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*Review*

# Overview of the e-Fuels Market, Projects, and the State of the Art of Production Facilities

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**Abstract:** E-fuels, or synthetic fuels produced from green hydrogen and captured $CO_2$, are a promising solution for achieving climate neutrality by replacing fossil fuels in transportation and industry. They help reduce greenhouse gas emissions and efficiently utilize renewable energy surpluses. This study aims to assess the current state and future potential of e-fuel production technologies, focusing on their scalability and market integration. A comprehensive literature review and market trend analysis, including modeling based on historical data and growth forecasts, were used to estimate market penetration. Results indicate that e-fuels could reach a 10% market share within the next 5 years, potentially reaching 30% in 20 years, particularly in aviation, maritime transport, and the steel industry. Ongoing projects expected to be completed this decade may cover about 20% of the global liquid fuel demand for transportation. However, challenges such as high costs, scalability, and recent project terminations due to funding shortages highlight the need for substantial investment, regulatory support, and innovation. Global collaboration and policy alignment are essential for the successful development and integration of e-fuels as a critical pathway to decarbonization.

**Keywords:** e-fuel; Fischer–Tropsch; e-methanol; hydrogen

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## 1. Introduction

Global fuel consumption remains a critical issue for both the modern economy and the environment. It largely relies on fossil fuels such as oil, coal, and natural gas. The production and combustion of these fuels are responsible for generating significant amounts of carbon dioxide, the primary greenhouse gas contributing to global warming. The greenhouse effect, caused by excessive greenhouse gases in the atmosphere, leads to severe climate changes, including rising sea levels, extreme weather events, and ecosystem degradation.

The transport sector generates nearly one quarter of total $CO_2$ emissions [1], and it is heavily dependent on oil products, which account for more than 90% of transport sector energy needs [2]. While renewable energy sources (RESs), such as wind, solar, and hydropower, are being intensively developed, their application in the transportation sector remains limited. Most vehicles worldwide still rely on liquid fuels, highlighting the need for alternatives that can reduce $CO_2$ emissions without requiring a complete overhaul of existing fuel infrastructure [3].

Ausfelder [4] indicates at least three solutions for $CO_2$ reduction in transportation sector: (I) direct electrification by battery driven vehicles, (II) indirect electrification by hydrogen fueled vehicles, and (III) non-fossil based fuels for the classical internal combustion

engines, such as e-fuel, bio-fuels, etc. Depending on the application area, the preference for technological solution is different, i.e., not all of them can be applied for each of the transportation sector. For instance, sustainable aviation fuels (SAFs) are recognized as an accessible intermediate-term solution for the reducing $CO_2$ in aviation [5], where it should be highlighted that the sector is responsible for 3% of global $CO_2$ emissions [6]. The primary reason for this accessibility is SAFs' ability to work with current aircraft engines and fuel systems, enabling a smooth transition without requiring significant modifications.

The e-fuels are environmentally friendly synthetic substances (carbon neutral) that differ from their traditional counterparts in the way they are sourced [7]. The production of e-fuel included several conversion steps such as water electrolysis, carbon dioxide capture, and fuel synthesis, where $CO_2$ and $H_2$ are combined through chemical process such as methanol synthesis, Fischer–Tropsch synthesis, Methane Synthesis (Sabatier process), etc. [8]. Alternatively, green hydrogen can be combined with nitrogen to produce e-ammonia. These e-fuels act as versatile energy carriers, capable of being stored, transported, and used across various energy sectors, such as transportation and industry [9], and utilized in combustion engines [10,11] or fuel cells [12,13]. They can provide real competition to biofuels used in transport and other energy sources [14,15]. Although essential components for e-fuel production like electrolysis and Fisher–Tropsch reactors are already commercially available, only a limited number of facilities are currently operational [16]. E-fuel production is still in its early stages and faces significant hurdles [17]. The main challenge lies in the high production costs, making the fuel economically impractical for end users at present.

E-fuels generated from green hydrogen and captured $CO_2$ are recognized as the key element of carbon neutral propulsion systems in transportation [1]. The International Energy Agency indicates that alternatives fuels, such as biofuels, hydrogen carriers (such as ammonia), and low-emission synthetic fuels [2], will play a key role in transportation beyond 2023 and can be used for energy production through various energy conversion methods such as fuel cells [14] or internal combustion engines [18].

Their main advantage lies in the compatibility with existing engines and infrastructure in aviation, shipping, and freight. As the modifications are not required, the e-fuels offer significant market potential and long-term benefits in reducing carbon emissions.

*Novelty of the Paper*

Since the topic of e-fuel production is currently of significant relevance, as evidenced by the themes of research and development project calls within grants awarded by the European Union, numerous new initiatives have recently emerged. These projects focus on the construction of pilot installations as well as facilities aimed at achieving the commercial-scale production of hydrogen and e-fuels. Few of them have been reviewed by [19] in terms of production potential and by [20] in terms of $CO_2$ utilization; other recent literature reviews concerning e-fuels such as [21] focus only on the recent technological progress in the production of e-fuels instead of the real amounts of plants that are being developed. The article [20] provides an overview of such projects, but it was published 3 years ago, and during that time, new projects and research facilities on e-fuels have been launched. In this article, in addition to presenting the current state of knowledge about e-fuel technology, a list of the latest projects and research installations using this technology is provided. A research paper [9] provides a comprehensive review of e-fuels as a pathway for the energy transition. It covers e-fuel production technologies, focusing on e-hydrogen and its derivatives like e-methanol, e-diesel, and e-ammonia. The study emphasizes the sustainability aspects, particularly the use of renewable energy and carbon-neutral synthesis processes. The technological maturity, energy conversion efficiency, and

sustainability metrics are thoroughly compared. Another research [6] focuses on the techno-economic assessment and life cycle assessment of e-fuel production. It systematically reviews production technologies, economic feasibility, and environmental implications while highlighting the importance of renewable energy integration for sustainable hydrogen production. The authors identify key knowledge gaps, such as the need for policy support and production cost optimization. Compared to the reviewed articles, this paper provides a more integrative analysis by combining a technological overview, a market analysis, and a detailed global review of both scientific and commercial e-fuel projects and installations. While previous works focused on either technical aspects or techno-economic assessments separately, this paper uniquely bridges the gap between scientific advancements, market trends, and commercial implementation prospects. The main goal is to assess the scalability of e-fuels, their market integration, and future development trends to determine their role in reducing fossil fuel dependency and facilitating large-scale decarbonization. The novelty of this work also lies in the summary of the amounts of the e-fuels and hydrogen that will be produced when actual plants currently in construction start delivering products to the market.

## 2. Methods for e-Fuel Production

Synthetic fuels are obtained through a synthetic method using hydrogen, carbon dioxide captured from the atmosphere, and electricity and solar energy, which are obtained in an equally environmentally friendly way [7]. According to Porsche, which has been contributing to the development of synthetic fuels for several years, a gallon of fuel can cost as much as about PLN 33 (USD 8.1) or less than PLN 9 (USD 2.2) for a liter of synthetic fuel [7].

A conceptual diagram of the synthetic fuel production process is shown in Figure 1.

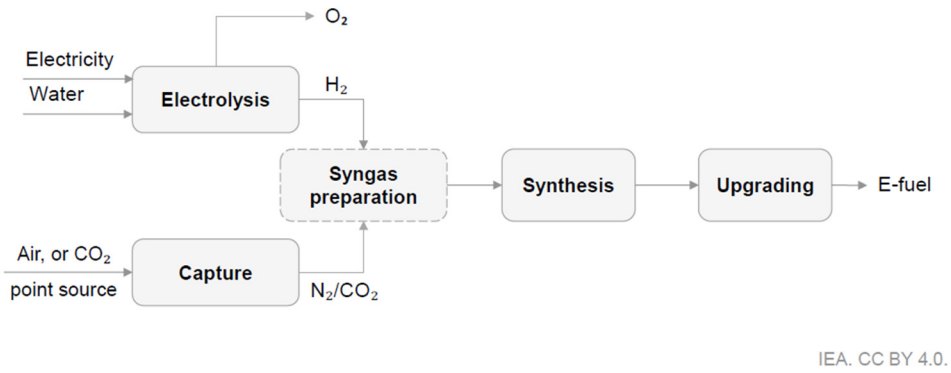



**Figure 1.** Schematic diagram of the synthetic fuel production process [22].

The production of e-fuels generally requires four steps [22]: the production of hydrogen, capture of nitrogen ($N_2$) or carbon dioxide ($CO_2$), conversion of feed gas to new molecules in synthesis, and final refinement of the raw product. Prior to synthesis, the components ($H_2$ and $CO_2$ or $N_2$) must be mixed in sufficient quantities to meet the stoichiometric requirements of the subsequent synthesis.

The production of liquid hydrocarbon fuels using the Fischer–Tropsch (FT) method requires an additional synthesis gas preparation step that converts $CO_2$ into carbon monoxide (CO), the more readily usable form of carbon required by this technology.

A more detailed diagram of e-fuel production (according to [23]) is shown in Figure 2. Main methods for converting hydrogen to e-fuels are presented there.

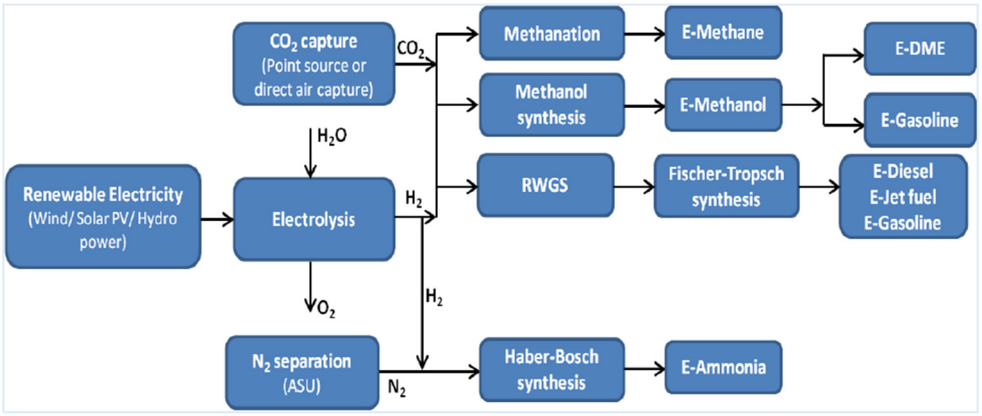



**Figure 2.** Schematic diagram of the production process of various synthetic fuels [23].

Large-scale commercial electrolyzers currently operate with efficiencies in the order of 65–70% in terms of calorific value (LHV), while the efficiency of the later stage of e-fuel synthesis ranges from 65 to 85% (LHV) [24], depending on the final product [22]. As a result, the overall thermal efficiency of the e-fuel production process ranges from 40 to 60% [22].

A Sankey diagram for the e-fuel production process according to [22] is shown in Figure 3.

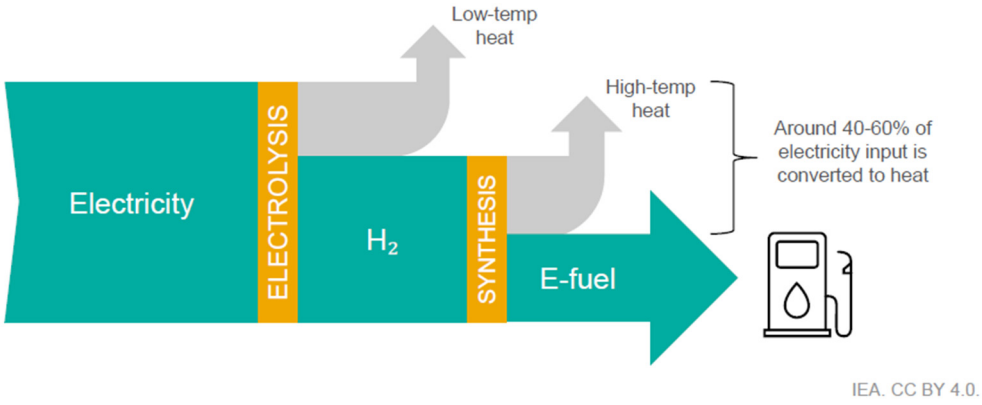



**Figure 3.** Sankey diagram for the e-fuel production process [22].

### *2.1. Traditional (RWGS–FT)*

One of the most prominent methods for the production of e-fuels is the Fischer–Tropsch (FT) synthesis, which enables the generation of long-chain hydrocarbons (C1–C70+). This includes compounds found in modern fuels, such as petrol and diesel, which, when synthesized, often exhibit superior properties compared to their counterparts derived from crude oil [25]. It is worth noting that the concept of synthetic fuel production via Fischer–Tropsch synthesis is not novel. The origins of this method date back to 1923, when Franz Fischer and Hans Tropsch, of the then Kaiser Wilhelm Institute for Coal Research (now the Max Planck Institute) in Germany, successfully converted CO and $H_2$ into liquid hydrocarbons. This was achieved in a high-pressure tubular reactor operating at temperatures of 400–450 °C [4]. Germany is pioneering in this technology, aiming for the decarbonization of the transport industry [26].

