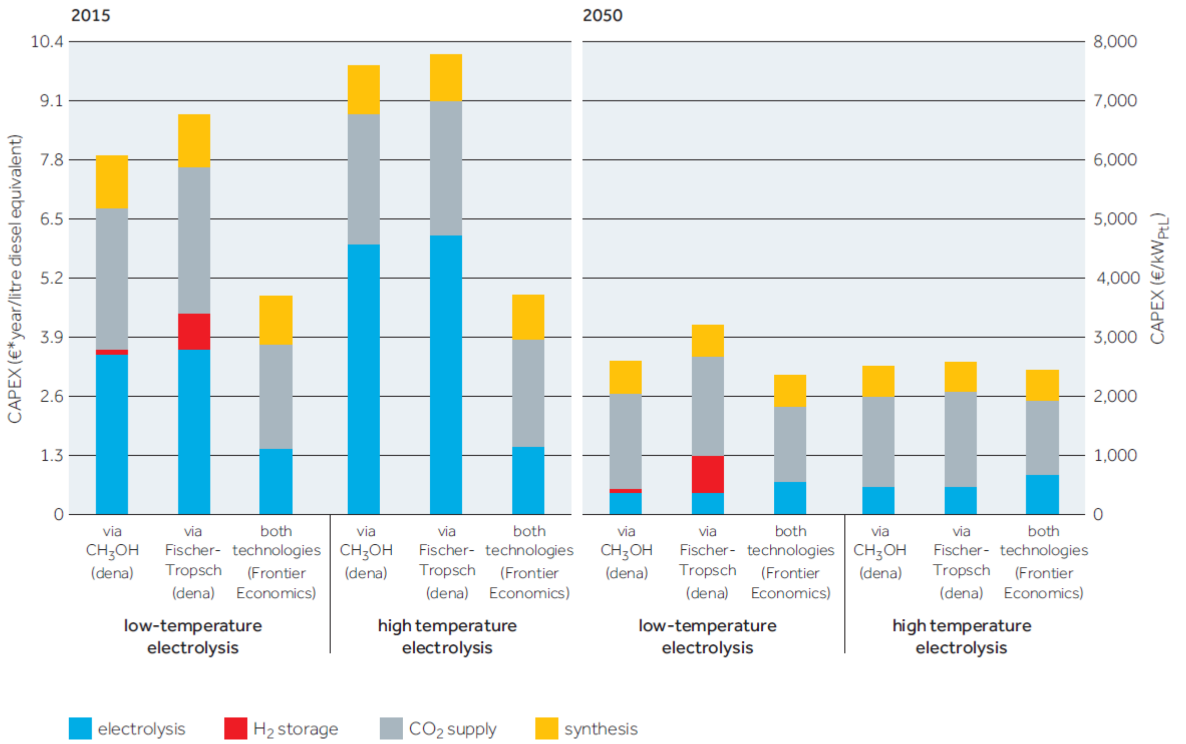
In Europe, the Belgian company, Tree Energy Solutions, is developing a green energy hub by the German port of Wilhelmshaven, where around 20,000 t/y of e-methane will be imported by 2025, which will be a small share of a larger LNG import. The synthetic fuel will be imported as a carrier for green hydrogen, meaning that upon arrival, the fuel will be once again broken down between hydrogen and CO_2. Around 99% of this CO_2 can be captured and re-sent for the production of a new batch of e-methane, making it a closed loop. The company claims that this is the most cost-effective way to import hydrogen into the country.

The French project, Jupiter 1000, is a demonstration project of e-methane production and utilization for the heat sector. The project counts with a range of companies expanding through the whole value chain of e-methane production. The project is ending its trials in 2023, and has a methane production of $25m^3/h$.

2.3 Technology Costs

The technology costs has been recently calculated by Concawe (Yugo and Soler, 2019), elaborating data from Frontier Economics (2018); LBST and DENA (2017).

Figure 8. CAPEX overview for RFNBO



Source: (Yugo and Soler, 2019)

Main notes are:

• CO_2 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.

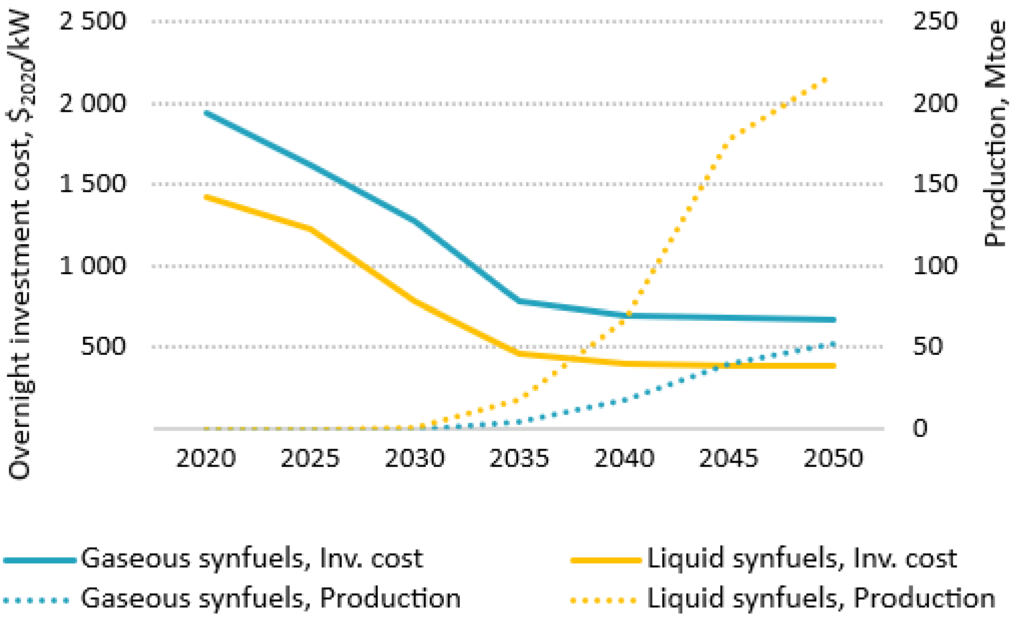
• To express CAPEX in €*year/ litre of diesel equivalent, values considered are: e-diesel LHV: 44 MJ/kg and e-diesel density: 0.832 kg/litre

• 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.

At global level, also the POLES-JRC model[2] predicts sharp drop for synfuels overnight investment until 2035, which thereafter is see trigger the production, Figure 9

[2] POLES-JRC (Prospective Outlook on Long term Energy Systems) is a global energy model to assess the contribution of the various energy types (fossil fuels, nuclear, renewables) and energy vectors, to future energy needs developed by JRC. Description of the model and the scenarios are given in Annex 3.

Figure 9. Dynfuels global overnight investment cost



Source: JRC POLES model

E-Methanol

Recently IRENA (IRENA and Methanol Institute, 2021) and Concawe made a cost assessment on e-Methanol production cost, with a reduction cost potential from 2020 to 2050 at around 35%, with results resumed in Table 14.

Table 14. E-methanol production costs

Cost projections			
Source	(IRENA and Methanol Institute, 2021)		
Note: range varying depending on cost of carbon; carbon credit was not accounted for and may decrease the values			
Year	2020	2030	2050
USD/t (approx.)	820-1620	410-750	250-630
Source	(IRENA and Methanol Institute, 2021)		
Note: based on DAC, range varying depending on cost of carbon; carbon credit was not accounted for and may decrease the values			
Year	2018	2030	2050
USD/t	1220-2380	600-1070	290-630
Source	(Soler *et al.*, 2022)		
Note: range depending on north, central and south Europe projected costs			
Year	2020	2030	2050

€/GJfinal fuel	49 – 91.1	42.1 – 63.6	42.8 – 65.3
Source	(Soler *et al.*, 2022)		
CAPEX			
Source	(Soler *et al.*, 2022)		
Note: Methanol synthesis plant with a capacity of 1368 MW based on its Lower Heating Value (LHV)			
Year	2020	2030	2050
€/kW	768	672	500
Million €	1051	920	684
O&M			
Source	(Soler *et al.*, 2022)		
Year	2020	2030	2050
Fixed (in million €) (3% of CAPEX)	31.53	27.6	20.52
Fossil based counterpart			
Source	(IRENA and Methanol Institute, 2021)		
USD/t	100-250		

Source: IRENA and Methanol Institute, 2021. Soler et al., 2022

E-Ammonia

IRENA and Methanol Institute (2021) and Concawe made an estimation of production cost for e ammonia production, with 40-60% potential cost reduction from 2020 to 2050, figures resumed in Table 15

Table 15, e-ammonia production costs

Cost projections		
Source	(IRENA and AEA, 2022)	
Note:		
Year	2020	2050
USD/t	720-1400	310-610
Source	(Fasihi *et al.*, 2021)	

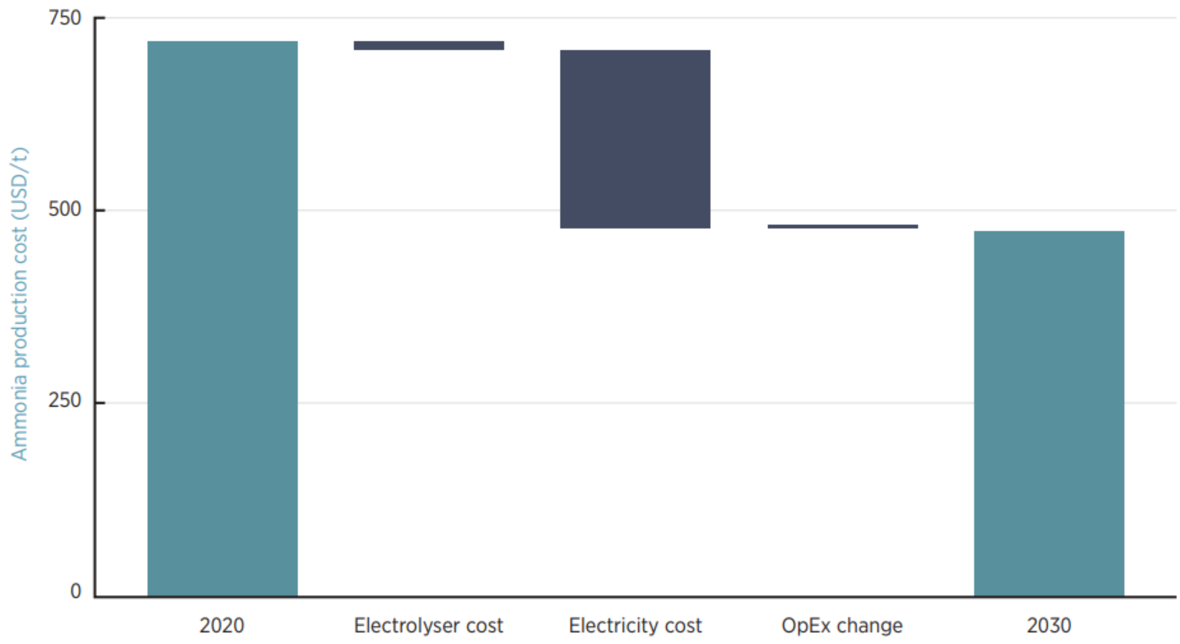
Note: WACC (weighted Average cost of Capital) 7%, "best sites"				
Year	2020	2030	2040	2050
€/t	440-630	345-420	300-330	260-290
Source	(Soler *et al.*, 2022)			
Note: range depending on north, central and south Europe projected costs				
Year	2020	2030	2050	
€/GJfinal fuel	45.9 – 87.7	39.8 – 60.7	33.3 – 50.9	
Source	(Soler *et al.*, 2022)			

