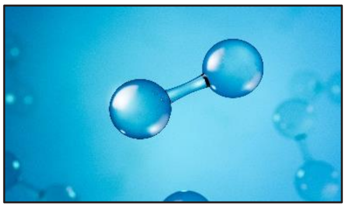
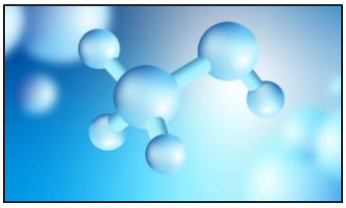
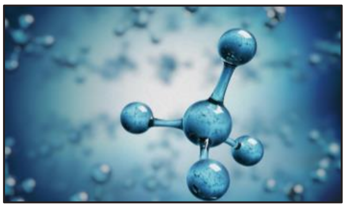
Task Number 64

A Report from the
Advanced Motor Fuels Technology Collaboration Programme


E-fuels and End-use Perspectives

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Summary / Abstract

The net-zero policy of most countries requires actions to reduce the use of and replace fossil fuels. These fuels are energy carriers that are currently used for mobility, industry, heating, and other purposes. There are some applications, such as aviation or international shipping and others “hard-to-abate” sectors, which cannot easily be electrified for long distances and where it is difficult to obtain low-carbon emission fuels. Therefore, demand for fuels will remain and these fuels will need to be produced from renewable energy or lower carbon intensity sources in the coming decades. The energy transition leads to new technologies being tested and deployed to replace the fossil fuels. One option for fuels with low-carbon emissions could be e-fuels. The technologies for e-fuel production and application are being developed around the world. Task 64 on “E-Fuels and End-use Perspectives” was set up in the AMF TCP to assess their significance at international level. The aim was to gain an overview of the status of e-fuels in the various countries involved. The application of these fuels, some of which are new, is relevant for AMF TCP as they can be used for motorized processes. Currently, there is still little experience in the use of these new fuels, as their production is still in infancy.

Several countries have launched strategic programs to increase the production of e-fuels. These initiatives provide incentives, support research or enact regulations that mandate a certain percentage of e-fuel use. Due to the energy-intensive production of e-fuels, it is being discussed that their use should be prioritized in sectors that are difficult to electrify, such as aviation, shipping, heavy duty road transport and industry. Water electrolysis, which is crucial to produce e-fuels, has a significant impact on production costs and carbon intensity. The key findings of task 64 are:

- E-fuels and biofuels will play an important role in the energy transition and to reach net-zero targets. There will be an increase in the technology diversity.
- Some e-fuels can be produced with mature technologies, but the combination of several technologies in a production plant can have a low overall technology maturity level.
- Strategic programs to support e-fuel production have been implemented in several countries. They consist of incentives for e-fuel production, support for research projects and/or regulations that make the proportionate use of e-fuels mandatory.
- The energy-intensive production of e-fuels raises the question of whether they should primarily be used for applications that are difficult to electrify. These applications can be found, e.g., in aviation, maritime transport, heavy goods traffic and industrial processes.
- Hydrogen production via water electrolysis has the largest impact on the carbon intensity of the product. Life-Cycle Assessments results show that using renewable electricity is key to having low-carbon e-fuels.
- The most important cost driver in the production of e-fuels is hydrogen production by water electrolysis, and e-fuel production costs depend primarily on electricity prices, which depend on the geographical location, and capital costs.

The collaborating countries in Task 64 are Brazil, China, Denmark, Finland, Germany, Japan, Switzerland, and the United States. Furthermore, collaboration and exchanges with IEA Bioenergy TCP, IEA Hydrogen TCP, IEA HEV TCP, IEAGHG and the International Transport Forum took place. The task was managed by Zoe Stadler, OST Eastern Switzerland University of Applied Sciences. In the task, workshops were organized on various e-fuel specific topics, during which the task participants formulated key messages and joint conclusions that served as the basis for the final report. These topics were: demo sites and pilot programs, resources, application, regulations, life-cycle assessments, techno-economic assessments, and stakeholders.

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The Technology Collaboration Programme in Advanced Motor Fuels (AMF) is an international platform for cooperation in the framework of IEA´s Technology Collaboration Programmes (TCPs). AMF´s vision is that advanced motor fuels, applicable to all modes of transport, significantly contribute to a sustainable society around the globe. www.iea-amf.org

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Definitions / Abbreviations

AMF	Advanced Motor Fuels: Technology Collaboration Programme by the International Energy Agency IEA
CCU / CCS	Carbon Capture and Usage / Carbon Capture and Storage
E-Fuels	Electro fuels (e-fuels) are synthetic fuels manufactured using captured carbon dioxide, carbon monoxide or nitrogen together with low-carbon hydrogen. In their report on e-fuels, the IEA defines e-fuels as "*fuels obtained from electrolytic hydrogen* ". It states: "*E-fuels are low-emission fuels when their hydrogen is produced using low-emission electricity and any carbon inputs are obtained in a way that leads to low life-cycle greenhouse gas emissions. E-fuels made from biogenic or air-captured CO_2 can potentially provide full emissions reduction, making them the primary production pathway that is consistent with achieving net zero emissions by mid-century.*" (IEA International Energy Agency 2024) The technologies to produce e-fuels are called "Power-to-X". Power-to-X converts electricity into a wide variety of end products (X).[1] E.g. CO_2 from processing of biomass or biogas can be used in the synthesis of e-fuels if the energy content is derived from non-biological sources.
FT	Fischer-Tropsch synthesis produces a type of synthetic crude oil. The Fischer-Tropsch products contain pure hydrocarbons such as paraffins and olefins, as well as oxygenated compounds such as alcohols, aldehydes, carboxylic acids, esters, and ketones. The products of a FT process depends on the catalyser, pressure, temperature and other process conditions such as e.g. H_2/CO ratio. An overview on FT processes is given in the following article: (Martinelli et al. 2020)
Hydrogen emission intensity	There are various terms that are commonly used to describe the type of hydrogen production (e.g., the use of colours to describe green hydrogen). These terms are often vague and are used differently from region to region, and no international standard exists.[2] The IEA therefore proposes the use of a passport that contains information on CO_{2eq} emissions, water requirements, land requirements, etc. (IEA International Energy Agency) This would enable an objective assessment and comparability of hydrogen from different sources. In this report, 'low-emission' is used to label hydrogen or e-fuels with low greenhouse gas emissions in their production.
IPCEI	Abbreviation for 'Important Project of Common European Interest'