The Fischer–Tropsch process encompasses a broad spectrum of conversion reactions, facilitating the formation of various hydrocarbons. The fundamental reactants in FT synthesis are hydrogen and carbon monoxide (collectively known as syngas), alongside a suitable catalyst. Under appropriate conditions of temperature and pressure, this process yields

organic chemicals such as linear alkenes and alkanes as well as liquid fuels like methanol and ethanol when specific reaction pathways are followed. The foundational reactions for the formation of alkenes and alkanes can be represented by the following equations:

$$2nH2 + nCO \rightarrow CnH2n + nH2O \quad (1)$$

$$(2n + 1)H2 + nCO \rightarrow CnH(2n + 2) + nH2O \quad (2)$$

$$2nH2 + nCO \rightarrow CnH(2n + 2)O + (n - 1)H2O \quad (3)$$

The FT process uses metal-based catalysts including Fe, Ni, Co, Ru, Rh, and Ru (being the most active, but also currently being too expensive for commercial use). Iron is the traditional choice, while cobalt, often supported on silica or alumina, is preferred for producing long-chain alkanes. Nanoparticle catalysts offer high activity due to their surface area but are sensitive to impurities, which can enhance or degrade their performance [27]. The catalyst choice is very important when defining the required final output of the reactor in order to decide on what our required final product is that we want to obtain [28]. Also, FT operates in two temperature regimes: low-temperature FT (200–250 °C), yielding long-chain molecules, and high-temperature FT (320–375 °C), favoring shorter chains. Primary products are typically 1-n-alkenes, but higher temperatures, pressures, or hydrogen-rich conditions promote n-alkane formation. Reaction conditions also lead to secondary processes like hydrogenation, isomerization, and cyclization, creating diverse products [29]. There are various routes for the improvement of the FT process investigated; for example, through the evaluation of the hydrogenation of $CO_2$ processes with MgO promoters over Fe-based catalysts [30] or synthesis long-chain paraffins on combined catalysts [31]. The latter methods have recently been considered to possible as stand-alone techniques for the production of e-fuels [32].

Technologies in FT reactors can be divided into (a) fluidized-bed reactors; (b) slurry bubble column reactor; and (c) fixed-bed and compact reactors [33].

Sasol has historically utilized circulating fluidized-bed reactors for FT synthesis; however, these have been largely replaced by fixed fluidized-bed reactors due to several limitations. Key challenges of the circulating design include high energy demands for catalyst circulation, significant catalyst attrition necessitating the use of attrition-resistant catalysts, and lower $\alpha$-product selectivity resulting in increased greenhouse gas emissions due to high-temperature operation [34].

Slurry bubble column reactors (SBCRs) were developed in 1938 and achieved a production rate of 11.5 tons of hydrocarbons per day. These reactors use synthesis gas reacting on a liquid-phase catalyst, with heavier hydrocarbons separated at the bottom and product gas exited at the top. Challenges like catalyst separation and scaling up have been addressed through recent modeling, enabling improved industrial feasibility. Increasing the temperature (258–290 °C) and pressure (up to 3 MPa) and adjusting the $H_2/CO$ ratio significantly affect conversion and product selectivity, reaching overall conversion from 0.79 to 0.97 [35]. This technology has been developed by companies such as Exxon [36] and Sasol [37].

Fixed-bed reactors are highly desirable for Fischer–Tropsch synthesis due to their plug-flow behavior, lower maintenance costs, and reduced catalyst attrition. Recent advancements in microchannel and multichannel fixed-bed reactors have improved heat transfer and mobility, making them suitable for unconventional and stranded feedstocks, although their high manufacturing costs remain a challenge. Microchannel reactors, such as those developed by Velocys [38], have demonstrated superior FTS activity, efficient heat removal, and higher CO conversion rates with reduced methane selectivity compared to conventional packed-bed reactors. Research into catalyst design, including shortening pore

lengths and optimizing cobalt nanoparticle placement, has improved product selectivity and reduced light gas formation. Additionally, emerging technologies such as supercritical media operation and structured packing reactors offer enhanced heat and mass transfer, potentially increasing C5+ productivity by up to 25%.

### 2.2. Sabatier/COx Methanation

The Sabatier process, a catalytic reaction between hydrogen ($H_2$) and carbon dioxide ($CO_2$) to produce methane ($CH_4$) and water, is a cornerstone of synthetic fuel production. This exothermic reaction, represented by Equation (4), has gained significant attention for its ability to utilize renewable hydrogen and captured $CO_2$, offering a sustainable pathway for e-methane production [39]. The reaction takes place at elevated temperatures, typically between 300 and 400 °C, and pressures around 1–10 bar, under the influence of a catalyst, commonly nickel-based, due to its high activity and cost-effectiveness.

$$CO_2 + 4H_2 \rightarrow CH_4 + 2H_2O \quad (4)$$

Sabatier reactors are designed to optimize the conditions necessary for efficient methanation while managing the exothermic heat release, which can otherwise destabilize the process. Modern reactor designs often incorporate advanced heat management systems, including heat exchangers, to ensure thermal stability and prevent catalyst deactivation due to excessive temperatures. These reactors can operate in a variety of configurations, including fixed-bed, fluidized-bed, and microchannel reactors. Fixed-bed reactors are the most common in industrial applications, where the catalyst is packed in a stationary bed and the reactant gases flow through it.

The choice of catalyst is critical for reactor performance [40]. Nickel-based catalysts, often supported on materials such as alumina or silica, provide high selectivity and conversion rates for $CO_2$ methanation. The activity of these catalysts can be further enhanced by doping with other metals, such as cobalt or ruthenium, which improve resistance to sintering and poisoning by impurities like sulfur. Advanced catalyst development is also focusing on reducing the operating temperature and pressure requirements, which can significantly improve the energy efficiency of the process.

Additionally, the integration of Sabatier reactors with upstream and downstream processes is crucial for their application in industrial settings. Renewable hydrogen is typically supplied by water electrolysis powered by renewable energy sources, while $CO_2$ is captured from industrial flue gases or directly from the atmosphere using direct air capture (DAC) systems [41]. Downstream, the synthetic methane can be used directly as a fuel or as a feedstock for further chemical synthesis. In power-to-gas systems, the methane produced in Sabatier reactors is injected into existing natural gas grids, effectively enabling large-scale energy storage.

Theoretical studies and computational modeling play an essential role in optimizing Sabatier reactor performance. Reaction kinetics and thermodynamics models are used to predict conversion rates and selectivity under varying conditions, guiding reactor design and operational strategies. Moreover, advances in process intensification, such as the use of microchannel reactors, allow for higher reaction rates and more compact designs, which are particularly suited for decentralized energy systems.

The industrial application of the Sabatier reaction is demonstrated in projects like the Norsk e-Fuel initiative, which integrates power-to-liquid (PtL) and power-to-methane (PtM) technologies. These projects aim to produce synthetic fuels at scale by combining electrolysis-derived hydrogen with $CO_2$ capture technologies. This marks a significant step forward in the pursuit of sustainable aviation fuels and synthetic natural gas production.

The market for electrofuels, or e-fuels, is expanding as more pilot and demonstration plants are being established across Europe and other regions. These plants focus on enhancing the efficiency and cost-effectiveness of methanation technologies. However, challenges remain, including scalability, high energy requirements for electrolysis, and the need for significant infrastructure to integrate $CO_2$ capture with fuel synthesis processes. Advances in catalytic efficiency, particularly with Ni-based catalysts, are addressing some of these challenges by improving the performance of the Sabatier reaction.

The Sabatier process remains a cornerstone of synthetic fuel production and a key driver of the emerging e-fuel market. While challenges related to energy efficiency, scalability, and infrastructure persist, significant strides are being made in catalysis and integration technologies, ensuring a promising future for carbon-neutral fuel solutions.

### *2.3. Methanol–$CO_2$ Electrolysis*

Sustainable aviation fuels (SAFs) are critical to achieving net-zero emissions in the aviation industry, particularly as alternatives to fossil-derived kerosene. Two of the most promising pathways for producing synthetic hydrocarbons suitable for jet fuel from $CO_2$ include the methanol route (Figure 4) and the $CO_2$ electrolysis route (Figure 5). Each method uniquely leverages $CO_2$ as a feedstock, renewable energy, and catalytic process to produce hydrocarbons in the $C_8$–$C_{16}$ range, essential for aviation fuels.

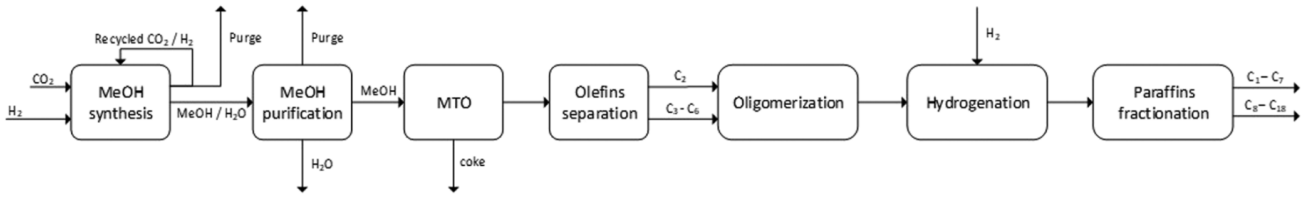



**Figure 4.** Methanol route for SAFs production [42].

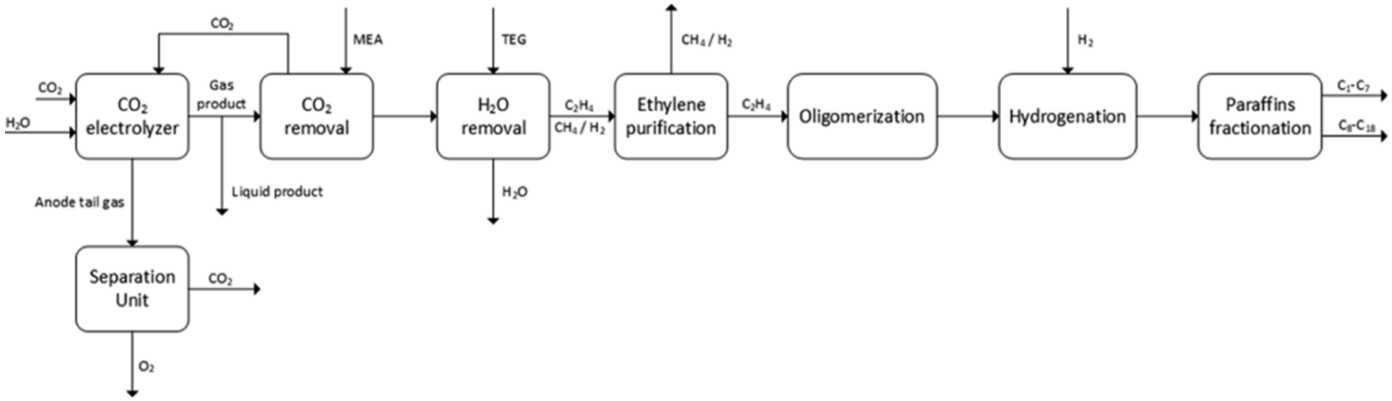



**Figure 5.** $CO_2$ electrolysis route for SAF production [42].

The methanol route begins with the catalytic hydrogenation of $CO_2$ to produce methanol ($CH_3OH$). This step uses a $Cu/ZnO/Al_2O_3$ catalyst at moderate pressures (50–90 bar) and temperatures (~250 °C). Methanol is then purified and processed through the Methanol-to-Olefins (MTO) step, where it is converted into light olefins ($C_2H_4$ and $C_3H_6$) using zeolite catalysts like SAPO-34. These light olefins are subsequently oligomerized into longer chain hydrocarbons within the $C_8$–$C_{16}$ range through acid or metal-based catalysts, followed by a hydrogenation step to saturate the olefins into paraffins. This pathway is attractive due to methanol's relative ease of production, transportation, and storage, and it achieves a high $CO_2$ conversion efficiency (~92%) with low energy intensity compared to alternative methods. However, its energy demands are dominated by

the production of green hydrogen, which accounts for approximately 83% of the total energy input.