Source: Soler et al., 2022

The main cost driver for the production for large-scale e-ammonia is linked to electricity which accounts for up to half of the cost of the e-ammonia production, and it is expected to account for up to 90% of projected cost reductions. This characteristic leads to a couple of important factors in the generation of the renewable chemical: (1) high up-front CAPEX investment costs but low OPEX costs; and (2) this means that the cost of production is highly impacted by the capital investment, making the weighted average capital cost (WACC) of major importance on the cost of the e-ammonia (since costs incurred later are minimal and so few of the overall costs are discounted in financial models). Beyond power generation, investment of small-scale plants has the synthesis loop as one of the main cost drivers, while large-scale plants have electrolysers as dominant cost driver.

With the assumption of a plant size of 1 Mt annually, an operational load factor of 70%, an annual interest rate of 7% and linear depreciation over 20 years. The annual OPEX is assumed to be 3% of the CAPEX." (IRENA and AEA, 2022, p. 47), potential e-ammonia cost reduction potential is resumed in Figure 10.

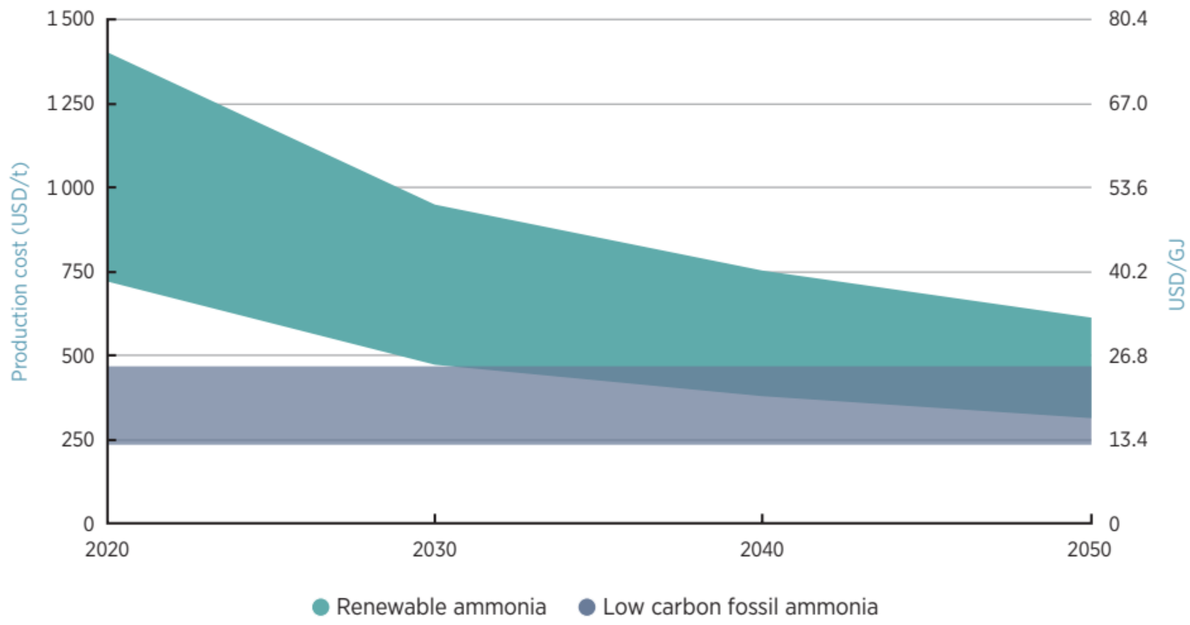
Figure 10. E-ammonia cost trend projection



Source: IRENA and AEA, 2022

Considering the CAPEX and OPEX for the production of hydrogen and nitrogen are already included in the respective cost of hydrogen and nitrogen. The hydrogen price is based on IRENA (2020), which assumes a low electricity cost, a long electrolyser lifetime and low CAPEX. The ammonia synthesis loop is estimated to add USD 25-50 per tonne (Salmon and Bañares-Alcántara, 2021), and nitrogen purification is estimated to add USD 2.5-5 per tonne. Figure 11 reports these costs here below.

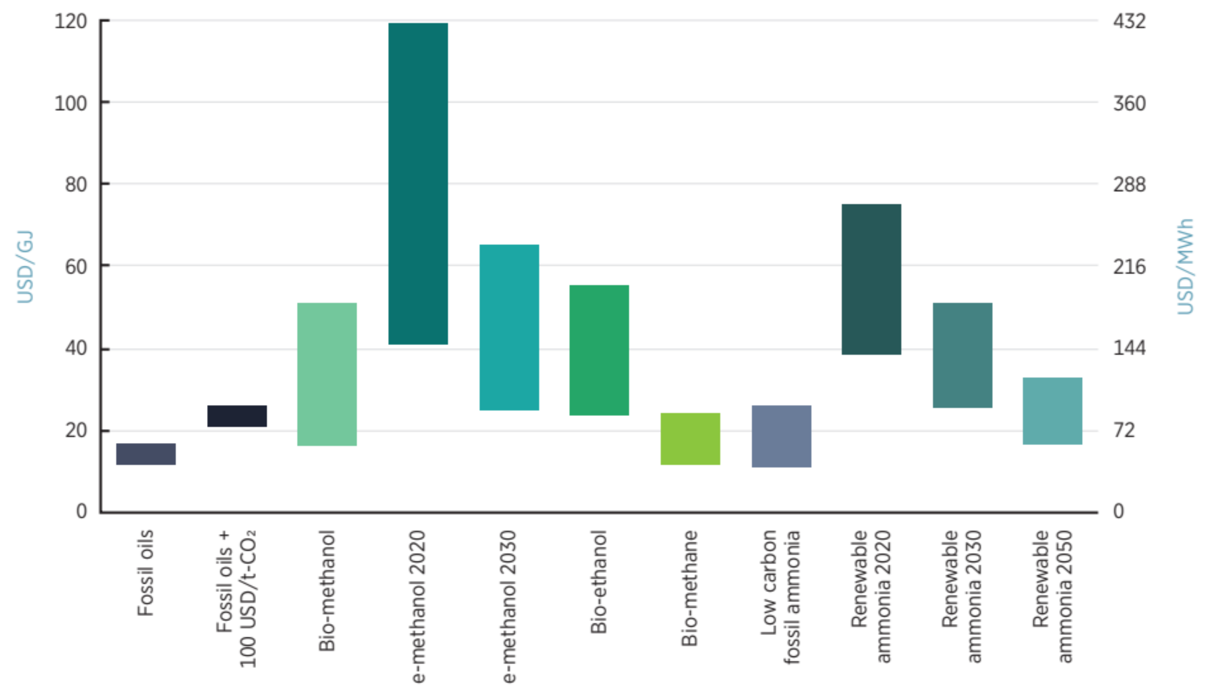
Figure 11. E-ammonia vs Low carbob Fossil Ammonia comparison trend cost



Source: IRENA and AEA, 2022

With low-carbon fossil ammonia from Alfa Laval *et al.* (2020). Fossil fuel values are based on average values (2010-2020); see IRENA and Methanol Institute (2021). Methanol cost values are based on IRENA and Methanol Institute (2021). Bio-ethanol and bio-methane estimates are based on IRENA and AEA (2022, p. 63). Comparison costs resumed in Figure 12.

Figure 12. E-ammonia cost comaparison vs other fuels



Source: IRENA and AEA, 2022

E-kerosene

Concerning the potential reduction of e-kerosene production cost, according to Concawe in Europe it can range from 12% to 28%, see Table 16

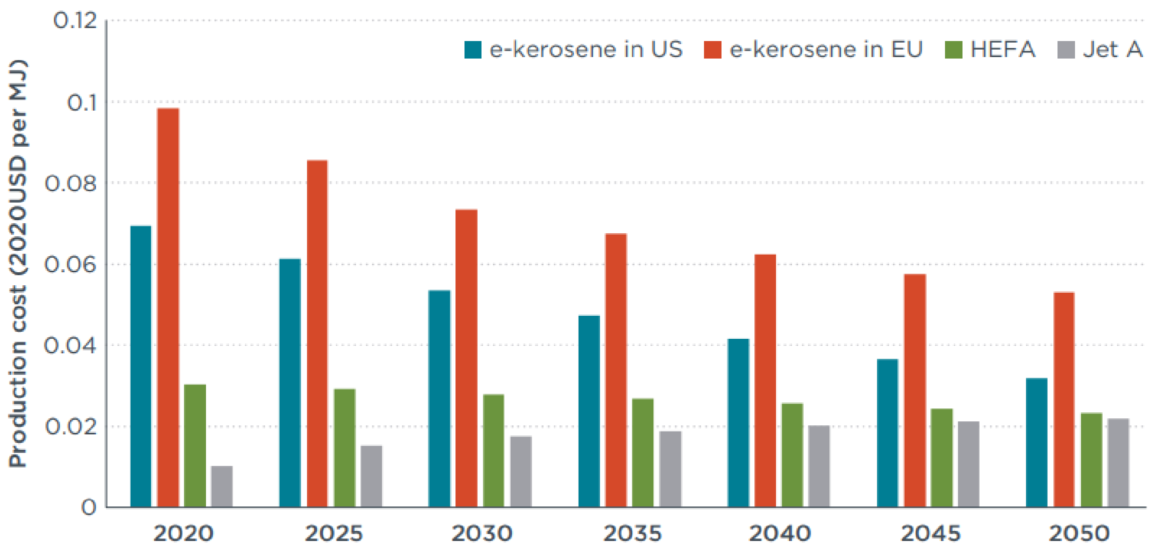
Table 16. E-kerosene production cost

Cost projections							
Source	(Zhou, Searle and Pavlenko, 2022)						
Note: Average in the EU							
Year	2020	2025	2030	2035	2040	2045	2050
USD/gallon	12.44	10.82	9.29	8.52	7.88	7.26	6.72
Source	(Soler *et al.*, 2022)						
Note: range depending on north, central and south Europe projected costs							
Year	2020	2030	2050				
€/GJfinal fuel	60.9 – 111.8	53.3 – 79.8	53.9 – 80.6				

Source: Zhou, Searle and Pavlenko, 2022

The e-kerosene, projection production price comparison US vs EU, and HEFA and JET A are visible **Figure 13**.