[1] Source: How PtX works - PtX Hub (ptx-hub.org)
[2] See IEA proposal for more precise terminology: https://www.iea.org/commentaries/why-clearer-terminology-for-hydrogen-could-unlock-investment-and-scale-up-production, accessed on 31.05.24

NTP

Normal temperature and pressure. NTP is defined as a temperature of 298.15 K and an absolute pressure of 1.01325 bar.

Renewable energy

Key to e-fuel production technologies are sustainable and renewable primary energy sources. The UN defines “renewable energy” as energy that is derived from natural sources that are replenished at a higher rate than they are consumed.[3] Examples for such sources are sunlight, tides, wind and biomass.

RFNBO

Renewable fuel of non-biological origin (RFNBO): '*In the EU, this refers to fuels that are produced using energy from other renewable energy sources. In practice this means the use of renewable power from geothermal, solar or wind power, where a local excess production can result during shorter or longer periods, thereby giving access to such energy at low costs*.'[4] Definition from RED II: *‘renewable liquid and gaseous transport fuels of non-biological origin’ means liquid or gaseous fuels which are used in the transport sector other than biofuels or biogas, the energy content of which is derived from renewable sources other than biomass*. [5]

STP

Standard temperature and pressure. STP is defined as a temperature of 273.15 K and an absolute pressure of exactly 105 Pa (100 kPa, 1 bar).

SynBioPTx

Synergies of biomass and electricity-based technologies

TCP

Technology Collaboration Programme

TRL

Technology Readiness Level. Where a topic description refers to a TRL, the following definitions apply, unless otherwise specified (based on (European Commission 2014)):

- TRL 1 – basic principles observed
- TRL 2 – technology concept formulated
- TRL 3 – experimental proof of concept
- TRL 4 – technology validated in lab
- TRL 5 – technology validated in relevant environment
- TRL 6 – technology demonstrated in relevant environment
- TRL 7 – system prototype demonstration in operational environment
- TRL 8 – system complete and qualified
- TRL 9 – actual system proven in operational environment (competitive manufacturing in the case of key enabling technologies).

[3] Source: What is renewable energy? | United Nations
[4] Source: Renewable fuels of non-biological origin (RFNBO) (etipbioenergy.eu)
[5] Source: Renewable fuels of non-biological origin (RFNBO) (etipbioenergy.eu)

Introduction

The net-zero policies of most countries require actions to reduce the use of fossil fuels. These fuels are energy sources that are currently used for mobility (on land, at sea and in the air), industry, heating, and other purposes. By increasing efficiency and electrification, the overall consumption of gaseous or liquid energy carriers can be reduced. However, there are some applications, such as aviation or international shipping and others “hard-to-abate” sectors, which will continue to play an important role and which cannot easily be electrified (for long distances). Therefore, some demand for fuels will remain and these fuels will need to be produced from renewable energy or lower carbon intensity sources in the coming decades.

There are different ways to produce low-carbon emission fuels: for example from biogenic material ("biofuels"), based on electricity ("electro-fuels" or "e-fuels") or, a process that is still at an early stage of development, directly with solar heat ("sun-to-liquid"). These different production technologies will complement each other, as they all have their advantages and disadvantages. The production of biofuels is currently the most established technology and the cheapest of the three options. However, the potential will not be sufficient to cover all future fuel needs. Further production technologies for renewable fuels are therefore required. Some of the e-fuels can already be produced today using mature technologies, others still need to be developed further. The former technologies are currently being used on a larger scale worldwide primarily in the petrochemical industry and not yet to produce e-fuels.

For the IEA TCP on Advanced Motor Fuels (AMF), the role of different fuels for use in engines (mainly mobile machines, but also stationary) is of particular interest. Currently, some regions and countries are implementing policies to reduce the number of internal combustion engines and to increase the number of battery-electric vehicles. These measures mainly affect smaller road vehicles such as cars and small lorries. However, they increase uncertainty regarding the use of internal combustion engines in other applications such as trains, small ships, construction machinery, etc.

Many e-fuel projects are being announced in the international media. In addition, countries around the world are adopting new policies to deal with emerging technologies. And they are also developing individual strategies for the use of renewable fuels in different energy applications.

To get an overview of the participating countries, this Task 64 "E-fuel and end-use perspectives" focuses on the current development of e-fuels in the different countries, including country-specific strategies and incentives.

Objectives

The focus within Task 64 is an informative exchange on the production and application of different e-fuels, as well as the corresponding regulatory framework. The output of the task is this report, addressing the following topics:

- Demo sites / pilot programmes: Consideration of different demo sites in different countries that focus on the development and improvement of e-fuel production technologies, including consideration of technology pathways, technological maturity and case studies.
- CO_2 and H_2 resources: The availability of CO_2, water resources, and electricity sources in different countries, with assessment of national feedstock potential for e-fuel production.
- Application side: Experiences and challenges in the application of e-fuels, especially with regard to the use of e-fuels in aviation, maritime and road transport.
- Regulations: Norms and/or regulations for the use of e-fuels in various countries. Incentives and regulations that promote the production and use of e-fuels.
- Life-cycle assessments (LCA): Accounting in some LCA may differ from country to country (e.g., REDII in the EU). Typical and expected net GHG effects as well as other environmental impacts (e.g., water consumption) of e-fuel production and use.
- Techno-economic assessments (TEA): Costs of the different e-fuel production value chains in various countries, and methodology for economic calculation. Costs on the application side of the switch to e-fuels.
- Stakeholders: Actors from research, industry and administration along the value chain (raw material supply, conversion technologies, e-fuel suppliers, e-fuel consumers), as well as bioenergy research centres, and academic institutions.