The $CO_2$ electrolysis route, on the other hand, directly reduces $CO_2$ electrochemically to ethylene ($C_2H_4$), which serves as the key intermediate. This process is carried out using gas-diffusion electrodes (GDEs) with a Cu-based catalyst, achieving a Faradaic efficiency of around 50% for $C_2H_4$ under lab-scale conditions. Despite its promise, this method faces high energy demands due to the electrochemical cell voltage required for $CO_2$ reduction. Once produced, ethylene undergoes oligomerization, similar to the methanol route, followed by hydrogenation to produce saturated hydrocarbons in the desired $C_8$–$C_{16}$ range. Although the $CO_2$ electrolysis route has the potential to achieve nearly 100% $CO_2$ efficiency and reduces the dependency on external hydrogen sources, its practical application remains limited due to the high energy intensity of the electrolysis process.

Comparatively, the methanol route demonstrates the lowest overall energy consumption and has been validated at higher technology readiness levels (TRLs). The $CO_2$ electrolysis route, while promising, remains at an earlier development stage and requires advancements in energy efficiency and electrocatalyst design to overcome current limitations.

Both pathways hold significant potential for aviation e-fuel production, particularly when powered by renewable energy sources. The continued optimization of catalytic processes, hydrogen production efficiency, and integration with renewable power systems will be pivotal in scaling these technologies to meet the growing demand for sustainable aviation fuels.

Syngas (a mixture of CO and $H_2$) is a crucial intermediate for the synthesis of liquid e-fuels, such as methanol or hydrocarbons, and its production via electrochemical methods represents a sustainable pathway for carbon-neutral fuel systems. Two major routes dominate syngas preparation: direct $CO_2$ electrolysis and co-electrolysis of $CO_2$ and $H_2O$, both powered by renewable energy. Among the various technologies available, Molten Carbonate Electrolysis (MCE) has emerged as a highly promising candidate, owing to its superior efficiency, scalability, and thermodynamic advantages.

In Molten Carbonate Electrolysis (MCE), $CO_2$ and $H_2O$ are electrochemically reduced at high temperatures (600–700 °C) to produce syngas [X3]. The molten carbonate electrolyte facilitates the transport of $CO_3^{2-}$ ions, enabling efficient electrochemical conversion with minimal polarization losses. Compared to other technologies, MCE benefits from high ionic conductivity and thermally integrated operation, which reduces the electrical energy demand by utilizing waste heat sources. A key advantage of MCE lies in its ability to co-electrolyze $CO_2$ and water in a single step, yielding syngas with an optimal $H_2/CO$ ratio suited for downstream fuel synthesis processes, such as Fischer–Tropsch or methanol synthesis. Experimental studies have demonstrated efficiencies exceeding 90% due to the synergistic utilization of thermal and electrical energy, making MCE a competitive solution for large-scale applications.

In contrast, Solid Oxide Electrolysis Cells (SOECs) also represent a viable high-temperature technology for syngas production [43]. SOECs operate at temperatures between 600 and 1000 °C and can electrochemically reduce $CO_2$ or co-electrolyze $CO_2$ and $H_2O$ to form syngas. The technology leverages oxygen-ion conducting solid electrolytes, such as YSZ or doped ceria, to transport oxygen ions across the cell. SOECs achieve high current densities and Faradaic efficiencies due to reduced overpotentials at elevated temperatures. However, SOECs are more susceptible to degradation, particularly at the electrode–electrolyte interfaces, due to thermal cycling and material instability [44].

The co-electrolysis of $CO_2$ and water offers a clear advantage over separate electrolysis steps, as it simplifies the process and reduces overall energy consumption. Co-electrolysis involves both $CO_2$ reduction to CO and water splitting to $H_2$, with the water–gas shift

reaction occurring in situ, producing syngas in a single thermodynamic equilibrium-driven process. MCE demonstrates superior performance in this regard, achieving near-equilibrium gas compositions with flexible $H_2$/CO ratios, which can be tailored for specific downstream synthesis requirements [45]. This contrasts with SOEC, where managing thermal gradients and electrode degradation remains challenging despite its high efficiency.

### *2.4. $CO_2$ Capture, Utilization, and Storage Strategies*

Each method for e-fuel production requires CO or $CO_2$ as an ingredient, which must be obtained from environment; thus, CCUS strategies play a crucial role in e-fuel production. CCUS solutions begin with capturing $CO_2$ at its source or directly from the air. Recent developments in this area include the following:

#### 2.4.1. Post-Combustion Capture

This method involves the separation of carbon dioxide from flue gases produced during combustion processes [46]. Recent advancements in this domain include the development of amine-based solvents that exhibit enhanced absorption efficiency and reduced energy demands during the regeneration process. Furthermore, the application of solid sorbents, such as metal–organic frameworks (MOFs), has gained significant attention due to their high selectivity and substantial capacity for $CO_2$ adsorption, positioning them as a promising alternative in this technology and delivering prospective results during the operation of pilot plants [47].

#### 2.4.2. Pre-Combustion Capture

This is predominantly employed within integrated gasification combined cycle systems, where fossil fuels are converted into a synthesis gas prior to combustion [48]. This approach enables the separation of $CO_2$ at higher concentrations and pressures, thereby improving capture efficiency. The field has witnessed considerable progress through the introduction of advanced catalysts and membrane technologies, which have substantially enhanced the efficiency and cost-effectiveness of the process [49].

#### 2.4.3. Oxy-Fuel Combustion

This is a technique that involves the combustion of fuels in an environment enriched with pure oxygen instead of air [50]. This method produces a flue gas that is predominantly composed of $CO_2$ and water vapor, simplifying the separation of $CO_2$. Recent innovations in this area focus on the development of more energy-efficient processes for oxygen production, such as cryogenic distillation and membrane-based separation technologies, which aim to mitigate the high energy demands traditionally associated with this method [51].

#### 2.4.4. Direct Air Capture

A range of ways to capture $CO_2$ at very low concentrations represent an innovative approach for removing $CO_2$ directly from the atmosphere, utilizing liquid or solid sorbents [52]. Prominent examples of this application include facilities developed by Climeworks [53] and Carbon Engineering [54], which have demonstrated scalability and operational efficiency. These systems often integrate renewable energy sources to reduce the carbon intensity of the capture process, making it a viable strategy for addressing diffuse and residual emissions within the broader context of achieving net-negative emissions.

Biogenic $CO_2$ sources (e.g., fermentation processes in bioethanol production or biomass combustion) can also be used in the e-fuel production process.

Depending on the $CO_2$ capture method adopted and its source, e-fuels can be divided into low-carbon, green/carbon-neutral and negative-carbon. The division of e-fuels de-

pending on the adopted $CO_2$ capture method and its source and with respect to the energy source is shown in Table 1.

**Table 1.** Division of e-fuels depending on the adopted $CO_2$ capture method and its source and with respect to the energy source.

| Category | $CO_2$ Capture Method and Source | Energy Source | Environmental Impact |
|---|---|---|---|
| Low-carbon | Industrial processes, flue gases | Partly renewable | Reduced emissions but not fully neutral |
| Green/Carbon-neutral | Atmospheric $CO_2$, biogenic $CO_2$ | Fully renewable | Completely carbon-balanced lifecycle |
| Negative-carbon | Atmospheric $CO_2$ | Fully renewable | Only if $CO_2$ emissions resulting from e-fuel combustion are lower than the amount of $CO_2$ captured from the atmosphere |

The last item in Table 1 (negative-carbon e-fuels) is only a theoretical technology at the time of writing this review. However, the authors believe that it will be developed in the coming years. This technology (negative-carbon) requires that less $CO_2$ is released into the atmosphere as a result of e-fuel combustion than was captured during the production process of this fuel.

## 3. Types of Liquid e-Fuels and Market Parameters

The analysis of liquid e-fuels plays a critical role in evaluating the feasibility of synthetic fuel production pathways, particularly for decarbonizing hard-to-abate sectors such as aviation and shipping. This section provides a comprehensive overview of the production costs and market parameters for key liquid e-fuels, including e-ammonia, e-methanol, e-naphtha, and others. With the exception of ammonia, $CO_2$ carbon is needed to produce e-liquids.

The averaged cost of e-ammonia and e-methanol at different $CO_2$ capture costs, according to [22], is shown in Figure 6.

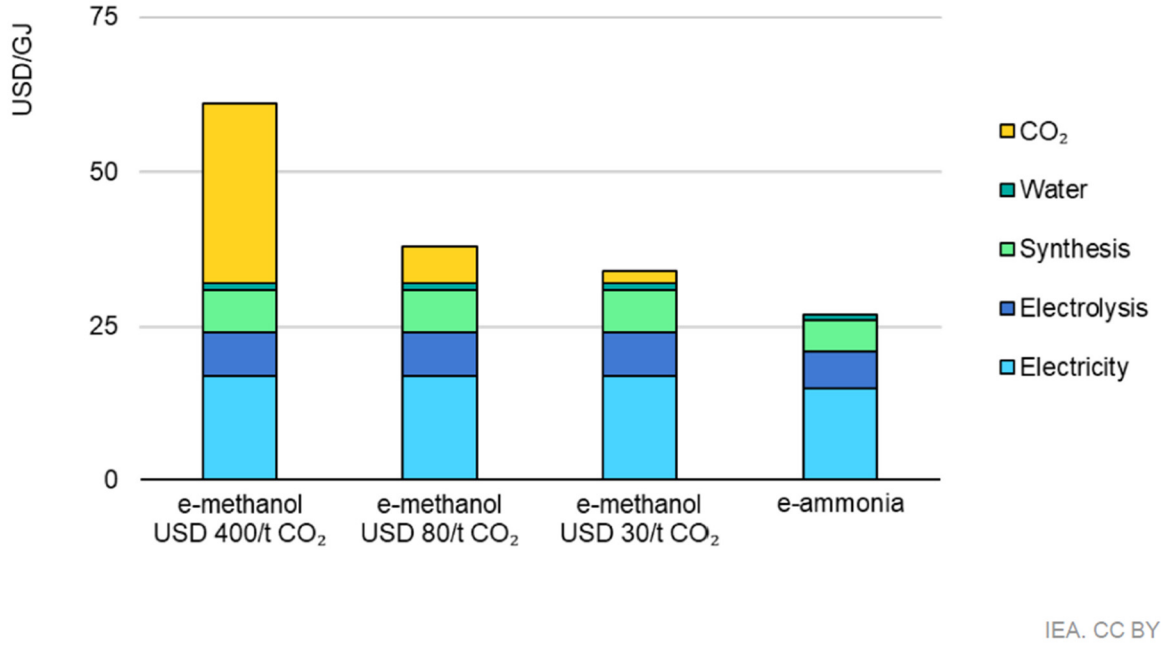



**Figure 6.** Averaged cost of e-ammonia and e-methanol with different $CO_2$ capture costs [22].

For e-methanol, the production cost depends primarily on the cost of $CO_2$ capture (energy consumption needed for $CO_2$ capturing and utilization process), which can account for up to 50% of the total cost at the higher end of the range (approximately 60 USD/GJ). The lowest cost (third bar in Figure 6) represents the lowest cost of $CO_2$ capture at the level of 30 USD/t$CO_2$, which represents capturing from high-concentration sources through post-combustion technologies, which are expected to be cheapest by 2030 and will not require high technologies for $CO_2$ separation. The second bar, where $CO_2$ capture costs are at the level of 80 USD/t$CO_2$, represents $CO_2$ sequestration from flue gases. In the first bar, the most expensive represents the price of 400 USD/t$CO_2$, assuming this level of cost for direct air $CO_2$ capture. All the prices are predicted for 2030 and are presented in [22]. In contrast, e-ammonia, which does not require $CO_2$ for its synthesis, has the lowest production cost among the considered e-fuels, at just over 25 USD/GJ. E-ammonia is produced via the Haber–Bosch process, combining nitrogen from air separation and hydrogen from electrolysis. The cost structure of these fuels is largely influenced by electricity consumption, contributing around 17 USD/GJ. Electrolysis accounts for approximately 7 USD/GJ, while fuel synthesis ranges from 5 to 7 USD/GJ. Water costs remain minimal in comparison, averaging approximately 1 USD/GJ per GJ of e-fuel produced. In turn, the averaged cost of e-naphtha by potential cost reduction measures according to [22] is shown in Figure 7.