Figure 13. E-kerosene cost comaparison vs other fuels.



Source: Concawe 2022

E-methane

The ICCT and Concawe made some projection about future production cost for e-methane production, with a potential reduction seen from 13% to 30% in 2030. Table 17 reports prices and cost demand.

Table 17. Price cost and demand projection on e-methane

Price projection			
Source	(Comer, Osipova and Pavlenko, 2022)		
Note: Many assumptions, one of the main assumptions is CO_2 price at $40/t			
Year	2020		2030
€/GJ	62.98		47.52
Cost projection			
Source	(Soler *et al.*, 2022)		
Note: range dependent on north, central and south Europe projected costs			
Year	2020	2030	2050
€/GJfinal fuel	54.2 – 96.2	47.1 – 68.4	44.7 – 64.9
Source	(Soler *et al.*, 2022)		
Demand			

Source	(Ram *et al.*, 2020)		
Years	2030	2040	2050
TWh	78	896	8,590
Other			
Source	(IRENA, 2019; Ram *et al.*, 2020; Comer, Osipova and Pavlenko, 2022)		

Methanation capital cost	$220/kW$_{fuel}$
Production costs (today)[3]	1380 USD/t
Fossil-based counterpart[4]	100-500 USD/t
Production costs (2050)	€20–€85/GJ

Source: IRENA, 2019; Ram et al., 2020; Comer, Osipova and Pavlenko, 2022)

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.

2.4 Public RD&I Funding and Investments

RFNBOs 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 H_2 production and CO_2 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 M€.

Table 18. Horizon 2020 projects on RFNBO.

Project Acronym	**Project Title**	**Feedstock**	**Technology**	**End-product**	**EU Contribution** **kilo €**
SUN-to-LIQUID	SUNlight-to-LIQUID: Integrated solar-thermochemical synthesis of liquid hydrocarbon fuels	Sunlight, CO_2	CSP, FT	Synthetic jet fuel	4,451 €
FReSME	From residual gasses to methanol	CO_2 from steel	Sorption-enhanced water–gas shift (SEWGS) technology + water electrolysis + catalytic conversion	methanol	11,407 €
eForFuel	Fuels from electricity: de novo metabolic conversion of electrochemically produced formate into hydrocarbons	CO_2	Electrobioreactor	Propane and isobutene	4,117 €

[3] Hydrogen: A renewable energy perspective (irena.org)
[4] Hydrogen: A renewable energy perspective (irena.org)

KEROGREEN	Production of Sustainable aircraft grade Kerosene from water and air powered by Renewable Electricity, through the splitting of CO_2, syngas formation and Fischer-Tropsch synthesis	CO_2	plasma driven dissociation of air captured CO_2, solid oxide membrane oxygen separation, FT	biojet	4,951€
CO_2Fokus	CO_2 utilisation focused on market relevant dimethyl ether production, via 3D printed reactor - and solid oxide cell-based technologies	CO_2	CO_2 hydrogenation involving both catalytic chemical and electrochemical conversion	DME	3,994€
eCOCO$_2$	Direct electrocatalytic conversion of CO_2 into chemical energy carriers in a co-ionic membrane reactor	CO_2	electrochemical: multifunctional catalyst integrated in a co-ionic electrochemical cell	synthetic jet fuel	3,949€
C2Fuel	Carbon Captured Fuel and Energy Carriers for an Intensified Steel Off-Gases based Electricity Generation in a Smarter Industrial Ecosystem	CO_2 from steel	electrochemical, several routes	biodiesel, formic acid	3,999 €
COZMOS	Efficient CO_2 conversion over multisite Zeolite-Metal nanocatalysts to fuels and OlefinS	CO_2 from steel and refinery	electrochemical: multisite Zeolite-Metal nano catalysts	propane, propene	3,997 €
SELECTCO$_2$	Selective Electrochemical Reduction of CO_2 to High Value Chemicals	CO_2	Selective Electrochemical Reduction of CO_2 to High Value Chemicals	carbon monoxide, ethanol or ethylene	3,772€
TAKE-OFF	Production of synthetic renewable aviation fuel from CO_2 and H_2	CO_2	conversion of CO_2 and H_2 to SAF via ethylene as intermediate	Aviation fuel	4,998 €
ECOFUEL	Renewable Electricity-based, cyclic and economic production of Fuel	CO_2	electrochemical conversion of CO_2 to transport fuels via light alkenes	transport fuels	4,858 €
METHASOL	International cooperation for selective conversion of CO_2 into METHAnol under SOLar light	CO_2	CO_2 reduction via artificial photosynthesis with corresponding photocatalysts	methanol	3,999€
NEFERTITI	Innovative photocatalysts integrated in flow photoreactor systems for direct CO_2 and H_2O conversion into solar fuels	CO_2, H_2O	photocatalysis for CO_2 and H_2O conversion to alcohols	Ethanol, longer chain alcohols	3,844 €
TELEGRAM	TOWARD EFFICIENT ELECTROCHEMICAL GREEN AMMONIA CYCLE	Air, water and renewable energy	Electrochemical ammonia synthesis and direct ammonia fuel cell	NH3 as energy carrier	3,468€
LAURELIN	Selective CO_2 conversion to renewable methanol through innovative heterogeneous catalyst systems optimized for advanced hydrogenation technologies (microwave, plasma and magnetic induction).	CO_2 and H_2	disruptive multifunctional catalyst systems for CO_2 hydrogenation	Renewable methanol	4,448 €

4AIRCRAFT	Air Carbon Recycling for Aviation Fuel Technology	CO_2/H_2	Novel multi catalyst reactor technology that combines electro-, chemo-, and biocatalysts to provide a net-neutral carbon-based fuel for aviation	Jet fuel (C8-C16)	2,239€
ORACLE	Novel routes and catalysts for synthesis of ammonia as alternative renewable fuel	N_2/H_2O	plasma-aided electro catalytic as well as electrified thermal catalysis	NH3	2,846 €
UP-TO-ME	Unmanned-Power-to-Methanol-production	CO_2 from biogas and H_2O	3D printed methanol synthesis reactor	renewable methanol	2,997 €
E-TANDEM	Hybrid tandem catalytic conversion process towards higher oxygenate e-fuels	CO_2 and H_2O	electro catalysis/solid thermocatalysis	oxygenate e-fuels	3,334€
SOREC2	SOlar Energy to power CO_2 REduction towards C2 chemicals for energy storage	CO_2, H_2O, sunlight	Photo electrochemistry technology (PEC)	ethanol or ethylene	3,084 €
DARE2X	Decentralised Ammonia production from Renewable Energy utilising novel sorption-enhanced plasma-catalytic Power-to-X technology	Air and H_2O	Water electrolysis + non-thermal plasma (sorption-enhanced plasma catalytic technology)	Ammonia	2,952
DESIRED	Direct co-processing of CO_2 and water to sustainable multicarbon energy products in novel photocatalytic reactor	CO_2, H_2O, sunlight	e hybrid photo-electrocatalysts	C2+ solar fuels, methanol and methane	3,058€
FreeHydroCells	Freestanding energy-to-Hydrogen fuel by water splitting using Earth-abundant materials in a novel, eco-friendly, sustainable and scalable photoelectrochemical Cell system	H_2O, sunlight	solar-to-chemical energy conversion (photoelectrochemical system)	H_2	3,748€
MOF2H₂	Metal Organic Frameworks for Hydrogen production by photocatalytic overall water splitting	H_2O, sunlight	MOF-based photocatalysis for sun-driven H_2 production	H_2	2,998€
ECO_2fuel	Large-scale low-temperature electrochemical CO_2 conversion to sustainable liquid fuels	CO_2, water, electricity	Innovative electrocatalytic CO_2 at 80 °C and 15 bar	Liquid fuels	16,620 €
FLExnCONFU	FLExibilize combined cycle power plant through power-to-X solutions using non-CONventional FUels	CO_2, water, electricity	1MW scale power-to-hydrogen-to-power system or ammonia to be in turn locally re-used in the same power plant to balance the load	Hydrogen, ammonia	9,887€
MefCO_2	Synthesis of methanol from captured carbon dioxide using surplus electricity	CO_2, water, electricity	methanol production with high CO_2 concentration-streams and H_2 as an input	Methanol	8,622 €

MegaSyn	Megawatt scale co-electrolysis as syngas generation for e-fuels synthesis	CO_2, water, electricity	First demonstration of mega-watt scale syngas production by co-electrolysis (SOECs) to e-fuels.	Liquid fuels	4,999€
SUN-to-LIQUID	SUNlight-to-LIQUID: Integrated solar-thermochemical synthesis of liquid hydrocarbon fuels	H_2O, CO_2 and solar energy	Concentrated solar radiation drives a thermochemical redox cycle, which inherently operates at high temperatures and utilizes the full solar spectrum	Liquid fuels	4,450€
ELCOREL	Electrochemical Conversion of Renewable Electricity into Fuels and Chemicals	CO_2, water, electricity	Electrochemical oxidation of water and electrochemical reduction of carbon dioxide based on the principles of quantum chemistry and innovative catalysts	Fuel and chemical s	3,616€
HELENIC-REF	Hybrid Electric Energy Integrated Cluster concerning Renewable Fuels	CO_2, water, heat	water thermolysis with innovative catalysts at temperatures below 300oC	Synthetic natural gas	2,578 €
Circlener gy	Production of renewable methanol from captured emissions and renewable energy sources, for its utilisation for clean fuel production and green consumer goods	CO_2, water, electricity	Innovative methanol production through CO_2 capture with ISCC certified technology	Methanol	1,827 €
COFLeaf	Fuel from sunlight: Covalent organic frameworks as integrated platforms for photocatalytic water splitting and CO_2 reduction	H_2O, CO_2 and solar energy	Artificial photosynthesis with polymeric photocatalysts based on covalent organic frameworks	methane or methanol	1,497 €