Based on these topics, workshops were organised in which key messages and joint conclusions were formulated. These serve as the basis for this task report, which provides an insight into ongoing activities worldwide as well as past and current technical, economic and regulatory challenges. In addition to the exchange of information, the report is intended to help raise awareness of the importance and global activities in the field of e-fuels.

Methodology and Description of Activities

The focus of the e-fuels task is on an informative exchange on the production and use of various e-fuels as well as on the corresponding legal framework. Workshops were organised on various topics. For each workshop, findings were collected, and key statements formulated that serve as the basis for this report.

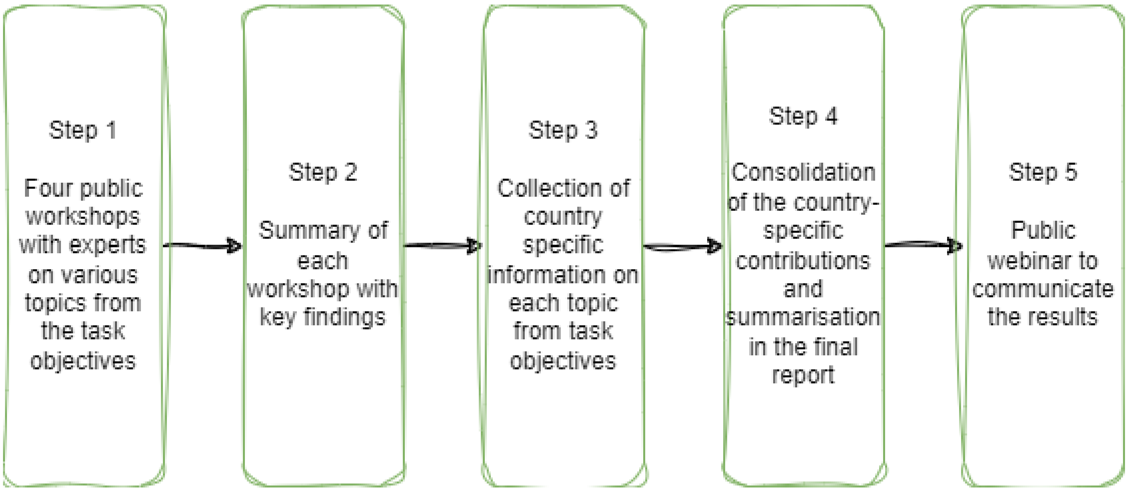

Figure 1: Procedure for collecting and consolidating the information in Task 64.

In this report, individual steps/topics of e-fuel production and utilisation correspond to chapters. The report starts with the production technologies and strategies in the countries, followed by the resources required for production and the perspective from the application side. The second half of the report deals with existing regulations, as well as findings from techno-economic analyses and life cycle assessments. This is followed by a list of stakeholders from the various countries. The most important findings and key messages are summarised at the end of the report.

The information and findings included in this report originate to a large extent from the countries involved in the task. In addition, experts were invited to give presentations at the workshops. The information was supplemented by a literature search.

Production Pathways of E-Fuels

Both biomass-based fuels and electricity-based fuels can be used when switching from fossil fuels to renewable energy sources. Due to the limited availability of biomass and renewable electricity in some cases, both fuel options should be seen as complementary and not in competition.

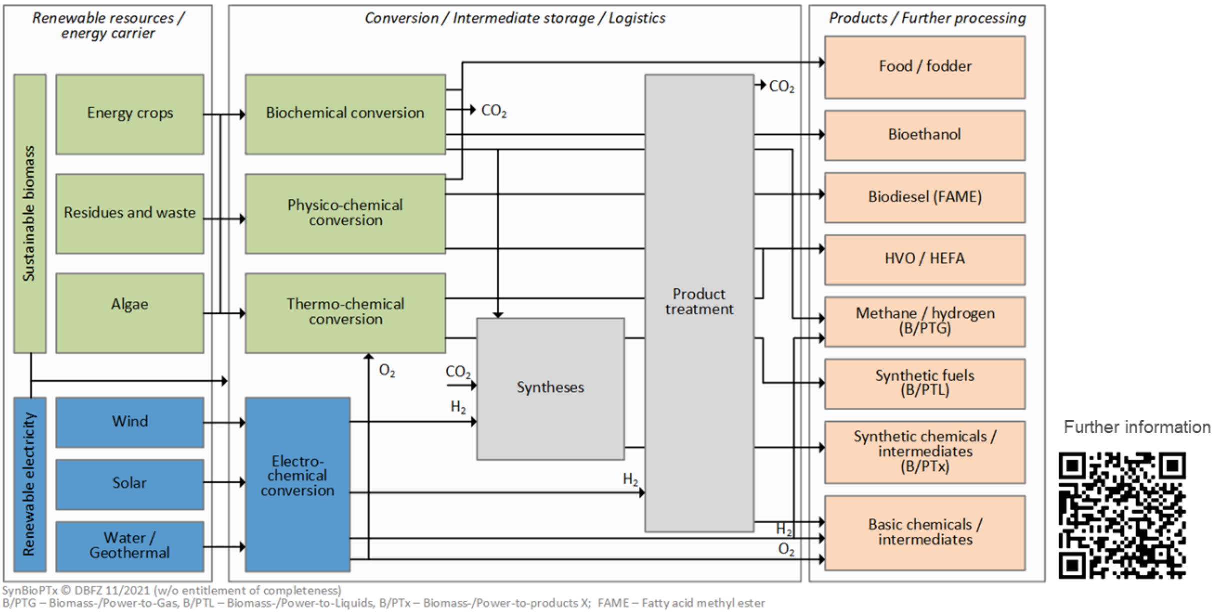

Figure 2: Production pathways of renewable fuels and other products. Source: (Schröder 2023)