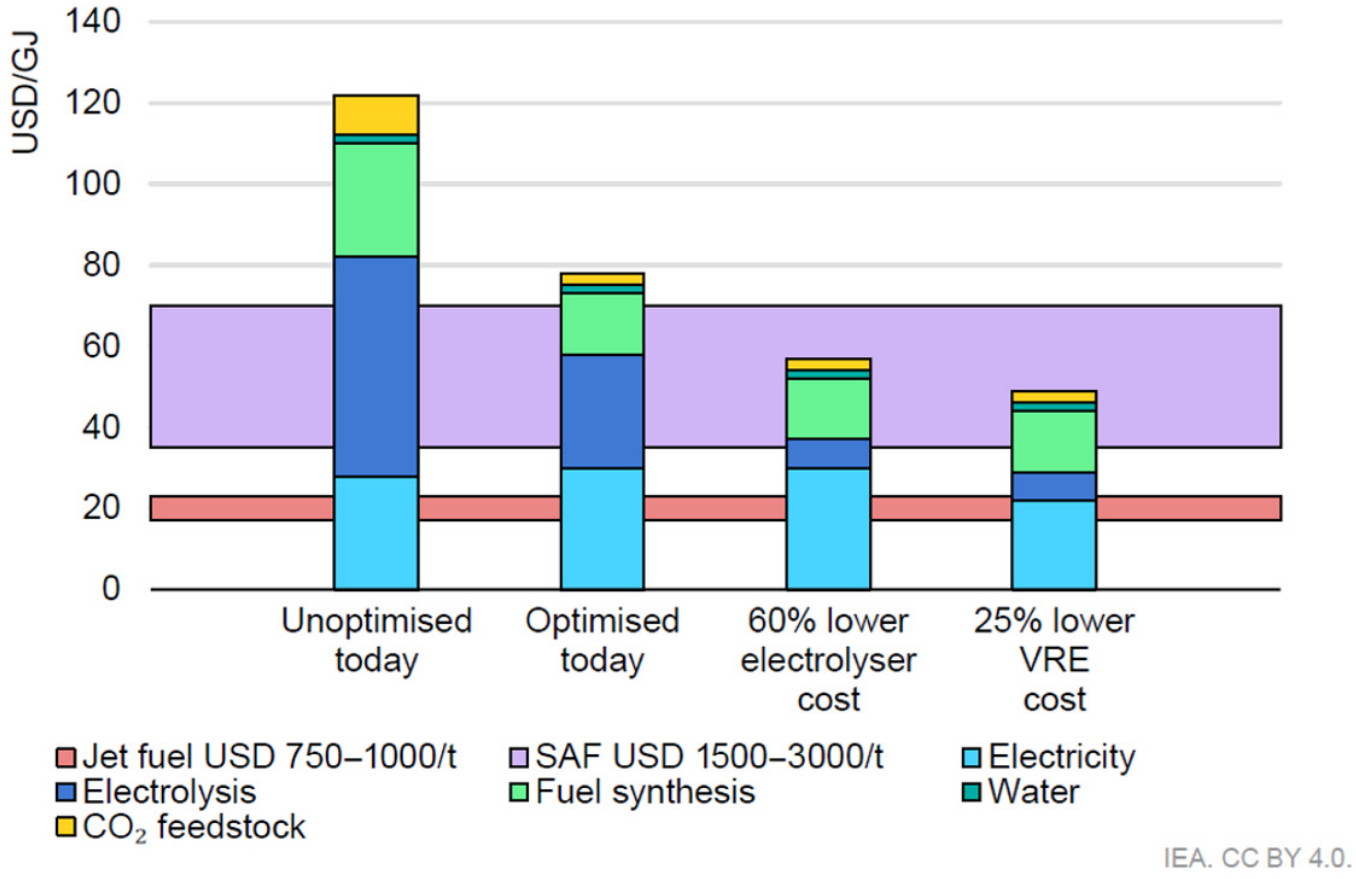



**Figure 7.** Averaged cost of e-naphtha by potential cost reduction measures [22].

This figure shows the costs for non-optimized and optimized installations, for installations with electrolyzer costs lowered by 60%, and for a case with VRE costs lowered by 25%. For the non-optimized installation, the cost of the e-naphtha exceeds 120 USD/GJ, while for the optimized installation, it is around 80 USD/GJ. For installation with electrolysis costs lowered by 60%, the cost is less than 60 USD/GJ, and for the last case (25% lower VRE cost), the cost is about 50 USD/GJ. The cost of electricity for e-naphtha changes from

around 20 to around 30 USD/GJ. In turn, electrolysis costs range from about 7 USD/GJ to about 50 USD/GJ (for a non-optimized installation). Fuel synthesis costs range from about 20 USD/GJ to about 30 USD/GJ. $CO_2$ costs (needed to produce e-naphtha) range from about 3 USD/GJ (value given per 1 GJ of e-naphtha) to about 10 USD/GJ. The cost of water here is approximately 2 USD/GJ (per 1 GJ of e-fuel).

The averaged cost of e-ammonia and e-methanol according to potential cost reduction measures, according to [22], is shown in Figure 8.

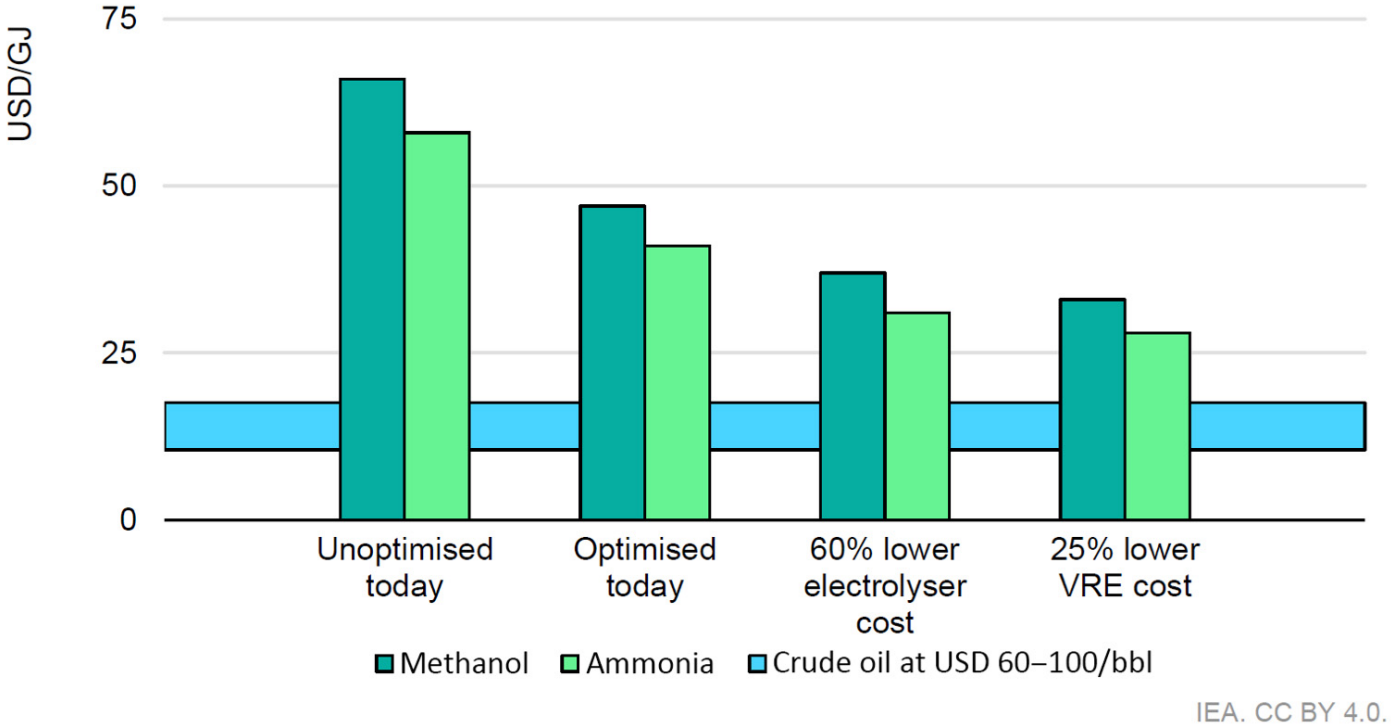



**Figure 8.** Averaged cost of e-ammonia and e-methanol by potential cost reduction measures [22].

For non-optimized installations (according to current technology), these costs are approximately USD 66/GJ and USD 58/GJ for methanol and ammonia, respectively. For the optimized installation, they are 45 USD/GJ for methanol and 41 USD/GJ for ammonia. For installation with 60% lower electrolyzer costs, e-fuel costs are 37 USD/GJ for methanol and about 30 USD/GJ for ammonia, whereas for installations with 25% lower VRE costs, e-methanol and e-ammonia costs are around 32 USD/GJ and around 28 USD/GJ, respectively.

The production costs of various e-fuels can also be presented on a per-unit-volume basis. Figure 9 shows the production costs of various e-fuels on a per liter diesel equivalent basis [23] (and per MWh). This figure shows the costs of many types of e-fuels, including liquefied bio-electro-methane (from biogas) (1.1 EUR/L diesel equivalent), compressed hydrogen (1.14 EUR/L diesel equivalent), bio-electro-methanol (1.2 EUR/L diesel equivalent), bio-electro-DME (1.25 EUR/L diesel equivalent), liquefied bio-electro-methane (from syngas) (1.26 EUR/L diesel equivalent), liquefied hydrogen (1.26 EUR/L diesel equivalent), electro-ammonia (1.5 EUR/L diesel equivalent), bio-electro-gasoline (MTG) (1.5 EUR/L diesel equivalent), electro-methanol (1.5 EUR/L diesel equivalent), liquefied electro-methane (1.55 EUR/L diesel equivalent), electro-DME (1.6 EUR/L diesel equivalent), bio-electro-diesel and bio-electro-kerosene (FT) (1.7 EUR/L diesel equivalent), bio-electro-kerosene (MTJ) (1.8 EUR/L diesel equivalent), electro-gasoline (MTG) (1.85 EUR/L diesel equivalent), electro-diesel and electro-kerosene (FT) (2.2 EUR/L diesel equivalent), and electro-kerosene (MTJ) (2.3 EUR/L diesel equivalent).