Source: TIM/CORDIS elaboration

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

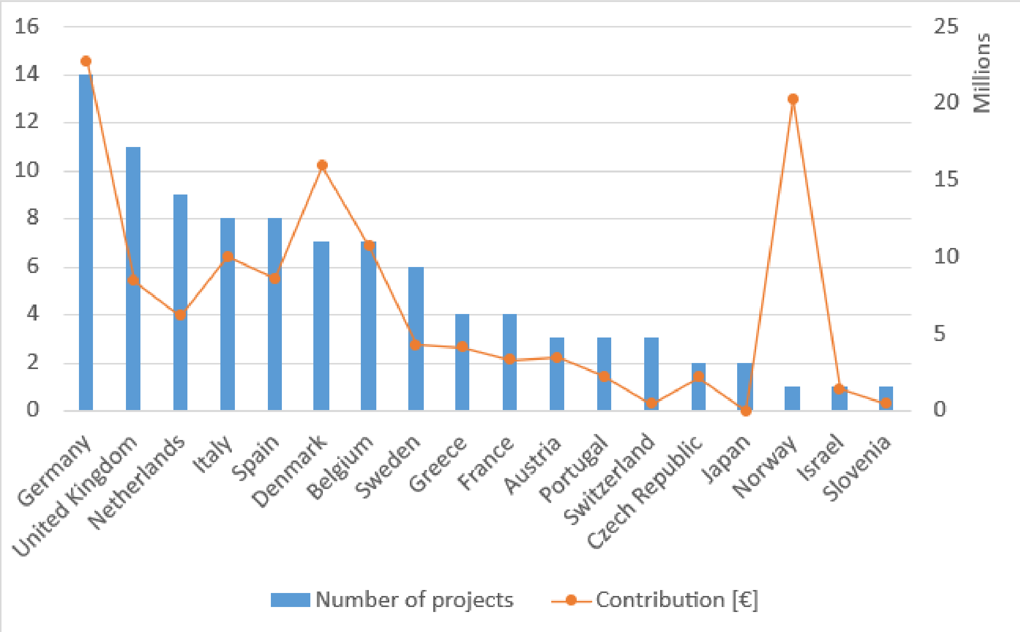
Concerning the technologies tested, in addition to the traditional hydrolysis and synthesis processes, there are also photo-electrochemical conversion, photo-catalysis, thermo-catalysis, sorption-enhanced water–gas shift, artificial photosynthesis.

The processes tested are delivering as output several different products: road, maritime and synthetic jet fuels; methanol; methane, propane and isobutene; ethanol; ethylene, ammonia.

It is worth to mention that other small (e.g. MSCA) activities and hybrid projects (thus including bio-feedstock) also study and demonstrate similar applications, including RFNBO.

As shown in Figure 14, Germany, Denmark and Norway received higher contribution related to the number of projects financed.

Figure 14. Public R&D financing country level



Source: JRC elaboration

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. Such calls potentially include RFNBO production. 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'.

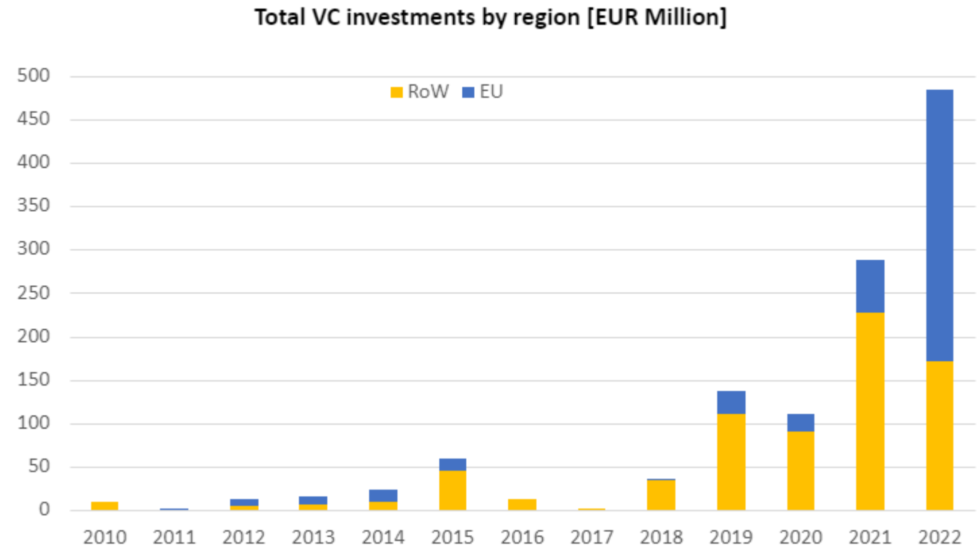
Finally, it worth mentioning that EC is funding mainly upstream processes for CCS/CCU and hydrogen production by means of the Innovation Fund (now at the 3rd round of large-scale projects (European Commission (EC), 2022). There no specific projects based only on RFNBO production, but many hybrids processes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

2.5 Private RD&I 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).

Global Venture Capital VC investments in RFNBO firms started to take off in 2019, display a sharp increase in 2021-22 (x 4.4 as compared to 2020) and reached EUR 484 million in 2022. Figure 15 recaps such findings here below.

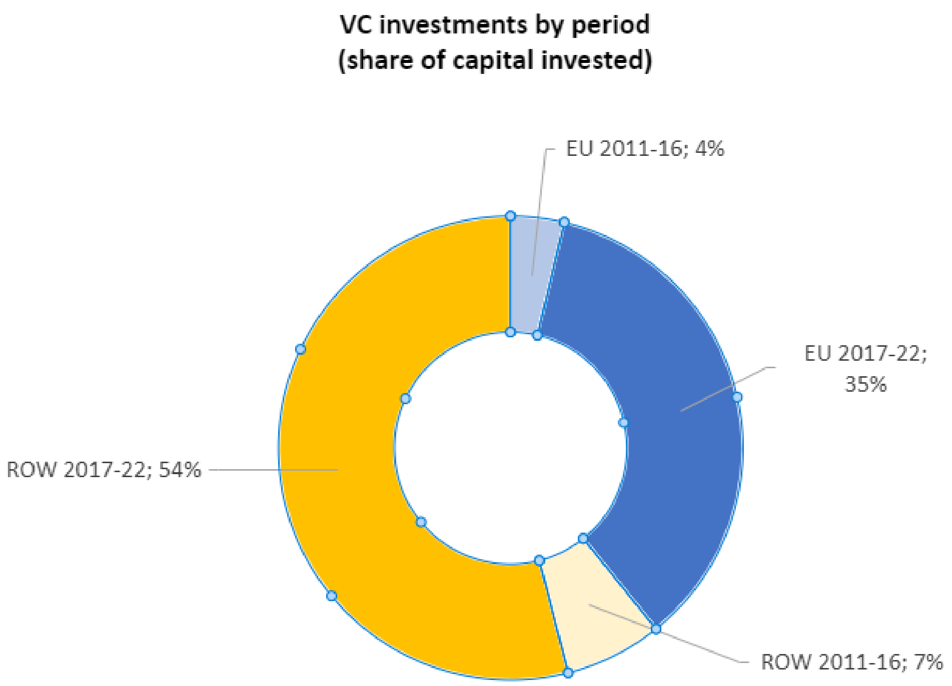
Figure 15. RFNBO VC investment by region



Source: JRC elaboration

Over the period 2017-22, global VC investments amount to EUR 1.06 Billion, which represents an eight–fold increase as compared to a previous 2011-16 period of very low investment levels. The EU hosts 35 % of active venture capital companies' investment over the 2017-22 period. Germany (2nd) hosts half of EU ventures and follows the US (1st), which hosts 40% of active VC companies. Figure 16 reports such findings here below.

Figure 16. RFNBO VC investment by period



Source: JRC elaboration

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

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

Over the 2017-22 period, the EU accounts for 52 % of global later stage investment (amounting to EUR 351.2 Million). This is essentially due to a large deal realised in 2022 by the German company Sunfire (DE, syngas electrolysis solutions), which by itself accounts for 35 % of global later stage investments over the 2017-22 period. The US and Canada rank next, supported by investments realised since 2019 in Lanzajet (US), Carbon Engineering (CA) and others.

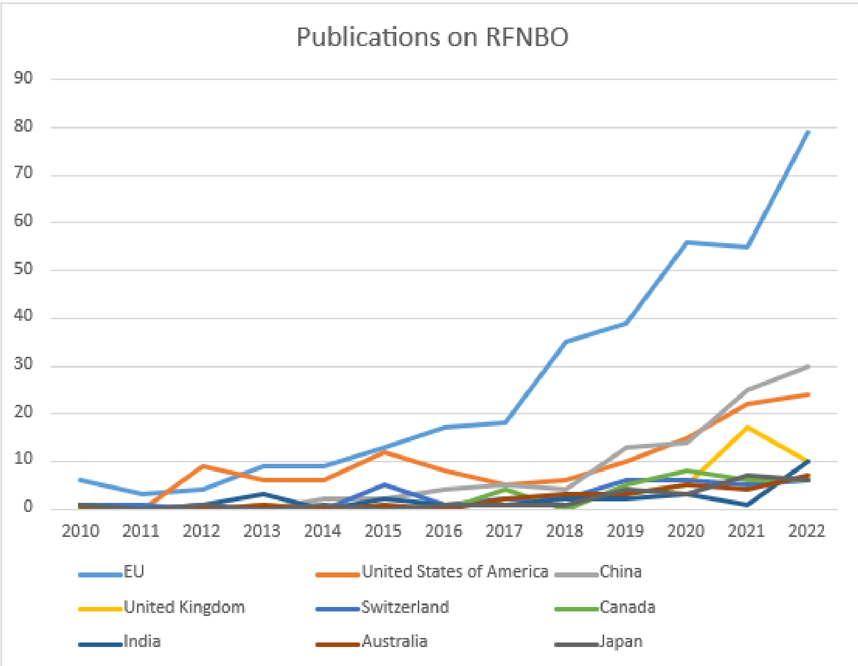
2.6 Patenting trends

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 Scientific publication trends

At global level the publications on RFNBO are gaining momentum from 2017 onward, with the EU leading the ranking with quadruplicating from 20 to 80 publications. Figure 17

Figure 17. RFNBO publications



Source: JRC elaboration

Share of EU publications among the top 10% most cited articles in the field.