E-fuels include a wide spectrum of products and accordingly also of different technologies. Using the synergies of biomass-based and power-based process routes and technologies in the meaning of the acronym SynBioPTx will allow to develop renewable technologies for fuels and other products further. A simplified scheme of possible multiproduct routes and synergies to use carbon sources, hydrogen and oxygen is shown in Figure 2. The basis for the production of e-fuels is electrolytic hydrogen.

Possible process routes for the provision of renewable fuels for the transport sector have been characterised in terms of their technologies and their technology readiness level (TRL) e.g., in the monitoring report (Schröder 2023). Also TRL of different synthetic production pathways including e-fuels have been analysed and is reported also in (Hauschild et al. 2023). It is to be noted that some single technologies might have a high TRL, in the combination in an overall plant however, the TRL can be lower. The TRL of the production technologies of synthetic fuels (biomass-to-X and power-to-X) varies between 3 ("Experimental proof of the technology") to 8 ("first-of-its-kind demonstration in full scale"), depending on the technology. The production of hydrogen via water electrolysis has a TRL of 9 ("proof of successful deployment").

Production of E-Hydrogen

The first stage of Power-to-X processes and therefore of e-fuel production is an electrolyser, in which water H_2O is split into hydrogen H_2 and oxygen O_2 using electricity (power). The chemical reaction equation, the reaction enthalpies and the aggregate states of the reactant and products are as follows:

					Reaction enthalpy: (products, reactants at 1.01325 bara and 298.15 K)
$2\ H_2O$	→	**$2\ H_2$**	**+**	**O_2**	
1 mol		1 mol		½ mol	+286.0 kJ/(mol H_2) +0.079 kWh/(mol H_2)
liquid		gaseous		gaseous	

The reaction enthalpy is positive, which means that the reaction is endothermic, and energy must be expended. In electrolysis, this energy is electricity, part of which can also be supplied via heat.

If a gas is not at too high a pressure, then a molecule takes up the same volume regardless of which molecule it is. The chemical reaction equation is given below together with the volumes of the substances at normal temperature and pressure (NTP) (temperature of 298.15 K and an absolute pressure of 1.01325 bara).

$2\ H_2O$	→	**$2\ H_2$**	**+**	**O_2**	Reaction enthalpy: (products, reactants at NTP)
0.8037 liter$_l$		1 m^3_g		½ m^3_g	+12‘757 kJ / (m^3_{NTP} H_2) + 3.544 kWh / (m^3_{NTP} H_2)
8.94 kg		1 kg		7.94 kg	+141‘820 kJ / (kg H_2) +39.41 kWh / (kg H_2)

There are different types of electrolyser technologies[6], which are described in the table below.

[6] For further information on electrolysers check: https://www.iea.org/energy-system/low-emission-fuels/electrolysers, accessed on 21.03.2024

Table 1: Different types of electrolyser technologies.

Production technology	Description / further details
Alkaline Electrolysis Cell (AEC)	Mature technology with proven reliability and lower capital costs. It is commercially available. Electrolysis occurs in a liquid alkaline solution. Well-suited for large-scale, steady-state hydrogen production. The AEC has a slower response time to fluctuations in power input, compared to PEM.
Anion Exchange Membrane / Alkaline Electrolyte Membrane (AEM)	Least developed of the four most common electrolysis technologies. It is a membrane technology that operates in an alkaline medium, allowing for the use of inexpensive materials and resulting in a smaller footprint. The process promises to be very efficient.
Polymer Electrolyte Membrane / Proton Exchange Membrane (PEM/PEMEC)	Uses a solid polymer electrolyte membrane and offers higher efficiency potential and faster response times, making it suitable for integrating with dynamic renewable energy sources (wind, solar). A PEM system has usually a compact design compared to alkaline systems. Disadvantages of the PEM technology are higher capital cost compared to alkaline currently and dependence on scarce materials (e.g., platinum group metals) for catalysts.
Solid Oxide Electrolysis Cell (SOE/SOEC)	Utilizes a solid ceramic electrolyte and operates at high temperatures (600-1’000°C). This allows for the potential of very high efficiencies but is still less mature than other methods. The technology can utilize heat from various sources, potentially improving overall system efficiency.

Production of E-Methane

In the power-to-methane process, the Sabatier reaction takes place, in which the hydrogen H_2 reacts with CO_2 to form methane. The chemical reaction, the number of moles and the aggregate states of the reactants and products at 1.01325 bara and 298.15 K are as follows:

4 H_2	**+**	**CO_2**	**→**	**CH_4**	**+**	**2 H_2O**	Reaction enthalpy: (products, reactants at 1.01325 bara and 298.15 K, water condensed)
4 mol		1 mol		1 mol		2 mol	-253.2 kJ / (mol CH_4) -0.0703 kWh / (mol CH_4)
gaseous		gaseous		gaseous		liquid	

The reaction enthalpy is negative, which means that the reaction is exothermic, and energy is released during the reaction. This energy is present in the form of waste heat. The chemical reaction equation together with the volumes of the substances at 1.01325 bara and 298.15 K is as follows:

4 H_2	**+**	**CO_2**	**→**	**CH_4**	**+**	**2 H_2O**	Reaction enthalpy: (products, reactants at 1.01325 bara and 298.15 K, water condensed)
4 m^3_g		1 m^3_g		1 m^3_g		1.6 $liter_l$	-11’294 kJ/(m^3_{NTP} CH_4) -3.137 kWh/(m^3_{NTP} CH_4)
0.50 kg		2.74 kg		1 kg		2.25 kg	-15’783 kJ / (kg CH_4) -4.384 kWh / (kg CH_4)

There are two different types of methanation technologies, which are described in the table below.