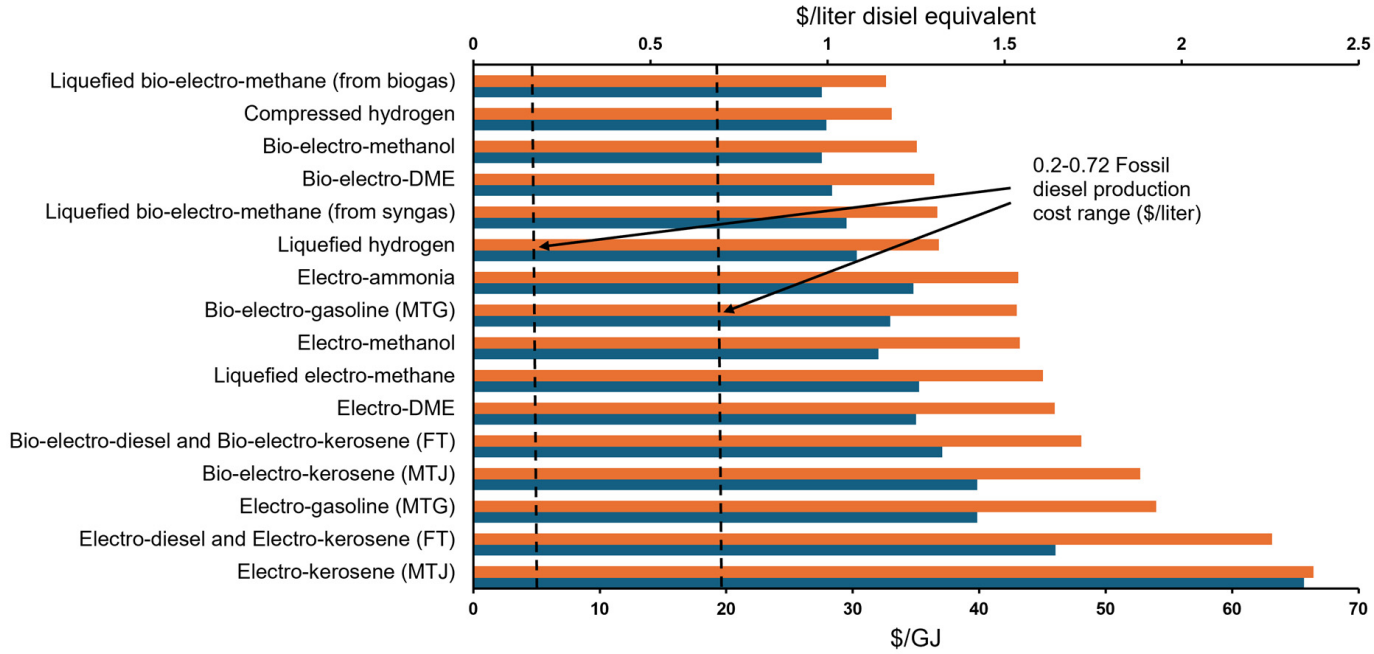



**Figure 9.** Production costs for e-hydrogen, biofuels, and e-fuels using values from a literature review [23].

A very detailed report on the production costs of various e-fuels can also be found in [55]. It should be emphasized that the values presented in these reports coincide with each other, so this summary mainly presents data on the production costs of e-fuels.

The cost assessment presented in Section 3 is based on a detailed techno-economic analysis, as outlined in references [22,23]. The evaluation systematically separates CAPEX and OPEX components to ensure a transparent representation of cost structures for liquid e-fuel production. CAPEX accounts for the initial investment costs associated with infrastructure deployment, including the procurement and installation of electrolyzer units, fuel synthesis reactors, balance-of-plant components, and auxiliary systems necessary for process integration and commissioning. CAPEX also includes the costs related to site preparation, construction, and grid connection where applicable. OPEX covers the recurring costs required to sustain continuous plant operation. The primary contributors to OPEX include electricity consumption, which dominates the cost structure due to the high energy demand of electrolysis processes, as well as the costs of $CO_2$ feedstock acquisition, water supply, system maintenance, and labor. According to the referenced reports, electricity costs alone can contribute over 50% of the total production cost for e-fuels such as e-methanol and e-ammonia, making it a critical factor in cost sensitivity analyses.

## 4. Overview of e-Fuel Projects and Facilities

This chapter provides an overview of the most important projects and installations that are developing the production of e-fuels on the commercial scale, with a focus on their technology, scale of production, and type of e-fuel. The importance of the planned commission is the key to estimating the scale of world switching to e-fuels instead of fossil fuels. Only large-scale projects are included in the list. The map with the locations of the projects is presented in Figure 10.

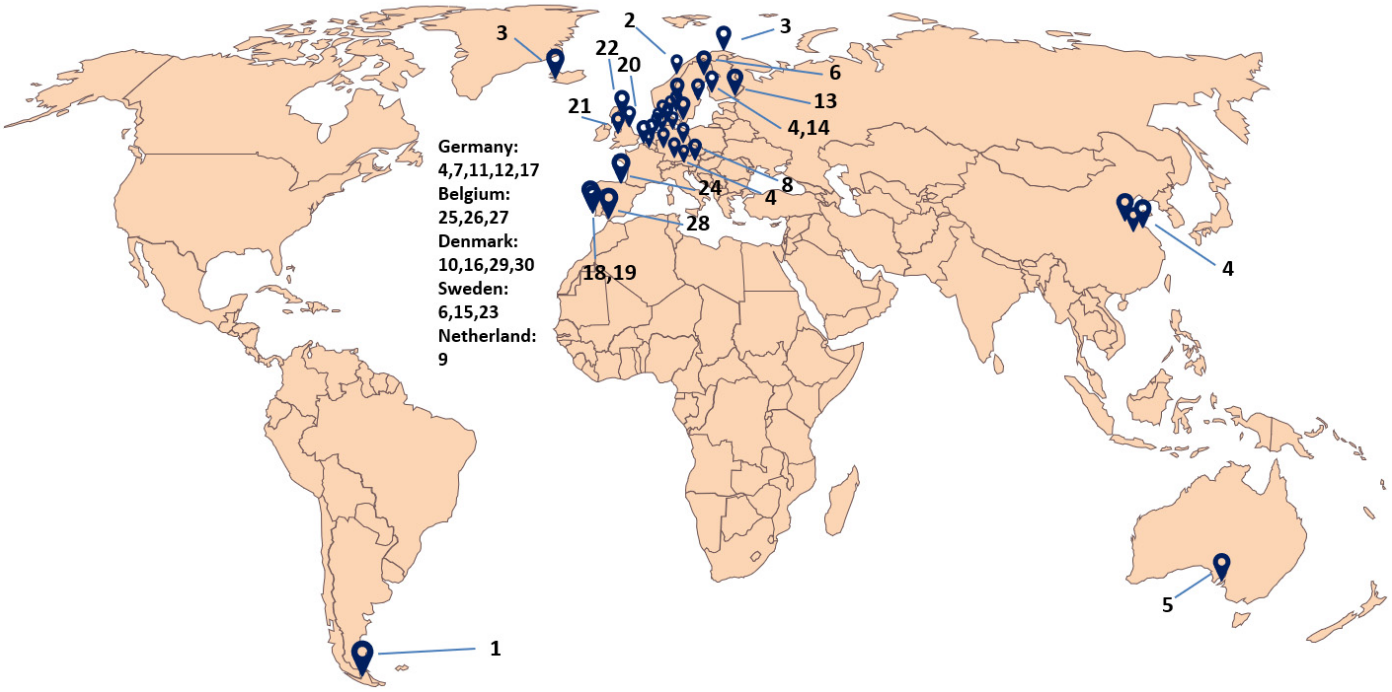



**Figure 10.** Map of the locations of the projects and facilities reviewed.

### *4.1. Haru Oni*

The Haru Oni project [56–58], located in Punta Arenas, Chile, launched in 2022, is a groundbreaking collaboration between Siemens Energy, HIF Global, and Porsche to produce sustainable e-methanol and e-fuels. Using wind power to generate renewable electricity and capture $CO_2$ from the atmosphere, the project produces e-methanol as a base for e-fuels. In its first year, it achieved a capacity of 750,000 L of e-fuel annually. The initiative is designed to support the decarbonization of the transportation sector and offer greener fuel alternatives. Porsche plays a crucial role in the Haru Oni project, providing both financial and technical support. The company aims to leverage e-fuels to prolong the use of internal combustion engines in classic cars and motorsport vehicles while reducing carbon emissions. Porsche's involvement underlines its commitment to sustainability and complements its efforts in electrifying its vehicle lineup. The e-fuels produced by Haru Oni are expected to meet the stringent quality standards required for high-performance engines, ensuring compatibility with Porsche's current and legacy vehicles. This collaboration illustrates a step toward a broader industry shift to renewable fuel technologies.

### *4.2. Norsk e-Fuel*

The Norsk e-Fuel project [59–61], located in Norway and starting in 2020, aims to produce sustainable aviation and marine fuels such as methanol and e-kerosene. In the first phase, the project will reach a capacity of 50 million L of SAF by 2026 and 250 million L of SAF by 2030, using $CO_2$ and hydrogen from renewable sources. The initiative contributes to reducing emissions in the transportation sector by supporting green energy solutions for the aviation and maritime industries. Actually, three projects are ongoing (with the opportunity for five in total at the moment). Project Mosjøen located in Nesbruket, Vefsn Municipality, Norway, is estimated to produce 40 million L of SAF. No information about planned commissioning is available.

### *4.3. Carbon Recycling International (CRI)*

Carbon Recycling International (CRI) [62–65], a plant located in Iceland and in operation since 2011, produces synthetic methanol using captured $CO_2$ and hydrogen, using

geothermal energy. Since 2015, the production facility, known as the George Olah Plant, has begun to reach a capacity of more than 4000 tons per year. The methanol produced serves as a fuel and chemical feedstock, supporting emission reductions and promoting sustainable fuel production. The company is implementing several different projects related to e-fuel production and $CO_2$ capture. CRI have declared that their actual total installed e-methanol production capacity reached over 200,000 tons per year, and after commissioning all delivered units, it is supposed to reach over 500,000 tons/year. The actual ongoing projects and operating units are as follows:

- Anyang city, China: capacity of 110,000 tons of low-carbon intensity methanol per year, commissioned in 2022.
- Tianying, China: planned 170,000 tons of e-methanol per year, with an expected start-up date in 2025.
- Finnmark county, Norway: installed production capacity of 100,000 tons per year and operating.
- Lianyungang, China: estimated 100,000 tons of methanol annually and operating.

### *4.4. Sunfire*

Sunfire [66,67], a Dresden, Germany-based company, is operating a 1000-ton-per-year pilot plant which started in 2019, focusing on power-to-liquid technology. The process converts carbon dioxide ($CO_2$) and hydrogen into synthetic liquid fuels such as e-diesel, supporting the decarbonization of the transportation sector. Sunfire is taking part in its own demonstration plant projects, especially in Germany, but they also have electrolyzer technology at the commercial level, which are sold to other commercial locations. As the capacity of the electrolyzers defines the possible scale of hydrogen production, as well as this information being clearly presented in Sunfire's materials, these values were adopted to estimate the scale of hydrogen and e-fuel production during and after commissioning the plants.

Sunfire has begun alkaline electrolyzers series production and the use of co-electrolysis units to deliver its electrolyzers to commercial H2/e-fuel plants, such as the following:

#### 4.4.1. P2X Solutions Oy

- Product: Sunfire-HyLink Alkaline,
- Use case: hydrogen for industry and synthetic methane, electrolysis capacity of 20 MW, pressurized alkaline electrolyzer
- Output: Up to 400 kg/h green hydrogen (converted also into the methane),
- Location and commissioning: Harjavalta, Finland (state: commissioning)

#### 4.4.2. MPREIS

- Product: Sunfire-HyLink Alkaline
- Use case: hydrogen for industry, electrolysis capacity od 3.2 MW, pressurized alkaline electrolyzer
- Output: Up to 60 kg/h green hydrogen
- Location and commissioning: Commissioned in 2022 Völs near Innsbruck, Austria (state: operating)

#### 4.4.3. Neste

- Product: Sunfire-HyLink SOEC
- Use case: hydrogen for high-quality biofuels, electrolysis capacity 2.6 MW, solid oxide electrolyzer operates at high temperatures of 850 °C
- Output: Up to 60 kg/h green hydrogen

- Location and commissioning: Port of Rotterdam, The Netherlands (state: commissioning), hydrogen for biofuels

#### 4.4.4. RWE 1

- Product: Sunfire-HyLink Alkaline
- Use case: hydrogen for industry, electrolysis capacity 10 MW, pressurized alkaline electrolyzer
- Output: Up to 200 kg/h green hydrogen
- Location and commissioning: Commissioned in 2024 Lingen, Germany (state: operating)

#### 4.4.5. RWE 2

- Product: Sunfire-HyLink SOEC
- Use case: hydrogen for industry, electrolysis capacity 250 kW, solid oxide electrolyzer
- Output: Up to 7 kg/h green hydrogen
- Location and commissioning: Commissioned in 2023 Lingen, Germany (state: operation)

#### 4.4.6. RWE 3

- Product: Sunfire-HyLink Alkaline
- Use case: hydrogen for industry, electrolysis capacity 100 MW, pressurized alkaline electrolyzer
- Output: Up to 1900 kg/h green hydrogen
- Location and commissioning: Planned in 2027, Lingen, Germany