The EU had 99 highly cited publication with a share of 36% among the top 10% most cited in the field, as reported in Figure 18

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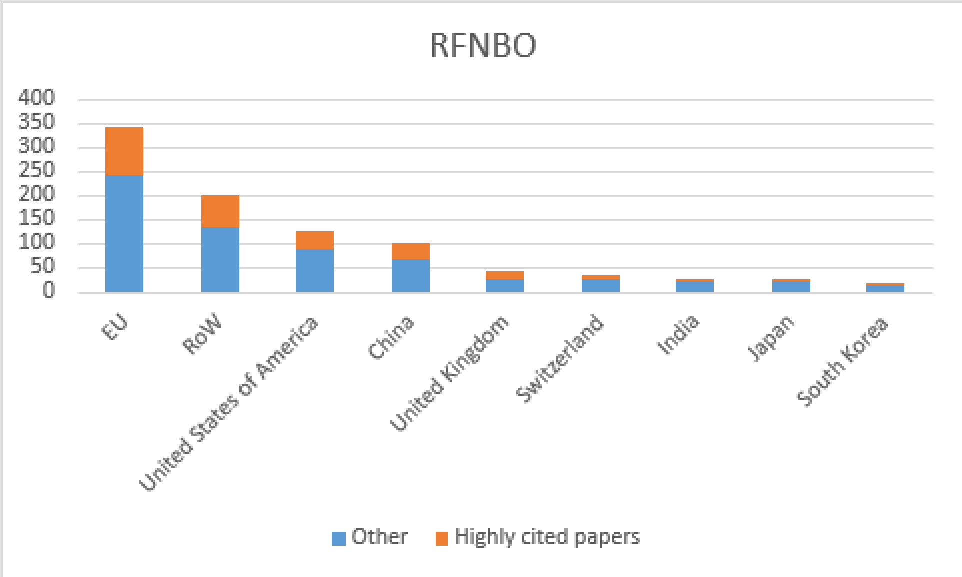
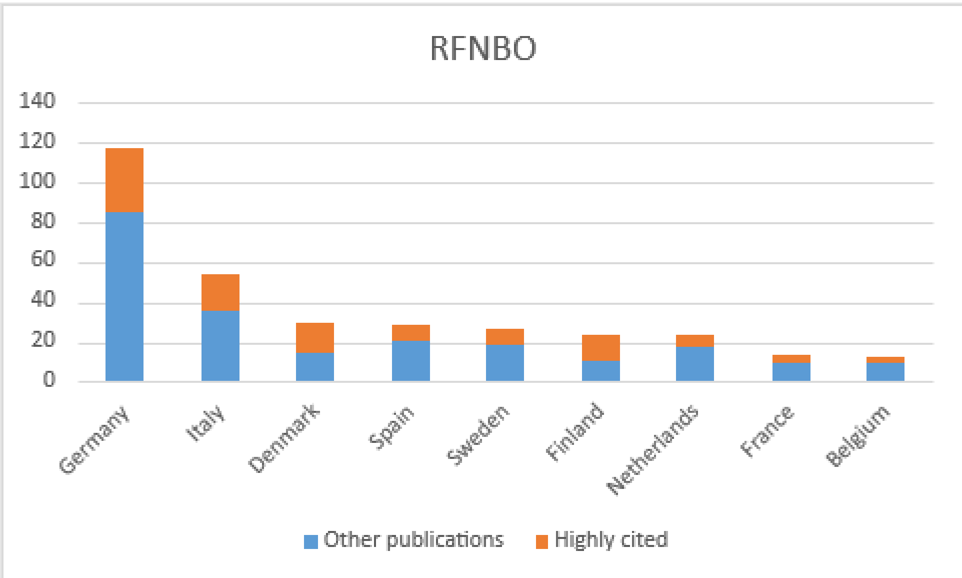
Figure 18. RFNBO global publications with share of highly cited papers



Source: JRC elaboration

At the EU level Germany leads the publication in the field with almost 120 publication and a share of 27% of highly cited articles, Figure 19.

Figure 19. RFNBO EU countries publications with share of highly cited papers



Source: JRC elaboration

The publication cluster shows a particular relation between the EU and the RoW with a connection with UK and Switzerland as well, as shown in Figure 20

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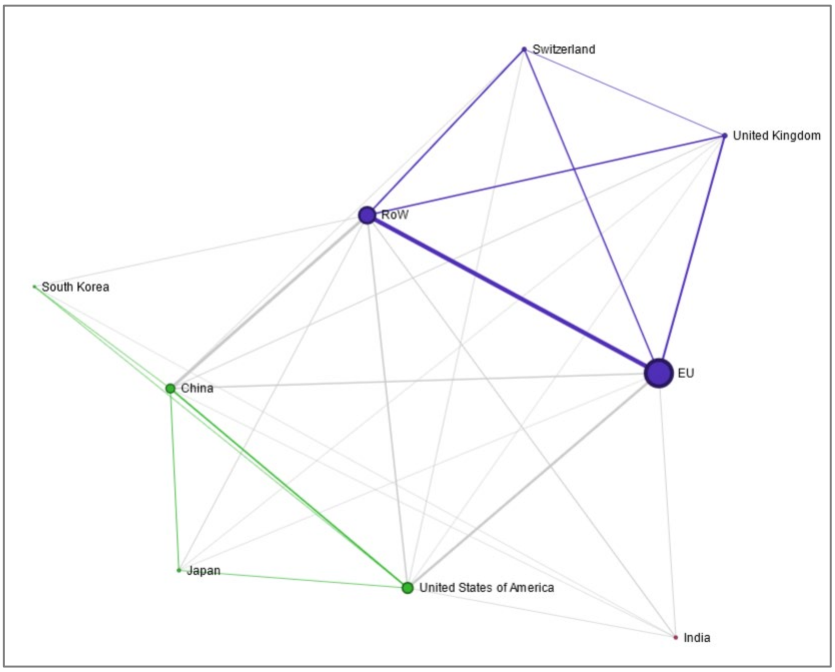
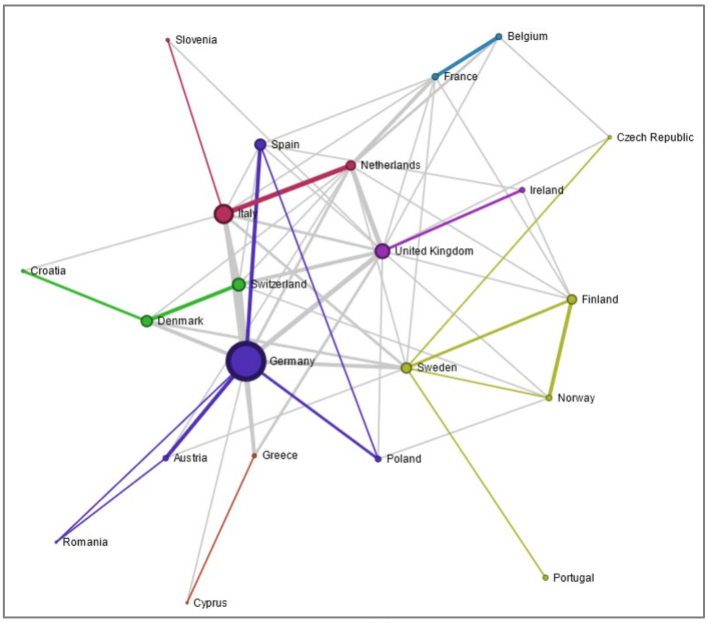
Figure 20. RFNBO global publication cluster



Source: JRC elaboration

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

Figure 21. RFNBO European publication cluster



Source: JRC elaboration

Sustainability/resilience

Today the biggest barriers to RFNBO industry development are the absence of hydrogen supply for this scope, and the upcoming phasing out of internal combustion engines for passenger cars towards the full electrification of the sector. Even if some Member States as Germany and Italy recently expressed their position (ICCT, 2022) against the EU regulation on "CO_2 emission performance standards for cars and vans" (EU, 2023), the possibility to create new economic businesses for this sector has not been attractive so far (except for transport sectors as aviation, which may be of high interest for the mid-term scenario). This barrier could be somewhat mitigated through a specific supporting scheme focusing on e-fuels supply in the hard-to-abate sectors which would be weaker given the unavailability of alternatives, i.e. direct electrification solutions. For such scenario, sustainability of e-fuels needs to meet the requirements set in the REDII and its delegated acts on hydrogen (see section 1.2) Therefore, without stable business models creating competitive cost levels to the counterfactual alternatives as fossil fuels and biofuels, the sector cannot be developed. However, once the hydrogen market will be developed and resilient energy- and fuel-supply scenarios will be consolidated, industry can be rapidly built since such technologies have the ability to scale up production fast enough to meet the potential demand, as well as regulatory barriers such as chain of custody for electricity/H_2/CO_2 source and planning arrangements will be already solved (since today they regard mostly electricity/H_2/CO_2 management and trading). Today the sector still relies on economic support from demonstration projects which are helping to break down cost barriers and promote standards.

3 Conclusions

Renewable fuels of non-biological origin (RFNBO), which are synthetic, gaseous or liquid fuels derived from renewable energy and renewable hydrogen, CO_2 or N_2, can play an important role for ensuring security of energy supply and the decarbonization of transport services that cannot be electrified (maritime, aviation) but also over the next decade in road transport.

The production of RFNBO will depend on the availability of excess renewable electricity and its price when available. RFNBO production can be integrated within existing value chains producing H_2 and recovering CO_2 and N_2, 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. Therefore, CO2 (captured from concentrated in flue gases or from power plants or industrial process or from DAC) or N2 availability, as well as the green hydrogen supply, are crucial to reduce the production costs.

RFNBO conversion pathways are at early technology development levels, requiring technology improvements, demonstration, de-risking and commercial validation when coupled with the technologies producing hydrogen and capturing CO_2. Current estimates show notable cost-competitive issues, so it is is essential to provide adequate incentives to support the technology development to become market attractive. Even more support is needed for scaling up and building of demo and first of a kind plants. Energy system models project that from 2035 onwards, RFNBO can be an important source for low carbon fuel supply in the hard-to-abate transport sectors such as aviation, maritime and heavy-duty road transport.

Summarizing, this report identified as major challenges all the techno-economic aspects related to the limited capacity of the renewable electricity sector offering the opportunity to produce abundant hydrogen supply, the slow-growing carbon capture solutions for providing (capture) CO_2 or N_2, the constraints in coupling such systems in providing stable operation, and the environmental aspects (level of GHG emissions savings) still related to such inputs.

On the other hand, the opportunities offered by RFNBO are the creation of new value chains based on renewable hydrogen supply and CCU, the use of the existing fuel infrastructures for fuel distribution and use (since liquid and gaseous RFNBO are fully drop-in fuel), the possibility to integrate bio-based value chains with e-fuels production.

Main indicators identified are: cost of renewable electricity and price of electricity in the energy market; mitigation of CO_2 emissions; contribution to energy security; contribution to energy security; energy efficiency from resource to final product; costs of renewable fuels of non-biological origin and the current context; cost of technologies deployed.

The report also identified key EU legislative proposals and strategies of interest to develop RFNBO, as: RePower EU and the Fit-for-55 Package introducing Refuel EU Aviation, Fuel EU Maritime, EU Hydrogen Strategy, RED II recast, EU Energy Integration strategy and the EU CO_2 emission performance standards for cars and HDVs is included in an EU regulation (Commission, 2020).