Table 2: Methanation technologies

	Description / further details
Catalytic Methanation	Exothermic conversion of H_2 and CO_2 at about 300 - 550 °C with catalysts (usually nickel-based). The catalytic reactor requires a smaller reactor volume compared to the biological methanation.
Biological Methanation	In the biochemical conversion, archaea (microorganism) serve as biocatalyst and convert H_2 and CO_2 into CH_4. The bioprocess takes place in aqueous solutions at temperatures between 40 - 70 °C. The mixing of the gases and the liquid is a challenge in the realisation.

Production of E-Ammonia

Ammonia synthesis from atmospheric nitrogen and hydrogen is carried out on a catalyst (usually iron-based) at pressures of around 150 to 350 bar and temperatures of around 400 to 500 °C. It is a well-known and established process that is used on a large industrial scale.

N_2	+	$3\ H_2$	→	$2\ NH_3$	Reaction enthalpy: (products, reactants at 1.01325 bara and 298.15 K)
0.5 mol		1.5 mol		1 mol	-46.1 kJ / (mol NH_3) -0.0128 kWh / (mol NH_3)
gaseous		gaseous		gaseous	

The reaction enthalpy is negative, which means that the reaction is exothermic, and energy is released during the reaction. The chemical reaction equation together with the volumes of the substances at 1.01325 bara and 298.15 K is as follows:

N_2	+	$3\ H_2$	→	$2\ NH_3$	Reaction enthalpy: (products, reactants at 1.01325 bara and 298.15 K)
0.5 m^3_g		1.5 m^3_g		1 m^3_g	-2'057 kJ/(m^3_{NTP} NH_3) -0.571 kWh/(m^3_{NTP} NH_3)
0.82 kg		0.18 kg		1 kg	-3'044 kJ / (kg NH_3) -0.855 kWh / (kg NH_3)

Production of E-Methanol

Methanol is an organic chemical compound with the chemical formula CH_3OH. Methanol is produced in catalysts (mainly copper-zinc oxide-aluminium oxide) from synthesis gas. It is a well-known and established process that is used on a large industrial scale. For more information on methanol production see AMF report from Annex 56 (Schröder et al. 2020).

CO	+	$2\ H_2$	→	CH_3OH	Reaction enthalpy: (products, reactants at 1.01325 bara and 298.15 K)
1 mol		2 mol		1 mol	-128.4 kJ / (mol CH_3OH) -0.036 kWh / (mol CH_3OH)
gaseous		gaseous		liquid	

The reaction is exothermic, and energy is released during the reaction. The chemical reaction equation together with the volumes of the substances at 1.01325 bara and 298.15 K is as follows:

CO	+	$2\ H_2$	→	CH_3OH	Reaction enthalpy: (products, reactants at 1.01325 bara and 298.15 K)
0.60 m^3_g		1.25 m^3_g		1 $liter_{fl}$	-2'673 kJ/(l CH_3OH) -0.743 kWh/(l CH_3OH)
0.87 kg		0.13 kg		1 kg	-3'375 kJ / (kg CH_3OH) -0.938 kWh / (kg CH_3OH)

Production of E-Fischer-Tropsch Fuels

Fischer-Tropsch synthesis does not produce pure end products, but a type of synthetic crude oil. It is often referred to as "Syncrude" to emphasize its similarity to crude oil. The composition of the Syncrude depends on the technology used, the catalyst, the synthesis reactor, the operating conditions and the degree of deactivation of the catalyst. The Fischer-Tropsch products contain pure hydrocarbons such as paraffins and olefins, as well as oxygenated compounds such as alcohols, aldehydes, carboxylic acids, esters and ketones. In Fischer-Tropsch synthesis, syngas is catalytically converted into a spectrum of hydrocarbon chains, including a fraction of oxygenates. (Martinelli et al. 2020)

The Fischer-Tropsch pathway can be used to produce fuels such as naphtha, diesel, gasoline and aviation fuels.

The formula for the Fischer-Tropsch process is:

$$(2n+1)\,H_2 + n\,CO \rightarrow\ C_nH_{2n+2} + n\,H_2O$$

Where n is typically between 10 and 20. If $n = 1$, the product is methane.

The Fischer-Tropsch synthesis is a combined CO polymerisation and hydrogenation reaction. It is a highly exothermic reaction with a reaction enthalpy of the order of $-160\ kJ\cdot mol^{-1}$ CO converted (Arno de Klerk 2014).

An alternative to the Fischer-Tropsch process is synthesis gas fermentation, which is a microbiological process in which a synthesis gas consisting of carbon monoxide (CO), hydrogen (H_2) and carbon dioxide (CO_2) is used as an energy and substrate source for fermentation. Through the metabolic processes of the microorganisms used, chemicals can be obtained in this way that can be used as biofuels or as platform chemicals in the chemical industry.

Targeted E-Fuel Technology Routes

The energy transition is currently leading to an increase in the diversity of technologies. Countries are also pursuing different strategies and the market is therefore developing in various directions in different regions.