#### 4.4.7. Salzgitter Mannesmann

- Product: Sunfire-HyLink SOEC
- Use case: hydrogen for green steel, electrolysis capacity 720 kW, solid oxide electrolyzer
- Output: Up to 18 kg/h green hydrogen
- Location and commissioning: Commissioned in 2020 Salzgitter, Germany (state: operation)

#### 4.4.8. TotalEnergies

- Product: Sunfire-HyLink SOEC
- Use case: hydrogen for chemical industry, electrolysis capacity 0.7 MW, solid oxide electrolyzer
- Output: Up to 15 kg/h hydrogen
- Location and commissioning: Commissioned in 2022 Leuna, Germany (state: operation)

#### 4.4.9. VNG, Uniper

- Product: Sunfire-HyLink Alkaline
- Use case: hydrogen for industry, electrolysis capacity 30 MW, pressurized alkaline electrolyzer
- Output: Up to 600 kg/h green hydrogen
- Location and commissioning: Commissioned (no data), Bad Lauchstädt, Germany

### *4.5. Hydrogen Park South Australia (HyP SA)*

Hydrogen Park South Australia (HyP SA) [68–71] is a pioneering project located in Australia's Tonsley Innovation District, which began operations in May 2021. It is the country's first plant to produce green hydrogen using renewable energy, using a 1.25 MW Siemens PEM electrolyzer, with an output volume of 2700 kg/month (according to operation reports). HyP SA supplies a gas mix containing up to 5% hydrogen to more than 3700 customers in Adelaide's southern suburbs, mainly through mixing with natural gas or

via trailers. This project supports the decarbonization of the industrial and transportation sectors, helping to reduce greenhouse gas emissions. In addition, HyP SA is supplying clean hydrogen to the industry and the transportation sector through transportation in special tanks. The initiative is a key step toward achieving Australia's goals to reduce emissions and promote sustainable energy sources. The project is supported by Australian Gas Networks Limited and has received funding from the Australian Renewable Energy Agency (ARENA).

### 4.6. Hybrit

Hybrit [72–74] is a Swedish initiative launched in 2016 by SSAB, LKAB, and Vattenfall to produce $CO_2$-free steel by replacing coal with green hydrogen in the production process. In 2020, a pilot plant for sponge iron production using hydrogen was commissioned in Luleå, and in 2021, the first batch of fossil-free steel was produced and delivered to Volvo. In 2022, a unique underground hydrogen storage facility, the first of its kind in the world, was inaugurated in Luleå, a key element in stabilizing steel production. The Hybrit project has the potential to reduce $CO_2$ emissions in Sweden by 10% and in Finland by 7%, contributing to the global decarbonization of the steel industry. In 2023, Hybrit received SEK 3.1 billion in support from the Swedish Energy Agency to build a demonstration plant in Gällivare to produce 1.35 million tons of sponge iron per year. The initiative represents a breakthrough in the drive for sustainable steel production and the reduction in global greenhouse gas emissions.

### 4.7. REFHYNE I

The REFHYNE I [75–77] project, launched in 2018 in Germany, involves the construction of Europe's largest PEM electrolyzer for the production of green hydrogen. Located at Shell Energy and Chemicals Park Rheinland in Wesseling, the 10 MW electrolyzer uses renewable energy to produce about 1300 tons of hydrogen per year. The goal of the project is to decarbonize refining processes by replacing traditionally used fossil fuel hydrogen with its green counterpart. REFHYNE I represents a key step toward reducing $CO_2$ emissions in the refining industry while supporting European climate goals. The project is being carried out by a consortium including Shell, ITM Power, and SINTEF, with financial support from the European Commission under the Clean Hydrogen Partnership program. In July 2021, the electrolyzer began producing green hydrogen, contributing to a sustainable energy transition in Europe. In addition, as part of the continuation of the project, the electrolyzer's capacity is planned to be increased to 100 MW in the REFHYNE II initiative, which will allow for the production of about 15,000 tons of green hydrogen per year.

### 4.8. H2Future

H2Future [78–80] is an Austrian demonstration project launched in 2017 to produce green hydrogen for the steel industry. As part of the initiative, a 6 MW PEM electrolyzer has been installed at voestalpine's plant in Linz, capable of producing about 1200 $m^3$ of hydrogen per hour, which translates into an annual production of 1500 tons. The project is being carried out by a consortium consisting of voestalpine, Siemens Energy, VERBUND, Austrian Power Grid, K1-MET, and TNO, with financial support from the European Union under the Fuel Cells and Hydrogen Joint Undertaking program. The goal of H2Future is not only to provide green hydrogen for steelmaking processes, but also to explore the possibility of integrating this energy carrier into the electricity grid and its application in other industrial sectors. The electrolyzer began production in November 2019, at the time representing the largest installation of its kind in the world. The project contributes to the decarbonization of heavy industry, supporting European climate goals by reducing $CO_2$

emissions. Additionally, H2Future is providing valuable data on the scalability of PEM electrolysis technology and its potential applications in other industries.

### *4.9. NortH2*

NortH2 [81–83] is an ambitious project launched in 2020 in the Netherlands to produce green hydrogen using energy from offshore wind farms in the North Sea. The consortium is made up of companies such as Shell, Gasunie, Groningen Seaports, RWE, and Equinor, which are working together to create an integrated value chain, including hydrogen production, storage, and distribution. The plan calls for a gradual increase in production capacity: from 1 GW in 2027 to 4 GW in 2030 and to more than 10 GW in 2040, allowing for the production of some 800,000 tons of green hydrogen per year. This amount of hydrogen could reduce $CO_2$ emissions by 8 to 10 megatons per year, supporting the decarbonization of industry and transportation in Europe. The NortH2 project also aims to transform the northern Netherlands into a key energy hub, promoting economic development and job creation in the region. The initiative is in line with European and Dutch climate goals, accelerating the energy transition and development of the hydrogen market in Europe.

### *4.10. Green Fuels for Denmark*

Green Fuels for Denmark [84–86] is an ambitious project launched in 2020 to produce sustainable fuels, such as e-methanol and e-kerosene, for the maritime and aviation sectors. The initiative is led by a consortium including Ørsted, A.P. Moller-Maersk, SAS, Copenhagen Airports, DFDS, and DSV, among others. The project involves the use of wind energy to produce hydrogen through electrolysis, which will then be converted into e-fuels when combined with captured $CO_2$. The planned full production capacity is 1.3 GW, which will produce about 250,000 tons of e-fuels per year after 2030. In December 2022, the project received DKK 600 million in support from the Danish Business Agency under the European IPCEI program, marking a significant step toward the realization of the first 10 MW, 100 MW, and 300 MW phases. Green Fuels for Denmark has the potential to reduce $CO_2$ emissions by 850,000 tons per year by 2030, contributing significantly to the decarbonization of the transportation sector and supporting Denmark's and the European Union's climate goals. The project also represents an important step in the development of power-to-X technology, promoting the integration of renewable energy sources with synthetic fuel production.

### *4.11. Westküste 100*

Westküste 100 [87–90] is a German project launched in 2020 to produce green hydrogen from wind energy and convert it into e-methanol, supporting the decarbonization of the chemical industry. The consortium consists of ten partners, including EDF Deutschland GmbH, Holcim Germany Group, OGE, Ørsted A/S, Raffinerie Heide GmbH, Stadtwerke Heide GmbH, Thüga AG, ThyssenKrupp Industrial Solutions, Region Heide Development Agency, and Westküste University of Applied Sciences. The project involves the construction of a 30 MW electrolyzer to produce green hydrogen, which will then be used to synthesize e-methanol. The planned annual production of e-methanol is 30,000 tons, which will contribute to reducing $CO_2$ emissions in the chemical and energy industries. Westküste 100 has received funding of EUR 30 million from the German Federal Ministry of Economic Affairs and Energy, with a total project budget of about EUR 89 million. The initiative is a major step toward establishing a regional hydrogen economy on an industrial scale, integrating different sectors and promoting sustainable energy sources. The project also aims to test technologies and processes that can be scaled in the future, supporting the energy transition and achieving climate goals.

### 4.12. H2Mare

H2Mare [91,92] is a German project launched in 2021 to produce green hydrogen and e-fuels directly offshore, using energy from offshore wind farms. The initiative focuses on integrating electrolyzers with wind turbines to produce hydrogen without connecting to the onshore power grid, reducing infrastructure costs. The project consists of four sub-projects: OffgridWind, H2Wind, PtX-Wind, and TransferWind, which together cover the entire value chain—from wind power generation to hydrogen production to synthesis of e-fuels such as methanol and ammonia. The planned annual production is around 50,000 tons of e-fuels, which will contribute to the decarbonization of the industrial and transportation sectors. H2Mare is supported by the German Federal Ministry of Education and Research (BMBF) as part of the Wasserstoff-Leitprojekte initiative, with a budget of about EUR 100 million. The project involves 35 partners from industry and science, including Siemens Gamesa, Siemens Energy, RWE, and the Fraunhofer Institutes. H2Mare aims to establish Germany as a technological leader in offshore green hydrogen production, while supporting the achievement of climate goals by reducing $CO_2$ emissions.

### 4.13. Power-to-Methanol Lappeenranta

The Power-to-Methanol Lappeenranta [93,94] project in Finland, launched in 2019, aims to produce e-methanol using renewable energy and captured $CO_2$. The planned annual capacity is 25,000 tons, which will contribute to providing sustainable fuels for the shipping sector, supporting its decarbonization. In addition, other initiatives related to e-methanol production are underway in Finland, such as Total Eren and Aliceco's planned construction of a new e-fuel plant that will use biogenic carbon dioxide and green hydrogen to synthesize e-methanol. These projects are part of a global drive to reduce $CO_2$ emissions in shipping by replacing traditional fossil fuels with more sustainable alternatives.

### 4.14. P2X Solutions

P2X Solutions [95,96], a Finnish company specializing in power-to-X technologies, has initiated a 20 MW electrolyzer project in 2021 in Harjavalta, Finland. The goal is to produce green hydrogen using renewable energy, which will then be converted into e-methanol and other synthetic fuels such as e-methane and e-ammonia. The planned annual production capacity of e-methanol is about 20,000 tons, which will contribute to reducing $CO_2$ emissions in the chemical and energy industries. In February 2024, Sunfire installed Finland's first 20 MW industrial electrolyzer in Harjavalta, a key step in the project's implementation. P2X Solutions also plans to build more production facilities in Joensuu and Oulu, aiming for a total production capacity of 1 GW of green hydrogen by 2031. These initiatives support the decarbonization of the industry and promote sustainable fuel production in Finland.

### 4.15. Liquid Wind

Liquid Wind [97,98] is a Swedish company founded in 2017, specializing in e-methanol production using wind energy and captured $CO_2$. The company aims to decarbonize the shipping sector by providing sustainable fuels. The first production facility, FlagshipONE, located in Örnsköldsvik, is expected to begin production in 2024, with a planned capacity of 50,000 tons of e-methanol per year. Ørsted, a Danish leader in renewable energy, took full ownership of the FlagshipONE project in 2022, underscoring the importance of the initiative in the context of the global energy transition. Liquid Wind plans to build more production facilities in Sweden, aiming to create a network of large-scale e-methanol facilities. Ørsted began the construction of FlagshipONE in May 2023, marking an important step in the project's implementation. However, in August 2024, Ørsted announced the cancelation of

the FlagshipONE project due to market difficulties and rising costs, challenging the future of such initiatives. Liquid Wind is still running other projects in Haapavesi, Sundsvall, Umea, and Ostersund, recently (November 2024) raising another EUR 44 million for its operation.

### 4.16. eMethanol Kassø Power-to-X

Launched in 2021, the eMethanol Kassø Power-to-X [99,100] project by European Energy in Denmark aims to produce e-methanol using renewable energy and captured $CO_2$. The main plant is located in Kassø, in the southern part of the country, and is powered by energy from a nearby 300 MW solar farm, making it the largest of its kind in the Nordic countries. The planned annual production capacity is 32,000 tons of e-methanol, which will be supplied to the chemical industry and the shipping sector, among others, supporting the decarbonization of these industries. In June 2024, European Energy signed an agreement with Danske Commodities to optimize the plant's energy consumption in order to increase the efficiency of e-methanol production. In addition, in October 2024, the project received a grant of more than EUR 50 million from the European Commission under the EU Innovation Fund, which will accelerate the development of the next phases of the investment. Cooperation with partners such as Maersk, Novo Nordisk, and the LEGO Group ensure a stable demand for e-methanol produced, highlighting the importance of the project in the context of the global energy transition. The eMethanol project represents a significant step toward reducing $CO_2$ emissions by replacing traditional fossil fuels with more sustainable alternatives.