The current EU funding programmes which involve RFNBO are: Horizon Europe, Horizon 2020, Innovation Fund, Connecting Europe Facility, INVESTEU and Catalyst EU partnership.

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 Million Euro, Germany, Denmark and Norway received higher contribution related to the number of projects financed.

Global VC investments in RFNBO firms started to take off in 2019, display a sharp increase in 2021-22 (x 4.4 as compared to 2020) and reached EUR 484 million in 2022.

Over the 2017-22 period, the EU accounted for 17.6 % of global early stage investments. This amounts to EUR 67.5 Million and essentially consist of grant funding (70 %). In the same period the EU accounted for 52 % of global later stage investment (amounting to EUR 351.2 Million).

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List of abbreviations and definitions

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

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Annexes

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

Theme	Indicator
Technology maturity status, development and trends	Technology readiness level
	Installed capacity & energy production
	Technology costs
	Public and private RD&I funding
	Scientific publication trends
	Assessment of R&I project developments
	Turnover
Value chain analysis	Gross Value Added
	Environmental and socio-economic sustainability
	EU companies and roles
	Global market growth and relevant short-to-medium term projections

Annex 2. Sustainability Assessment Framework

Parameter/Indicator	***Input***
Environmental	
LCA standards, PEFCR or best practice, LCI databases	Life Cycle Assessments (LCA) are commonly used to quantify the GHG emissions savings of bioenergy, by comparing the bioenergy system with a reference (fossil) energy system following a life cycle approach. The utilization of by-products that can displace other materials, having GHG and energy implications, must also be considered in the analysis. Several LCA models are available for GHG emission estimation, such as Biograce, E3 Database in Europe, the Argonne National Laboratory GREET model in the US and the GHGenius model in Canada. LCA requires large amounts of data on a specific product or service for assessing the complete supply chain. The wide range of results of LCA studies occurred depending on the data that are generally valid for certain regions and conditions. Several LCA databases for the GHG and energy balance of bioenergy systems are available worldwide, such as ECOINVENT, ELCD (European reference Life Cycle Database), GEMIS (Global Emission Model for Integrated Systems), CPM LCA Database or US Life Cycle Inventory Database (LCI) from NREL (Scarlat Nicolae *et al.*, 2019). In EU, the overarching legislation setting the LCA rules of the sector is the RED II, which provides the methodology for assessing greenhouse gas emissions savings from renewable liquid and gaseous transport fuels of non-biological origin and from recycled carbon fuels. Captured and used CO_2 can receive a credit for avoided emissions if it had not already received other credits before. To ensure that renewable fuels of non-biological origin contribute to greenhouse gas reduction, the electricity used should be of renewable origin. For this scope, another, parallel delegated act on hydrogen sets the guidelines for temporal and geographical correlations between the electricity production and the fuel production. The delegated act also provides updated input data as the carbon intensity of raw materials, reagents, fossil-fuels, etc. **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 compared to the fossil fuel comparator (94 gCO_2e/MJ). During 2022, the Commission published a specific delegated act setting a specific methodology to calculate the GHG emissions for RFNBO. Some calculations of the GHG emissions has been performed by the JRC (WTT v5) (Prussi *et al.*, 2020) for a large number of for renewable fuels of non biological origin pathways. However, it is worth to mention that JECv5 methodology differs from the RED II methodology in some aspects described

	in the report. The GHG emissions for a selection of pathways is presented in the next: **GHG footprint for RFNBO [g CO_{2eq}/MJ]** Syndiesel from renewable electricity, CO_2 from flue gas: 0.8 - 0.9 g CO_2eq/MJ Syndiesel from renewable electricity via FT route, CO_2 from flue gas: 0.76 - 0.78 g CO_2eq/MJ Syndiesel from renewable electricity via FT route, CO_2 from biogas upgrading: 0.8 - 0.8 g CO_2eq/MJ Syndiesel from renewable electricity via FT route, CO_2 from air via TSA: 0.8 - 0.8 g CO_2eq/MJ MeOH from renewable electricity, CO_2 from flue gas: 1.78 - 1.82 g CO_2eq/MJ DME from renewable electricity, CO_2 from flue gas: 1.7 - 1.7 g CO_2eq/MJ SNG from renewable electricity and CO_2 from flue gas: 1.7 - 3.0 g CO_2eq/MJ SynLNG from renewable electricity, CO_2 from biogas upgrading: 6.7 - 6.7 g CO_2eq/MJ Another recent paper from the JRC authors also provides other figures as regards e-fuels produced with DACs (Rocio Gonzales, 2023)
Energy balance	JRC performed the balance of the energy expended in different renewable fuels of non-biological origin pathways (WTT, v5)) (Prussi *et al.*, 2020), without accounting for the contributions related to plant construction, decommissioning and maintenance. The energy expended ratio is given for a selection of pathways is presented in the next: **Energy [MJ/MJ final fuel]** Syndiesel from renewable electricity, CO_2 from flue gas: 1.42 - 1.64 MJ/MJ Syndiesel from renewable electricity via FT route, CO_2 from flue gas: 1.55 - 1.55 MJ/MJ Syndiesel from renewable electricity via FT route, CO_2 from biogas upgrading: 1.13 - 1.13 MJ/MJ Syndiesel from renewable electricity via FT route, CO_2 from air via TSA: 1.78 - 1.89 MJ/MJ MeOH from renewable electricity, CO_2 from flue gas: 1.21 - 1.39 MJ/MJ DME from renewable electricity, CO_2 from flue gas: 1.30 - 1.49 MJ/MJ SNG from renewable electricity and CO_2 from flue gas: 0.95 - 1.09 MJ/MJ SynLNG from renewable electricity, CO_2 from biogas upgrading: 1.03 - 1.19 MJ/MJ
Ecosystem and biodiversity impact	RED II requires that the electricity used for the production of renewable fuels of non-biological origin should be of renewable origin, to ensure they contribute to greenhouse gas reduction. Potential impacts on ecosystem and biodiversity can be also related to the infrastructures of the renewable electricity plants, which should be located in dedicated areas at low impact.
Water use	Water consumption is of high interest in relation to the environmental sustainability of renewable fuels of non-biological origin. Hydrogen production via electrolysis generally requires an ecosystem rich in non-salted water (later discussed) which should not impact on the well-established industry, agriculture systems and local population. However, some

	processes might be developed to use saline water and thus avoiding the competition for water use. Water is needed for the production of renewable electricity (solar, wind, hydro, geothermal). A large proportion of life cycle water use is required for the manufacturing and construction of solar photovoltaic, wind power and geothermal facilities. Operational water for PV and wind is mainly used for cleaning purposes. Water consumption for hydropower production mostly relates to the water losses through evaporation in hydropower reservoirs that can be important, depending on the plant, location etc. Water consumption for renewable electricity generation varies between wide margins (Macknick *et al.*, 2012) (Meldrum, Heath and Macknick, 2013): Wind: 0.004 (0 – 0.04) 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 electrolysers (PEM) require 9.1 l / kg hydrogen, 10 l / kg and 10.7 l / kg respectively. Some Direct Air Capture (DAC) plants can extract water from air during operation, producing water, estimated at 1 l water per kg of carbon dioxide captured or about 3.8 l water per kg of fuel produced (Altgelt *et al.*, 2021). The results show that the water consumed over the lifecycle of hydrogen production can be significantly higher than the water employed for electrolysis alone. On a LCA basis, the water consumption for hydrogen varies between 11.7 -19.8 l / kg H_2 (for SMR process) to 30.3 l/ kg H_2 for electrolysis (Altgelt *et al.*, 2021). Water consumption for renewable fuels of non-biological origin can vary widely (Altgelt *et al.*, 2021): e-diesel from wind electricity and DAC via FT: 0.3 - 3.6 l / kg e-diesel from PV electricity and DAC via FT: (-0.8) – 2.5 l / kg e-kerosene from wind electricity and DAC via FT: 5.0 – 8.0 l / kg e- kerosene from PV electricity and DAC via FT: 3.1 – 6.4 l / kg
Air quality	Air pollutants such as carbon monoxide, nitrogen oxides, hydrocarbons and particulate matter are major exhaust emissions from fossil fuels combustion in vehicles. Excessive exposure to these pollutants can have significant impact on human health. The combustion of renewable fuels of non-biological origin also produces emissions in the form of carbon monoxide, hydrocarbons and particulates. However, the emissions from renewable fuels of non-biological origin and their impact on air quality depend on the type of fuel, related to the wide variability of fuels that can be produced. Renewable fuels of non-biological origin in the form of drop-in fuels (i.e. e-diesel or e-gasoline) have the same chemical structure and thus the same air emissions like the fossil fuels. Oxygenated fuels (such as alcohols) produce lower nitrogen oxides and

	soot emissions than fossil fuels. Biodiesel combustion results in lower gaseous pollutants hydrocarbons, aromatic hydrocarbons, carbon, and sulphur emissions and slightly higher amounts of nitrogen oxides relative to petroleum diesel (US eia, 2022). In the case of ammonia, soot emissions are reduced significantly due to the lack of carbon in the fuel molecule, while the NO_x emissions increase significantly due to the fuel-bound nitrogen compared to the fossil fuel. Air emissions with impacts on air quality could also come from the production of PV panels or wind blades and accidental releases of toxic gases and particulates could affect occupational health. Air emissions with impacts on air quality might also appear at waste processing from decommissioning of the PV and wind plants. Accidental releases of toxic gases and vapours can be prevented by minimizing wastes produced during the processes through choosing safer technologies, processes and less toxic materials.
Land use	The production of renewable fuels of non-biological origin generally requires renewable electricity technologies (with the exemption of biomass electricity) and thus the land use impact is limited to the land use for various renewable electricity sources (PV, wind, hydro, geothermal) and the land use for fuel processing plants.
Soil health	The production of renewable fuels of non-biological origin are, by definition from renewable electricity (with the exemption of biomass electricity) and thus the impact on soil is limited to the area used for renewable electricity production. Soil health may be impacted by the wastewater resulted from the cleaning of the surface of the PV panels or from the waste processing and landfilling resulted from decommissioning PV or wind plants.
Hazardous materials	The production of renewable fuels of non-biological origin do not use hazardous materials for the manufacture of various plant components. There are some hazardous materials in the manufacturing process of the PV panels (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 published a specific delegated act setting the rules for counting electricity as renewable. The methodology ensures that there is a temporal and geographical correlation between the electricity production unit and the fuel production. Given the enormous amount of additional renewable electricity generation needed, the production of renewable fuels of non-biological origin should incentivise the deployment of new renewable electricity generation capacity (principle of additionality). The economic operator has to provide evidence or data on the production of renewable liquid and gaseous transport fuel of non-biological origin and the electricity used, obtained in accordance with a voluntary national, or international schemes, setting standards for the production of biofuels, bioliquids or biomass fuels, or other fuels.
Social	
Health	Air pollutants from fuel combustion in vehicles, such as carbon monoxide, nitrogen oxides, hydrocarbons and particulate matter, are found to be major exhaust emissions. Excessive exposure to these pollutants can have significant