Projected Demand for E-Fuels and E-Chemicals

A large increase in e-fuel production is expected in order to meet future demand for fuels and chemicals from renewable sources. A recent study by Galimova et al. evaluates the role of e-fuels and e-chemicals in a global energy system transition from 2030 to 2050 by analysing the demand for these fuels, potential for production, and costs. (Galimova et al. 2023) Their research assumes an energy system transition to 100% renewable energy across power, heat, transport, industry, and desalination sectors for the world comprised of 145 regions. The study has identified the following demand for e-fuels and e-chemicals:

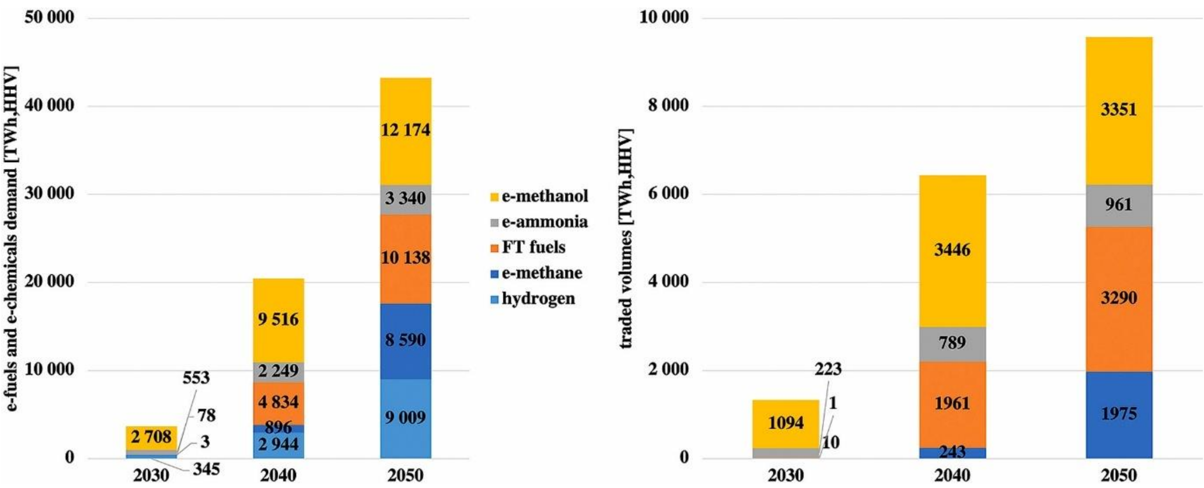

Figure 3: Development of the global demand for e-fuels and e-chemicals from 2030 to 2050 (left) as well as the projected trade volumes (right). Source: (Galimova et al. 2023)

The research done by (Galimova et al. 2023) is a first of its kind to present the global trading of e-fuels and e-chemicals, and therefore has some limitations. For example, in this research, the production of e-fuels does not consider the possible lack of power grid connections between fuel synthesis and electricity generation sites. And in addition, this approach does not enable the identification of the best possible sites within regions as that would require higher spatial resolution. Nevertheless, some results of this research by (Galimova et al. 2023) are listed below:

- The global demand for fuels and chemicals, comprised of fossil, bio, and renewables, including hydrogen is not expected to grow until 2050 but to decline because of efficiency gains enabled by direct electrification in future energy systems, especially in the transport sector.
- Europe, Eurasia, MENA (Middle East and North Africa), Northeast Asia, and SAARC (South Asian Association of Regional Cooperation) regions rely on imports to satisfy their demand, whereas Southeast Asia can balance the demand within its region.
- By 2050, South America secures itself as one of the main exporters of e-fuels and e-chemicals.
- Sub-Saharan Africa emerges as another important exporter as it is expected to export

more than 4’500 TWh_{th} of e-fuels and e-chemicals representing more than 50% of the traded volume in 2050.

- North America and MENA regions are expected to balance most of their respective demands within their regions and only partially import e-fuels and e-chemicals to cover their demand.

(Galimova et al. 2023) comes to the conclusion that 23–32% of the total demand will be traded between countries, depending on the type of e-fuel and e-chemical. Figure 3 shows that it is expected that hydrogen will be produced more in the country of demand, while the other e-fuels, which have advantages in transportation like for example a higher energetic density, will be more involved in trade.

Country Specific Strategies of Different Countries

The following table gives an overview on the different technology routes, that are currently considered in the strategies of the countries within AMF task 64.

Table 3: Envisaged use of e-fuels in the different countries involved in task 64.

Country	Envisaged technology routes of e-fuels: from production to application
Brazil	Brazil aims to keep the high level of renewables in its energy matrix. To reach this goal, the country aims to increase the amount of biofuels and e-fuels, but the latter has not yet reached a commercial status. It also includes the research and development studies in new routes/technologies to produce advanced fuels such as: SAF, diesel, hydrogen, HVO, and sustainable marine fuels (methanol, ammonia). Some technologies such as ATJ (Alcohol-to-jet) can be detached in Brazil once it has a large availability of natural feedstocks. Brazil has a significant experience in the production of biomass-based ethanol and biodiesel. Brazil includes hydrogen as a new type of energy source to be used in a near future, in chapter 12 of the Ten-Year Energy Expansion Plan (PDE) 2031 Report. Brazil has issued its National Program in Hydrogen (Ministério de minas e energia 2022), and determined milestones included in the Three-Year Work Plan 2023-2025 of the National Hydrogen Program (PNH2). By 2025, the goal is to disseminate low-carbon hydrogen pilot plants in all regions of the country. By 2030, the goal is to consolidate Brazil as the most competitive producer of the molecule in the world and, by 2035, the consolidation of low-carbon hydrogen hubs. According to MME (Ministry of Mines and Energy) estimates, the country has the technical potential to produce 1.8 gigatons of hydrogen per year and at a lower production cost (Agência Gov 2023) considering the international average. Renewable hydrogen can be produced by disruptive technology and will be relevant in the context of energy matrix decarbonization, insertion of distributed energy resources as well as storage and flexibility strategies. As Brazil has a large biomass capacity, the production of low carbon emission hydrogen (H_2 from biomass or biofuels reforming, gasification, or anaerobic digestion, with or without CCS) and turquoise hydrogen (H_2 from methane pyrolysis without CO_2) is especially interesting for Brazil. A possible way to produce hydrogen from biomass is via biorefinery, which can produce hydrogen next to biodiesel, bioethanol, and other biobased chemicals. For the last 15 years, ethanol and biodiesel have been the two key renewable fuels. Going forward, the advance of many projects on biogas, SAF,