### 4.17. HySynGas

The HySynGas [101,102] project is an initiative aimed at blending green hydrogen with LNG to create a sustainable energy mix for various industries. Led by a consortium that includes Vattenfall and other energy stakeholders, the project features a 50 MW power-to-gas facility capable of producing hydrogen and synthetic methane. The hydrogen is produced using renewable energy sources, ensuring a low carbon footprint for the fuel. The resulting blend of LNG and green hydrogen supports decarbonization in sectors like transportation and heating. The project's innovative approach demonstrates the feasibility of integrating green hydrogen into existing LNG supply chains, enhancing sustainability while leveraging established infrastructure. This collaboration highlights the potential for diverse energy partnerships to address global emission challenges effectively.

### 4.18. H2Sines

The H2Sines project [103–105], launched in Portugal in 2020, aimed to produce green hydrogen and e-ammonia using renewable energy, with a planned annual capacity of 1,000,000 tons of e-ammonia. The initiative was intended to support the decarbonization of the global fertilizer and energy industries through the export of sustainable fuels. The consortium implementing the project included companies such as EDP, Galp, REN, Martifer, and Vestas. In July 2020, H2Sines was selected by the Portuguese government to apply for Important Project of Common European Interest (IPCEI) status in the European Union. However, in April 2024, ENGIE, a key partner in the project, confirmed the termination of the H2Sines.RDAM initiative, which included the transportation of liquid hydrogen from Sines to Rotterdam. This decision affected the further development of the H2Sines project, putting its future in question. Despite these challenges, Portugal is continuing its green hydrogen production efforts with other projects in the Sines region, such as GreenH2Atlantic, which involves the construction of a 100 MW electrolyzer to produce green hydrogen.

### 4.19. GreenH2Atlantic

GreenH2Atlantic [106,107] is an innovative project in Sines, Portugal, focused on developing a 100 MW green hydrogen production facility. Commencing in December 2021, the project aims to produce green hydrogen using renewable energy sources to decarbonize various industries, including energy and transportation. It plans to achieve a production capacity of approximately 30,000 tons of green hydrogen annually. The facility will operate using electrolyzers that leverage repurposed infrastructure from a decommissioned coal-fired power plant, marking a significant step in Portugal's energy transition. The project partners include major stakeholders such as EDP, Galp, ENGIE, and Vestas, with technological contributions from companies like McPhy and Efacec. The facility is designed to operate at ambient temperatures, utilizing advanced alkaline or polymer electrolyte membrane (PEM) electrolyzers. This initiative aligns with the EU's hydrogen strategy, supporting a carbon-neutral Europe by 2050.

### 4.20. HyGreen Teesside

The HyGreen Teesside project [108–110], located in Hartlepool, England, is BP's ambitious initiative to establish a green hydrogen production facility. Launched in 2021, the project aims to generate up to 500,000 tons of green hydrogen annually by 2030. This hydrogen will be produced using renewable energy sources and is part of BP's broader strategy to support the UK's net-zero goals. The electrolyzer, with a planned capacity of 500 MW, is a critical component of the facility. Operating temperature and specific electrolyzer technology details are yet to be confirmed, but the project is intended to reduce hydrogen production costs over time. The first phase is expected to achieve 80 MW of production capacity, with a final investment decision made by 2023 and operations commencing by 2025. HyGreen Teesside is part of a larger regional effort to decarbonize industrial sectors and transform Teesside into a hub for clean energy innovation.

### 4.21. HyNet North West

HyNet North West [111–115] is a UK project launched in 2020 to produce blue and green hydrogen and develop the infrastructure to distribute it, supporting the decarbonization of industry and transport in the North West England region. The planned annual production capacity is 350,000 tons of hydrogen, which will help reduce $CO_2$ emissions by about 10 million tons per year by 2030. The project also includes carbon capture and storage (CCS) in depleted natural gas deposits under the seabed in Liverpool Bay. In March 2021, HyNet North West received GBP 33 million in funding from UK Research and Innovation to support project work, with a planned start-up in 2025. HyNet North West is a key component of the UK's strategy to achieve climate neutrality by 2050, promoting the development of hydrogen technologies and reducing emissions in hard-to-decarbonize sectors; however, recent information shows that no electrolysis will likely be applied in the project, so the fuel will not really be an e-fuel, but a hydrogen generated via a methane reforming process.

### 4.22. Green Hydrogen for Scotland

The Green Hydrogen [116–118] for Scotland project is an initiative launched in 2020 to produce green hydrogen using renewable energy, with a planned capacity of 4000 tons per year. The aim of the project is to support the decarbonization of Scotland's public transport and industrial sectors through the provision of clean hydrogen fuel. The first phase of the project, dubbed "Green Hydrogen for Glasgow", involves the construction of a production facility on the outskirts of Glasgow that will use wind and solar energy to power a 10 MW electrolyzer. The project is being carried out in partnership with ScottishPower

Renewables, BOC (part of Linde), and ITM Power, combining expertise in renewable energy and hydrogen technologies. The initiative supports Glasgow's drive to become the UK's first net-zero-emission city by 2030, providing hydrogen to power buses, trucks, and other commercial vehicles. The project is part of Scotland's broader strategy to develop a hydrogen economy, aiming to reduce greenhouse gas emissions and promote sustainability. The initiative also plans to establish a network of hydrogen refueling stations, facilitating the integration of the fuel across different sectors of the economy.

### 4.23. Stegra: H2 Green Steel

Stegra $H_2$ Green Steel [119–122] is a Swedish project initiated in 2021 to produce $CO_2$-free steel by replacing coal with green hydrogen in the production process. The plant, located in the northern Swedish region of Boden-Luleå, plans to start production in 2025, with an initial capacity of 2.5 million tons of steel per year, with a target of reaching 5 million tons by 2030. The project will include one of the world's largest electrolyzers, with a capacity of 700 MW, which will produce green hydrogen from renewable energy, replacing traditionally used coking coal. The investment aims to reduce $CO_2$ emissions by 95% compared to conventional steelmaking methods, helping to decarbonize the steel industry and support global climate action. The project has received financial support from the European Investment Bank and the Nordic Investment Bank, which have combined to provide nearly EUR 400 million for the construction and development of the steel plant. In addition, H2 Green Steel has entered into a seven-year agreement with Lindab to supply 159,000 tons of near-zero-emission steel, demonstrating the growing demand for green materials in industry. The implementation of this project is a significant step toward sustainable steelmaking and could become a model for other initiatives around the world.

### 4.24. Repsol (Bilbao)

Repsol [123–127] is implementing a project in Bilbao to produce e-fuels, such as e-diesel and e-kerosene, using green hydrogen and captured $CO_2$. The initiative, launched in 2021, aims to support the decarbonization of the transportation sector by providing sustainable fuels. The production facility, located at the Port of Bilbao, will be able to produce 2100 tons of e-fuels per year, equivalent to about 8000 L per day. The production process involves electrolyzing water using renewable energy to produce green hydrogen with 100 MW electrolyzers, which is then combined with $CO_2$ captured from the atmosphere or industrial processes to create synthetic fuels. The project is part of Repsol's broader strategy to achieve carbon neutrality by 2050 by investing in low-carbon technologies and promoting a closed-loop economy. The partnership with Aramco and the use of advanced technologies such as HyCOgen and FT CANS developed by Johnson Matthey and BP enable the efficient production of e-fuels with a low carbon footprint. The Bilbao project represents a significant step toward reducing $CO_2$ emissions in the transportation sector, offering an alternative to traditional fossil fuels and supporting global climate action.

### 4.25. Power to Methanol Antwerp BV

The "Methanol Antwerp BV" project [128,129] was an initiative located in Antwerp, Belgium, that aimed to produce 8000 tons of sustainable methanol annually. Scheduled to commence operations by the end of 2023 or early 2024, this project planned to use captured $CO_2$ combined with hydrogen derived from renewable electricity to create methanol, significantly reducing greenhouse gas emissions. Unfortunately, in late 2024, the project has been terminated by its leading consortium due to economic challenges and high energy costs.

### *4.26. Hyoffwind*

The "HyOffWind" project [130–132] is a pioneering initiative located in Zeebrugge, Belgium, aimed at establishing the country's first industrial-scale power-to-gas facility. It is designed to convert renewable electricity into green hydrogen, contributing significantly to decarbonization goals. Commencing in 2020 with feasibility studies, the project plans to achieve operational hydrogen production by 2026. Initially, the plant will have a capacity of 25 MW, with plans for potential expansion to 100 MW. The project is a collaboration among key partners, including Virya Energy, HyoffGreen, Messer, and Fluxys, leveraging alkaline electrolyzer technology to produce green hydrogen with a capacity of 14,000 tons/year.

### *4.27. North-C-Methanol*

The North-C-Methanol project [133–135], located in the North Sea Port, Belgium, focuses on producing green methanol by utilizing renewable energy and industrial carbon dioxide emissions. Commencing in 2024, the project integrates a 63 MW electrolyzer to generate green hydrogen and oxygen using offshore wind energy. The hydrogen is combined with $CO_2$ captured from local industries, such as steel and biofuel production, to synthesize methanol. The facility aims to produce 44,000 tons of methanol annually, operating under catalytic synthesis conditions and will reduce $CO_2$ emissions by approximately 140,000 tons per year.

### *4.28. SolWinHy Cadiz*

The "SolWinHy Cádiz" project [136,137], based in Arcos de la Frontera, Cádiz, Spain, focuses on producing green e-methanol powered exclusively by renewable energy sources. Scheduled to commence operations in early 2027, the facility will produce 29,000 tons of e-methanol annually, using a combination of a 130 MW solar PV system and a 54 MW wind farm. An 80 MW electrolyzer will generate green hydrogen, which is then combined with biogenic $CO_2$ to create e-methanol, ensuring the entire process operates independently of the national electricity grid. The project is set on a 463-hectare site, with most of the e-methanol production intended for export to Germany. This initiative marks a significant step towards decarbonization by supplying sustainable fuels for industrial and transportation use.

### *4.29. The HØST PtX*

The HØST PtX project [138,139], based in Esbjerg, Denmark, is a power-to-X initiative focused on producing green hydrogen and ammonia at a gigawatt scale using renewable energy. Scheduled to begin operations by 2028, it aims to generate up to 140,000 tons of green hydrogen per year. The project utilizes advanced industrial electrolysis technologies powered by wind energy from the North Sea region. Green hydrogen and ammonia produced at HØST will serve industries such as fertilizers, fuels, and other hard-to-electrify sectors, contributing to decarbonization. With a planned electrolyzer power of over 1 GW, it represents a key step in Denmark's leadership in renewable energy solutions.

### *4.30. The Fjord PtX*

The Fjord PtX project [139,140], located in Aalborg, Denmark, focuses on producing sustainable aviation fuel (SAF) through power-to-X technology. Construction is planned to start in 2026, with operations commencing in 2029. Using renewable energy, the facility will produce approximately 75,000–90,000 tons of SAF annually, sufficient to meet the entire demand for domestic flights in Denmark. The project will also recycle 330,000 tons of $CO_2$ annually, primarily from waste incineration, and supply surplus heat for district heating,

benefiting 11,000 households. It will utilize an electrolyzer powered by up to 400 MW of renewable electricity to achieve its sustainability goals.

## 5. Summary

Table 2 collects all the relevant information on the projects analyzed and indicates the scientific and commercial sources of information for the installations indicated.