	impact on air quality and human health. Renewable fuels of non-biological origin in the form of drop-in fuels (i.e. e-diesel or e-gasoline) have the same chemical structure and thus the same air emissions and the same health impact as fossil fuels. Some fuels produce lower gaseous pollutants emissions of hydrocarbons, aromatic hydrocarbons, carbon monoxide and sulphur emissions and slightly higher amounts of nitrogen oxides relative to fossil fuels with corresponding health threats. Various air pollutants emissions could come from the production as well as from recycling of PV panels or wind blades from accidental releases of toxic gases and particulates with potential occupational health impacts.
Public acceptance	Public acceptance is essential for successful development and take up of renewable energies. Public acceptance for the production of renewable fuels of non-biological origin relates mostly to the photovoltaics or wind electricity generation. Photovoltaics and wind power production are generally accepted by the public as public awareness has increased the last years. Some concerns have been expressed in particular to some impacts on land use (in the case of the use of agricultural land), biodiversity and environmental impact (offshore wind impacts on marine ecosystems, impacts on migrating birds, etc.), aesthetical reasons, etc.
Education opportunities and needs	The need for further R&D for technological development of renewable fuels of non-biological origin also requires the need for education programs on new technologies that involved the production of renewable electricity (wind, solar, hydro, etc.) and fuel synthesis technologies and environmental sciences. Education opportunities concern the development of new processes, improvement of process performances, process control process integration and optimisation, opportunities for development of new analysis and testing methods, development of new materials.
Rural development impact	Renewable liquid and gaseous transport fuels of non-biological origin provides good opportunities for local and distributed renewable electricity production and fuel synthesis plants. This has significant positive impact on sustainable rural development, providing job opportunities along the supply chain, including skilled labour that can be a driver of industry development in rural areas. This provides new income-generating opportunities in rural areas, enhanced economic security of rural communities by supporting economic activities and economic growth.
Industrial transition impact	Renewable fuels of non-biological origin can contribute significantly on short term to the decarbonization of transport, energy diversification in the transport sector and energy security, while promoting innovation, growth and jobs and reducing the dependence on energy imports. Renewable fuels of non-biological origin can play a key role in the transition, acting as energy storage solution of the excess renewable electricity, balancing the electricity grid and producing renewable fuels for the decarbonisation of transport on short term. The production of renewable fuels of non-biological origin requires a carbon source that can be provided, on short term, from concentrated sources (flue gas from combustion plants, from alcohol fermentation, from biogas upgrading to biomethane, etc.) or through Direct Air Capture. Bioenergy with Carbon Capture and Utilisation (BECCU) for the production of renewable fuels of non-biological origin using biogenic carbon is a promising option for achieving carbon-neutrality.
Affordable energy access (SDG7)	Sustainable energy is a key enabler for sustainable development. Energy poverty in a wide context is related to access and affordability of energy. Renewable fuels of non-biological origin can offer great opportunities for the use of solar and wind plants to produce fuels (energy) for transport in local

	communities. Renewable fuels of non-biological origin, together with advanced biofuels, will be of utmost importance in the near- and medium-term to decarbonize aviation, shipping and long-distance heavy road transport, where other options are less suitable.
Safety and (cyber)security	*Not relevant to specific technology.*
Energy security	Renewable fuels of non-biological origin will rely mostly on the local solar and wind resources, contribute to reducing the need for imported fossil fuels and diversifying the energy supply, that would avoid creating import dependencies elsewhere and rely on short supply chains, as well as improve EU energy security and resilience. Renewable liquid and gaseous transport fuels of non-biological origin play an important role in the endeavour for a rapid clean energy transition and the reduction of its dependency on fossil fuel imports set in the REPowerEU initiative.
Food security	The most significant concerns for the use of biomass for bioenergy include the risks of increased competition between food and non-food uses of biomass. Renewable fuels of non-biological origin avoid the competition for food and feed and negative impacts on food security. Since food security, according to FAO and other authors (Brandão *et al.*, 2021), has multiple dimensions: availability, accessibility, stability and utilization, the production of the renewable fuels of non-biological origin contributes to enhanced economic conditions of rural communities, new job opportunities, increasing overall food availability, food accessibility and affordability.
Responsible material sourcing	Responsible sourcing has become a topic of interest to address sustainability risks in the global mineral supply chains. Several responsible sourcing initiatives exist for various materials, most of them aligned with the OECD guidance for responsible supply chains of minerals from conflict-affected and high-risk areas. The OECD Guidance focuses on issues of human rights, forced and child labour, occupational health and safety, human well-being, legality of operations and payment of taxes. EU Regulation (EU) 2017/821 established the requirements for supply chain due diligence obligations for materials originating from conflict-affected and high-risk areas. Responsible consumption and production is addressed by the SDG 12 *Ensure sustainable consumption and production patterns* that aims to ensure responsible consumption and production patterns in the world, by ensuring the efficient and sustainable use of natural resources by 2030. Some companies have taken voluntary commitment for responsible sourcing into account social and environmental considerations in their supply chains and their products. Sustainability assessment, using a variety of standards and frameworks, has also become a more common practice at the corporate level and plays a prominent role for responsible sourcing.

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

This annex provides an overview of the energy system models and scenarios used in CETO to support the technology development assessment and the strategic overview on clean energy technologies.

A3.1 POTEnCIA Model Overview

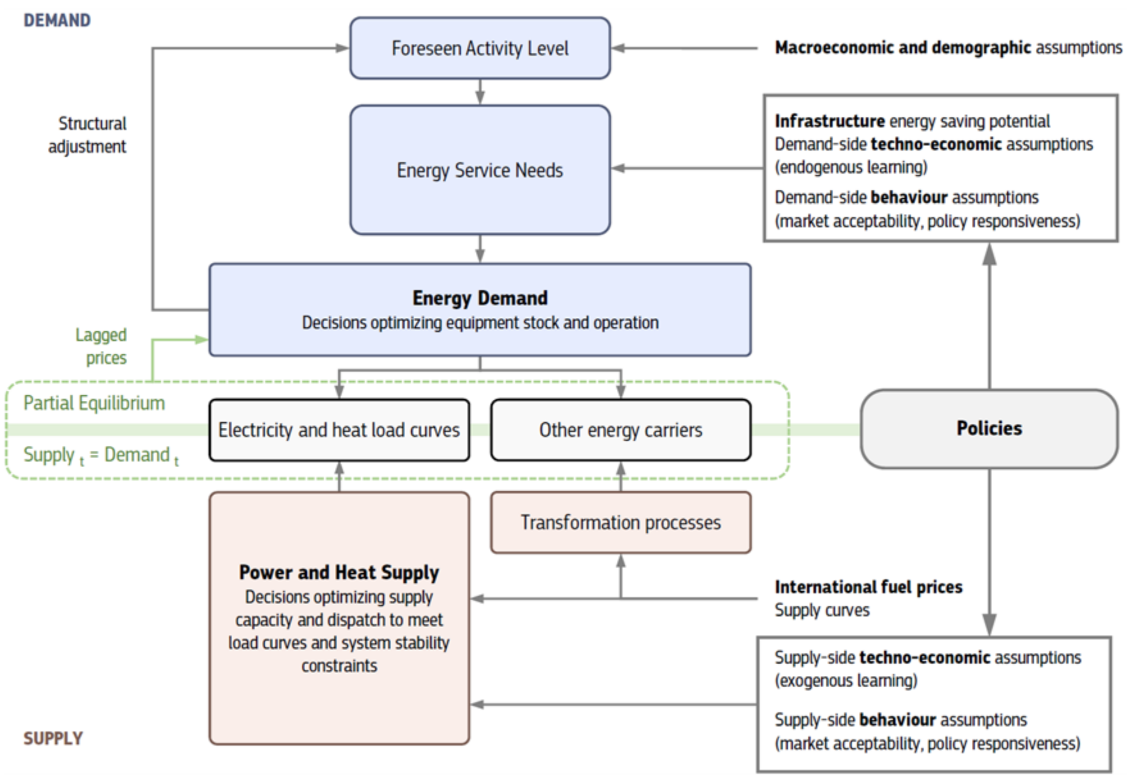
The Policy Oriented Tool for Energy and Climate Change Impact Assessment (POTEnCIA) is an energy system simulation model designed to compare alternative pathways for the EU energy system, covering energy supply and all energy demand sectors (industry, buildings, transport, and agriculture). Developed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

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

The core modelling approach of POTEnCIA (Figure A3-1); detailed in the POTEnCIA model description and in the POTEnCIA Central Scenario report) focuses on the economically-driven operation of energy markets and corresponding supply-demand interactions, based on a recursive dynamic partial equilibrium method. As such, for each sector of energy supply and demand, this approach assumes a representative agent seeking to maximize its benefit or minimize its cost under constraints such as available technologies and fuels, behavioural preferences, and climate policies. This core modelling approach is tailored to each sector, for instance to represent different planning horizons and expectations about future technologies under imperfect foresight. In particular, power dispatch modelling uses a high time resolution with full-year hourly dispatch to suitably depict the increasing need for flexibility from storage and demand response, and the changing role of thermal generation in a power system dominated by variable renewable energy sources. Within this sector modelling framework, investment decisions of the representative agents are simulated with discrete-choice modelling. The model then finds an overall equilibrium across different sectors using price signals for resources such as traditional and renewable energy carriers while accounting for efficiency and environmental costs.

This core modelling approach is implemented individually for each EU Member State to capture differences in macroeconomic and energy system structures, technology assumptions, and resource constraints. The national model implementation is supported by spatially-explicit analyses to realistically define renewable energy potentials and infrastructure costs for hydrogen and CO2 transport. Typical model output is provided in annual time steps over a horizon of 2000-2070; historical data (2000-2021) are calibrated to Eurostat and other official EU statistics to provide accurate initial conditions, using an updated version of the JRC Integrated Database of the European Energy System (JRC-IDEES). JRC-IDEES has been developed in parallel to POTEnCIA, and an updated release is planned in 2024 to ensure the transparency of POTEnCIA's base-year conditions and to support further research by external stakeholders.