Country	Envisaged technology routes of e-fuels: from production to application
	HVO, hydrogen, ammonia, among others, should complete this biofuels slate. Furthermore, it shall be highlighted the wind and solar potential in the future electric energy matrix and how the biofuels production can be source of biogenic CO_2, specially from ethanol and cellulose production.
China	Hydrogen is expected to play an essential role in China's future pathway towards to the announced target of Carbon Neutrality before 2060. 2019: Fuel cell vehicles were mentioned in the 2019 Annual Report on the Work of the Central Government for the first time. 2020: Hydrogen was introduced into the draft amendment of China's Energy Law for soliciting public comments. 2020: Development Plan for the New Energy Vehicle Industry (2021-2035): Focusing to the technological breakthroughs regarding hydrogen storage and infrastructure. Another associated Technology Roadmap 2.0 suggests 100 thousand FCVs by 2025 and 1 million FCVs by 2035. However, a clear national-level strategy and plan for hydrogen industry is still under development. Methanol, gasoline, and aviation fuels are seen as products in the e-fuel projects. Methanol is the most common product. From a technological perspective, many research efforts have been concentrated in the development of catalyst systems. For example, improving the selectivity of methanol of CO_2 hydro conversion technology.
Denmark	In Denmark, the use of e-methanol is important for the shipping industry. E-LNG is lacking a national distribution network. E-ammonia is an upcoming solution while there are safety issues near cities and ports. Another discussed issue is the transport of CO_2, as there are concerns about what happens if a very large CO_2 tank leaks.
European Union	In Europe, there are four IPCEIs ('Important Project of Common European Interest') on the subject of hydrogen: Hy2Tech, Hy2Use, Hy2Infra and Hy2Move. The IPCEIs on Hydrogen contribute to a value chain for renewable hydrogen at low costs, as well as to the objectives of key EU policy such as the European Green Deal, the EU Hydrogen Strategy and the REPowerEU Plan. 22 EU countries and Norway jointly design and coordinate IPCEIs on hydrogen. Renewable hydrogen is promoted in the EU via several instruments including the targets set out in the Renewable Energy Directive. Two delegated acts outline detailed rules on the EU definition of renewable hydrogen. Targets and demand for RFNBOs in the EU are summarized in (EXERGIA et al. 2024). Table 4-6 in (European Commission: Directorate-General for Research and Innovation 2024) gives an overview on capacity development of existing and announced e-kerosene projects.
Finland	The focus in Finland is put on e-methane, e-methanol, paraffinic fuels and e-diesel. It is highlighted, that CCU (Carbon capture and utilization) is regarded

Country	Envisaged technology routes of e-fuels: from production to application
	as much more positive than CCS, as there are difficulties with the storage.
Germany	The Power-to-X / e-fuels opportunities have been addressed in Germany starting in the early 2010ies. Meanwhile this topic is among others part of the German National Hydrogen Strategy (NHS)and R&D on synthetic fuels is pushed, especially for aviation. The goal is to have hybrid multi-fuel refineries and to be a leading provider of hydrogen technologies by 2030. With fuel synthesis (e.g. Fischer-Tropsch) usually multiple products are produced, and all of them need to be used at least for economic reasons. Many projects are focussing on methanol as key product or intermediate as well as Fischer-Tropsch routes. Moreover, also methane is considered. Often these projects are considering biomass-based technologies to provide the renewable carbon source (esp. fermentation processes like biogas or bioethanol production and the coproduct CO_2). An overview and what e-fuels can do for the energy transition in transport - and what they cannot do is reflected e.g. in (Agora Verkehrswende 2023).
Japan	For e-fuels, the focus is on hydrogen and ammonia. The aim is to reduce production costs and thus achieve commercialization, to increase the development and production of the necessary technologies and finally to establish the use of synthetic fuels. For mobility purposes, the fuels are intended primarily for trains and buses, in addition to ships and aviation. Passenger cars are assumed to be powered by hybrid electric vehicles. The most important uses for e-fuels are therefore considered to be aviation, shipping and heavy-duty transport. However, as there will still be passenger cars with combustion engines, they will also need renewable fuels. In Japan, consumers are very interested in using e-methane or biogas. Since Japan's land area is limited, suitable overseas production sites are needed.
Switzerland	Electricity-based energy sources are necessary to achieve the net zero target, but for energy and cost efficiency reasons they should only be used in those areas where there are few alternatives. These include heavy-duty traffic and international air traffic. Therefore, in Switzerland, the Federal Office of Civil Aviation pushes the development of sustainable aviation fuels (SAF). A national hydrogen strategy will be published at the end of 2024.
United States	Net zero carbon e-fuels are intended for use in hard-to-electrify transportation subsectors for deep decarbonization (long-haul trucks, offroad, aviation, and marine). In the United States, SAF is regarded as an important e-fuel (mainly produced by alcohol-to-jet and HEFA technologies). E-methanol is also of great interest as it is a commodity chemical for various applications, e.g., chemical intermediate, fuels or fuel intermediate, and is easy for transportation. Otherwise, e-fuels aren't assumed to play a major role in the near future as their production is too tiny in comparison to other projects. In the U.S., the