**Table 2.** Summary of recent large-scale projects concerning e-fuel production and green hydrogen generation.

| No. | Project Name | Location (Country) | Year of Commencement | Fuel Type | Declared Capacity | Electrolyzer Type | Electrolyzer Power (MW) | Source |
|---|---|---|---|---|---|---|---|---|
| 1 | Haru Oni | Chile | 2020 (first fuel delivered 2022, planned final scale 2027) | E-fuels | Planned 700,000 tons/y of e-methanol and e-gasoline together | PEM | 1.2 | [56–58] |
| 2 | Norsk e-Fuel | Norway | 2020 planned commissioning in 2026 | E-fuels (kerosene) | 40,000 tons/year in first stage | SOEC electrolysis | n/a | [59–61] |
| 3 | Carbon Recycling International (CRI) | Iceland | Depending on location since 2015, final power in 2025 | Synthetic methanol | Over 500,000 tons | Alkaline | Various size depending on location | [62–65] |
| 4 | Sunfire | Germany | 2019 | Hydrogen, Synthetic fuels | Total for all locations ~26,000 tons/year H2 | Alkaline, SOEC | Various size depending on location | [66,67] |
| 5 | Hydrogen Park South Australia (HyP SA) | Australia | 2021 | Green hydrogen | Up to 2700 kg/month | PEM | 1.25 | [68–71] |
| 6 | Hybrit | Sweden | 2018–2024 pilot phase | Hydrogen for steel production | 1.8 million tons annually | Alkaline | 4.5 | [72–74] |
| 7 | REFHYNE I project at the Shell Rhineland Refinery in Germany Made by Sunfire | Germany | 2021 | Green hydrogen | 1300 tons per year | PEM | 10 | [75–77] |
| 8 | H2FUTURE Voestalpine's Steel Works in Austria | Austria | 2019 | Green hydrogen | 1200 cubic meters of hydrogen that the cells generate each hour | PEM | 6 | [78–80] |
| 9 | NortH2 | Netherland | 2020 (Planned results between 2030–2035) | Green hydrogen | 400,000 tons/year $H_2$ production in 2030 and 1 million tons green hydrogen production by 2040 | | 1 GW in 2027, 4 GW by 2030 and 10+ GW by 2040 for electrolysis | [81–83] |
| 10 | Ørsted-Green fuels for Denmark | Denmark | 2023 (final power at 2030) | 2025: hydrogen for heavy road transport 2027: hydrogen + e-methanol + e-kerosene | 100,000 tons of e-methanol and e-kerosene | n/a | 10 (2025), 100 (2027), 300 (2029) | [84–86] |
| 11 | Westküste 100 | Germany | 2020 (project start) | E-fuels (e-kerosene) | 30,000 ton/year | PEM | 30 | [87–90] |
| 12 | H2Mare | Germany | 2025 | E-fuels | 50,000 ton/year | PEM | n/a | [91,92] |
| 13 | Power-to-Methanol Lappeenranta | Finland | 2026 | E-methanol | 25,000 ton/year | n/a | n/a | [93,94] |
| 14 | P2X Solutions (Sunfire units) | Finland | 2023/2026/2028 | Hydrogen and e-fuels | 20,000 ton/year | Alkaline | 20/30/100 | [95,96] |
| 15 | Liquid Wind | Sweden | Operation 2026/2027 | E-methanol | Total in 3 locations: 360,000 ton/year | n/a | n/a | [97,98] |

**Table 2.** *Cont.*

| No. | Project Name | Location (Country) | Year of Commencement | Fuel Type | Declared Capacity | Electrolyzer Type | Electrolyzer Power (MW) | Source |
|---|---|---|---|---|---|---|---|---|
| 16 | eMethanol Kassø Power-to-X | Denmark | 2028/2029 | E-methanol | 42,000 ton/year | PEM | 50 | [99,100] |
| 17 | HySynGas | Germany | 2020 (no further information about the project) | Hydrogen, e-methane | 50,000 ton/year | n/a | 50 | [101,102] |
| 18 | H2Sines | Portugal | Planned 2027, project terminated in 2024 | Hydrogen (green) and ammonia | 1,000,000 ton/year | n/a | 400 | [103–105] |
| 19 | GreenH2Atlantic | Portugal | 2021 (start operation 2027) | Hydrogen (green) | 10,000 ton/year | Alkaline | 100 | [106,107] |
| 20 | HyGreen Teesside | England | 2022 (start operation 2026) | Hydrogen (green) | 2400 ton/year | PEM | 60 (500 in final stage) | [108–110] |
| 21 | HyNet North West | United Kingdom | 2022 (start operation 2027) | Hydrogen (blue) | 300 ton/year | n/a | 40 | [111–115] |
| 22 | Green Hydrogen for Scotland | Scotland | 2021 (start operation 2023, no information about operation) | Hydrogen for transport (green) | 4000 ton/year | n/a | 10–20 | [116–118] |
| 23 | Stegra H2 Green Steel | Sweden | 2025 (final capacity at 2030) | Hydrogen (green) converted to electricity and fuels for iron and steel production process | 100% coverage of own steel plant consumption (non exportable) | Alkaline | 700 | [119–122] |
| 24 | Repsol (Bilbao) | Spain | 2024 (start of construction) | Gasolines and kerosene | 8000 L/day | n/a | 100 | [123–127] |
| 25 | Power to Methanol Antwerp BV | Belgium | 2020, project terminated in 2024 due to economical challenges | E-methanol | 8000 ton/year | n/a | 5 | [128,129] |
| 26 | Hyoffwind | Belgium | 2020 (final capacity 2026) | Hydrogen, Syngas | 14,000 ton/year ($H_2$) | Alkaline | 25 (with plans for 100) | [130–132] |
| 27 | North-C-Methanol | Belgium | 2020 (planned 2024 but no current data about operation) | E-methanol | 44,000 ton/year | n/a | 63 | [133–135] |
| 28 | SolWinHy Cadiz | Spain | Planned for 2027 | E-methanol | 29,000 ton/year | n/a | 80 | [136,137] |
| 29 | HØST PtX | Denmark | Planned for 2029 | H2/Ammonia | 100,000 tonnes H2/year or 600,000 ton ammonia | n/a | 1000 | [138,139] |
| 30 | Fjord PtX | Denmark | Planed for 2028 | E-fuel and SAF | 75,000 ton/year SAF | n/a | 400 | [139,140] |

The important point that is striking is that most of the projects are located around Europe (see Figure 10). The few locations mentioned under CRI (Section 4.3), which started cooperation with China, are located there, Haru Oni (Section 4.1) is located in Chile, and HYP SA is located in Australia.

Presented in Table 2, projects will reach an amount of almost 4400 mln kg of hydrogen and e-fuels until around 2030 (assuming that no more projects will be terminated before commissioning). Of this value, e-fuels account for around 2100 mln kg/year and green hydrogen for around 2400 mln kg/year (which, if converted to e-fuels, would give around three times more e-fuels, measured as a mass of those fuels). This gives the total amount

of around 10,000 mln kg/year of e-fuel production, which accounts for quite a noticeable amount of the fuel market.

This value has been compared to actual fuel consumption in the European Union [141].

Data concerning gas oil, diesel oil, and kerosene-type jet fuel has been recalculated to mln kg of fuels per year (see Table 3).

**Table 3.** Estimated fuel consumption in transport sector in EU-27.

| EU-27 Consumption | Gas Oil and Diesel Oil [ktoe] | Kerosene-Type Jet Fuel [ktoe] | Total [ktoe] | Total [Estimated mln kg/Year] |
|---|---|---|---|---|
| 2021 | 174,254.18 | 4054.32 | 178,308.50 | 207,372.78 |
| 2022 | 175,636.32 | 5912.19 | 181,548.52 | 211,140.92 |
| 2023 | 170,283.84 | 6664.48 | 176,948.32 | 205,790.89 |

To show the scale of the projects reviewed, considering the total average annual fuel consumption over the past three years in the European Union (kerosene + gas oil + diesel oil) for the transportation sector was estimated to be over 200,000 million kg per year (see Table 3), the 10,000 mln kg/year may be possible to achieve through the reviewed projects, which could potentially cover almost 5% of total EU-27 fossil fuel consumption for transportation using e-fuels, reducing $CO_2$ emissions significantly. This is estimated to happen within the next 5–6 years, and all the time, new agreements for investments in e-fuel generation facilities are being signed and new financings are being deployed.

While the projected production of 10,000 million kg/year of e-fuels by 2030 indicates substantial progress, its large-scale adoption remains subject to several critical challenges. The primary barriers include the high cost of production driven by electricity prices and electrolyzer CAPEX, as well as the efficiency losses associated with multi-step energy conversion processes. E-fuels are most competitive in hard-to-abate sectors such as aviation and maritime transport, where direct electrification is impractical. However, their market penetration will depend on policy support, including carbon pricing, subsidies, and mandates for renewable fuels. Additionally, the availability of sustainably sourced $CO_2$ and green hydrogen remains limited, creating supply chain constraints. While the reviewed projects demonstrate promising capacity expansion, their contribution to fossil fuel displacement will be modest unless accompanied by continued technology improvements, economies of scale, and global investment alignment. Long-term feasibility also requires addressing the integration of e-fuels into existing fuel distribution infrastructure.

## 6. Conclusions

The global need for e-fuels is growing rapidly, largely due to the drive to decarbonize industry and transportation. This article has reviewed the key aspects of e-fuel production, including the methods of synthesis, the importance of green hydrogen and captured $CO_2$, and the integration of renewable energy sources into these processes. Additionally, the article provides an overview of major commercial and pilot projects worldwide, highlighting their contributions to scaling up e-fuel production and the potential impact on the global fuel market (see Table 1). Leading countries in this technology are Germany, Denmark, Spain, and Sweden, where high-capacity plants have been built to support the development of this sector.

As discussed, e-fuels allow for significant $CO_2$ emission reductions while utilizing existing infrastructure, making them a practical intermediate solution for the transition to renewable energy. The article estimates that the reviewed projects will collectively achieve an annual production capacity of approximately 10 million metric tons of e-fuels and green hydrogen by 2030, representing about 5% of the European Union's transportation fuel consumption. This underscores the near-term potential of e-fuels to make a meaningful contribution to climate goals.

E-fuels are produced mainly from green hydrogen and captured $CO_2$, allowing us not only to reduce emissions from transportation, but also to make efficient use of surplus renewable energy. However, the widespread adoption of e-fuels still requires further development of production infrastructure and a drop in the cost of power-to-X technology, which is key to their competitiveness. It is estimated that e-fuels could reach a 5% share of the European Union fuel market for transportation in the next 5–6 years. In a 20-year timeframe, assuming regulatory support and continued investment, their share could rise to over 30%.

Achieving a 70% share of e-fuels in the fuel market may be feasible within 30–35 years, although this will require significant investment and further technology development to ensure the scalability and stability of the supply. A transition to 100% e-fuels by the end of the century is theoretically possible but would require a transformation of both the energy and industrial sectors on a global level. Regulations that favor sustainable $CO_2$ use and political stability will also be needed to ensure long-term support for such initiatives. Another issue is that e-fuels are not necessarily green fuels, as nowadays, $CO_2$ is mostly captured from industrial processes or fossil fuel combustion. This means that e-fuels might be $CO_2$-neutral fuels (as these $CO_2$ emissions would end up in the atmosphere anyway), but, if not captured again, using this kind of e-fuel only partially reduces $CO_2$ emissions. Using $CO_2$ for the production of e-fuels and capturing it again (closed cycle of $CO_2$) should be considered in the future.

In the near future, e-fuels are poised to become pivotal in decarbonizing hard-to-abate sectors such as aviation, maritime transport, and heavy industries. Key advancements include improved electrolyzer efficiency exceeding 75% for green hydrogen production, the development of scalable direct air capture and closed loop $CO_2$ cycle technologies, and catalysts with enhanced selectivity for e-fuel synthesis. E-methanol appears to be the most promising e-fuel due to its relatively simple synthesis pathway, high energy density, compatibility with existing fuel infrastructure, and potential for direct use or use as a feedstock for further synthetic fuel production.

At the moment, e-fuels offer a great opportunity to realize climate neutrality, but achieving a full replacement requires broad international cooperation and stable policies. These collaborations include not only infrastructure construction but also joint research and development, which can reduce production costs and improve process efficiency. Therefore, the future of e-fuels will depend on the involvement of the public and private sectors, as well as the adaptation of existing energy systems, but the experience of the last decade and ongoing projects show that the opportunity to replace most fossil fuels with e-fuels is real and achievable in the coming decades.

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