Figure A3-1. The POTEnCIA model at a glance



Source: Adapted from the POTEnCIA Central scenario report

A3.2 POTEnCIA CETO Climate Neutrality Scenario overview

The technology projections provided by the POTEnCIA model are obtained under a Climate Neutrality Scenario aligned with the broad GHG reduction objectives of the European Green Deal. As such, this scenario reduces net EU27 GHG emissions by 55% by 2030 versus 1990, and reaches the EU27´s climate neutrality by 2050 under general assumptions summarized in Table A3-1. To suitably model technology projections under these overarching GHG targets, the scenario includes a representation of general climate and energy policies such as emissions pricing under the Emissions Trading System, as well as key policy instruments that have a crucial impact on the uptake of specific technologies. For instance, the deployment of bioenergy and renewable power generation technologies to 2030 is consistent with the EU's Renewable Energy Directive target (42.5% share of renewables in gross final energy consumption by 2030). Similarly, the adoption of alternative powertrains and fuels in transport is also promoted by a representation of updated CO2 emission standards in road transport and by targets of the ReFuelEU Aviation and FuelEU Maritime proposals.

Table A3-1. General assumptions of the POTEnCIA CETO Climate Neutrality Scenario

General scenario assumptions	Modelled scenario and policy assumptions
GDP growth by Member State	GDP projections based on EU Reference Scenario 2020, with updates to 2024 from DG ECFIN Autumn Forecast 2022
Population by Member State	Population projections based on EU Reference Scenario 2020, with updates to 2032 from EUROPOP 2019

International energy markets	Natural gas import projections consistent with REPowerEU targets for supply diversification and demand reduction. International fuel price projections to 2050 aligned with REPowerEU

Source: JRC

A3.3 POLES-JRC Model

POLES-JRC (Prospective Outlook for the Long term Energy System) is a global energy model well suited to evaluate the evolution of energy demand and supply in the main world economies with a representation of international energy markets. POLES-JRC is hosted at the JRC and is particularly adapted to assess climate and energy policies.

POLES-JRC covers the entire energy system, from primary supply (fossil fuels, renewables etc.) to transformation (power, biofuels, hydrogen) and final sectoral demand (Figure A3-2). International markets and prices of energy fuels are simulated endogenously. Its high level of regional detail (66 countries & regions covering the world with full energy balances, including all OECD and G20 countries) and sectoral description allows assessing a wide range of energy and climate policies in all regions within a consistent global framework: access to energy resources, taxation policy, energy efficiency, technological preferences, etc. POLES-JRC operates on a yearly basis up to 2050 and is updated yearly with recent data and model updates.

The POLES-JRC model is used to assess the impact of European and international energy and climate policies on energy markets and GHG emissions, by DG CLIMA in the context of international climate policy negotiations and by DG ENER in the context of the EU Energy Union.

POLES-JRC has also been applied for the analyses of various Impact Assessments in the field of climate change and energy, among them: the "*Proposal for a revised energy efficiency Directive*" (COM(2016)0761 final) and "*The Paris Protocol – A blueprint for tackling global climate change beyond 2020*" (COM(2015) 81 final/2).

Moreover, POLES-JRC provided the global context to the *EU Long-Term Strategy* (COM(2018) 773) and formed the energy/GHG basis for the baseline to the CGE model JRC-GEM-E3.

POLES-JRC forms part of the *Integrated Assessment Modelling Consortium* (IAMC) and participates in inter-model comparison exercises with scenarios that feed into the IPCC Assessment Reports process.

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

A3.3.1 Power system

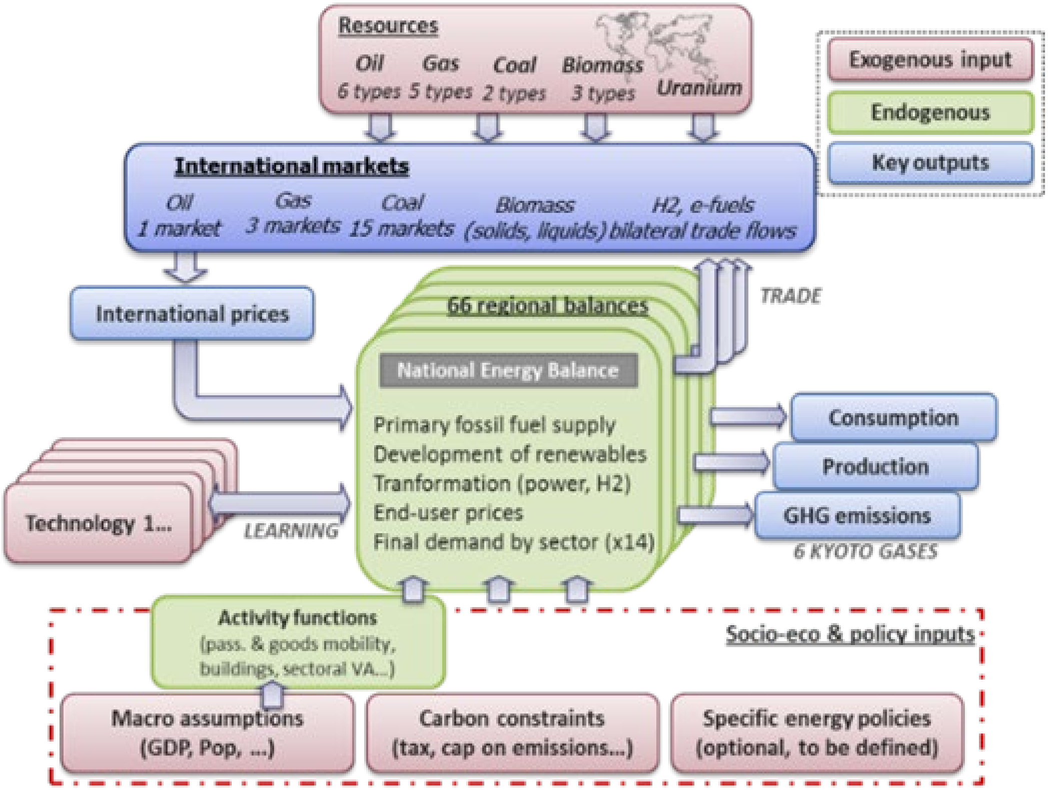
POLES-JRC considers 37 power generating technologies, covering existing technologies as well as emerging technologies. Each technology is characterised by its installed capacity, cost parameters (overnight investment cost, variable & fixed operating and maintenance cost), learning rate and other techno-economic parameters (e.g. efficiencies). The cost evolution over time is taken into account by technology learning driven by accumulated capacity.

For renewable technologies maximum resource potentials are taken into account. Similarly, the deployment of carbon capture and storage (CCS) technologies is linked to region-specific geological storage potential. In addition to these technical and economic characteristics, non-cost factors are applied to capture the historical relative attractiveness of each technology, in terms of investments and of operational dispatch.

With regard to the clean energy technologies covered by CETO, the model includes power generation using photovoltaics (utility and residential), concentrated solar power (CSP), on-shore and off-shore wind, ocean energy, biomass gasification and steam turbines fuelled by biomass, geothermal energy as well as hydropower.

CCS-equipped combustion power technologies are considered as well. Moreover, electricity storage technologies such as pumped hydropower storage and batteries are also included

Figure A3-2. Schematic representation of the POLES-JRC model architecture



Source: JRC

A3.3.2 Electricity demand

The total electricity demand is computed by adding the electricity demand from each sector (i.e. residential, services, transport, industry and agriculture). The evolution over time of the sectoral electricity demand is driven by the activity of each sector and competition between prices for electricity and other fuels.

POLES-JRC uses a set of representative days with an hourly time-step in order to capture load variations as well as to take into account the intermittency of solar and wind generation. The usage of representative days also allows to capture hourly profiles by sector and end-uses.

With a view to other CETO technologies influencing electricity consumption, the model includes heat pumps in the residential and service sector, batteries for electric vehicles and electrolysers.

A3.3.3 Power system operation and planning

The power system operation assigns the generation by technology to each hour of each representative day. The supplying technologies and storage technologies must meet the overall demand.

The capacity planning considers the existing structure of the power mix (vintage technology), the expected evolution of the demand, and the production cost of technologies.

A3.3.4 Hydrogen

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

Hydrogen can used as fuel in all sectors. Moreover, hydrogen is used to produce fertilisers as well as to produce fuels used in the transport sector (i.e. gaseous and liquid synfuels and ammonia). POLESJRC models global hydrogen trade and considers various means of hydrogen transport (pipeline, ship, truck, refuelling station).

A3.3.5 Bioenergy

POLES-JRC receives information on land use and agriculture through a soft-coupling with the GLOBIOM model[1]. This approach allows to model bioenergy demand and supply of biomass adequately by taking into account biomass potential, production cost and carbon value. Moreover, the emissions from land use and forestry (CO_2) as well as agriculture (CH_4 and N_2O) are derived from GLOBIOM.

Power generating technologies using biomass are biomass gasification (with and without CCS) and biomass fuelled steam turbines.

Hydrogen can be produced from biomass via gasification and pyrolysis. Moreover, the production of 1st and 2nd generation biofuels for gasoline and diesel is considered.

A3.3.6 Carbon Capture Utilization and Storage (CCUS)

POLES-JRC takes into account CCUS technologies for:

- Power generation: advanced coal using CCS, coal and biomass gasification with CCS, and gas combined cycle with CCS;
- Hydrogen production: Steam reforming with CCS, coal and biomass gasification with CCS, and coal and biomass pyrolysis;
- Direct air capture (DAC) where the CO_2 is stored or used to produce synfuels (gaseous or liquid);
- CO_2 storage in geological sites.

A3.3.7 Model documentation and publications

A detailed documentation of the POLES-JRC model and publications can be found at:

- https://publications.jrc.ec.europa.eu/repository/handle/JRC113757
- https://ec.europa.eu/jrc/en/poles

A3.4 POLES-JRC CETO Global 2°C Scenario

The global scenario data presented in this CETO technology report refers to a 2°C scenario modelled with the POLES-JRC model. The 2°C scenario assumes a global GHG trajectory consistent with a likely chance of meeting the long-term goal of limiting the temperature rise over pre-industrial period to 2°C in 2100.

The 2°C scenario was designed with a global carbon budget over 2023-2100 (cumulated net CO_2 emissions) of approximately 1150 $GtCO_2$, resulting in a 50% probability of not exceeding the 2.0°C temperature limit in 2100. A single global carbon price for all regions is used in this scenario, starting immediately (2023) and strongly increasing. The 2°C scenario is therefore a stylised representation of an economically-efficient pathway to the temperature targets, as the uniform global carbon price ensures that emissions are reduced where abatement costs are lowest. This scenario does not consider financial transfers between countries to implement mitigation measures.

The POLES-JRC model has been updated with the latest technologies costs from recent literature. Most of the historic data used in the 2°C scenario refers to data used in the GECO 2022 scenarios (energy balances, energy prices, capacities).

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