Country	Envisaged technology routes of e-fuels: from production to application
	inflation reduction act (IRA) incentivizes the production of clean hydrogen, SAF, and clean fuels (with the latter two including e-fuels). Current activities in the United States are: • The USDRIVE Net Zero Carbon Fuel Tech Team evaluates the economics and environmental implications of various e-fuel production pathways through TEA and LCA, respectively (Dees et al. 2021; Chen et al. 2023). • CO_2 Reduction and Upgrading for e-Fuels Consortium of the Department of Energy (DOE) Bioenergy Technology Office (BETO) is a multi-national laboratories project, which aims to develop and derisk advanced e-fuel production technologies through various conversion routes. The objective of the consortium is to provide a strategic R&D vision for CO_2-to-fuels efforts and an integrated portfolio of relevant technologies. • The U.S. Federal Aviation Administration (FAA) co-leads the effort on e-fuel potentials for the International Civil Aviation Organization through the involvement in the Fuels Task Group where emission accounting for the e-fuel production for SAF is discussed. • DOE evaluated the opportunities and challenges of carbon capture utilization and storage (CCUS) options in the United States and released a report titled The Pathway To: Carbon Management Commercial Liftoff (U.S. Department of Energy 2023). This presents the key takeaways when aiming to develop and derisk advanced e-fuel production technologies. • In DOE's recent report, 2023 Billion-Ton Report: An Assessment of U.S. Renewable Carbon Resources (U.S. Department of Energy 2024), available U.S. CO_2 resources were thoroughly evaluated.

Commonalities and Differences

According to these country-specific technology routes of e-fuels, the following commonalities among the strategies of different countries can be summarised:

- **Renewable Energy Focus**: Many countries are aiming to increase the share of renewable energy sources in their energy matrices. This includes the development and utilization of biofuels, e-fuels, and hydrogen derived from renewable sources. The final costs shall also be considered, mainly for developing countries.
- **Technological Development**: There is a strong emphasis on research and development to improve technologies related to the production, distribution, and utilization of e-fuels. This includes advancements in catalyst systems, fuel synthesis processes (such as Fischer-Tropsch) and further downstream processes (such as methanol to olefins or jet), and the development of new routes for producing advanced fuels (such as syngas fermentation).
- **Decarbonization Goals**: All countries are motivated by goals related to decarbonization and reducing carbon emissions. E-fuels are seen as a potential pathway to achieve these goals, particularly in hard-to-abate sectors, like aviation and shipping as well as heavy duty road and off-road applications, where electrification may not be feasible.
- **Diversification of Fuel Sources:** There is a recognition of the need to diversify fuel sources to enhance energy security and resilience. This includes exploring multiple types of e-fuels such as methanol, methane, ammonia, and hydrogen.

However, also differences among the strategies of different countries could be identified:

- **Prioritization of Specific e-Fuels**: Different countries prioritize different e-fuels based on their domestic resources, technological capabilities, and specific needs of their industries. For example, Brazil focuses on synergies with biofuels like ethanol, biodiesel and the emerging synthetic fuels, and develops the growing solar and wind sources, as well, while China emphasizes methanol and Japan prioritizes hydrogen, methane and ammonia.
- **Target Sectors**: The sectors targeted for the use of e-fuels vary among countries. Some focus on transportation, including aviation, shipping, and heavy-duty transport, while others also consider industrial applications and chemical manufacturing.
- **Policy Emphasis**: Each country has its own policy framework and incentives to promote the development and adoption of e-fuels. This may include subsidies, regulations, and government-led initiatives to support research, development, and commercialization efforts.
- **International Collaboration and Trade**: Some countries, particularly those with limited domestic resources or land area, may rely on international collaboration and trade to access e-fuels. This involves considering overseas production sites and partnerships for sourcing and distribution.

While there are common goals and approaches among countries regarding the development of e-fuels, the specific strategies and priorities are shaped by each country's circumstances, resources, and policy landscape.

Examples of E-Fuel Production Projects by Country

There are pilot and demonstration projects to produce e-fuels in many countries. The following subchapters provide an insight into current, planned or completed projects. The information does not claim to be exhaustive and provides an insight rather than an overview.

Austria

Innovation Liquid Energy project: In the IFE (https://iwo-austria.at/innovation-fluessige-energie/, Innovation Liquid Energy) project, a stationary overall system with H_2O+CO_2 high-temperature electrolysis (Co-SOEC) and Fischer-Tropsch synthesis is developed for the production of synthetic fuel. The goal of the 1 MW demo plant is to produce about 160’000 litres of e-diesel, 150’000 litres of wax and 150’000 litres of naphtha per year.

Process: Co-SOEC + Fischer-Tropsch
Product: e-diesel, wax, naphtha

Power-to-Methane project in Gabersdorf: Hitachi-Zosen Inova (HZI) operates a biogas methanation plant in Gabersdorf, Austria. At the plant, biogas is mixed with hydrogen from electrolysis and then upgraded in a methanation reactor to methane. The hydrogen is produced in a PEM electrolyser with power from PV panels on a nearby solar field and afterwards compressed and stored in either a low-pressure storage (30 bar) or a high-pressure storage (300 bar). The CO_2 stems from biogas production; only a small amount of the total CO_2 available is converted into methane, however.

Product: e-methane

Belgium

Project Columbus: Columbus is an innovative Carbon Capture and Utilisation (“CCU”) project in Wallonia: Columbus - Pioneer of the energy transition | Columbus (columbus-project.com). This project will concentrate CO_2 from an innovative type of lime kiln and combine it with hydrogen to produce synthetic methane. The hydrogen will be produced by a 100 MW electrolysis unit, powered by renewable electricity.

Product: e-methane

Brazil

Camaçari Industrial Complex (BA): There is a project with Thyssen-Krupp technologies in which electrolysers with a total capacity of 60 MW shall be installed, and initial investment of R$ 120 million. The plant will feed one of the largest ammonia plants by capacity when it starts its production.

Product: Ammonia

It was produced by EDP Brasil in the Pecém Complex, in Ceará, low carbon emission hydrogen in a pilot plant. The low carbon emission Hydrogen unit (Pecém H2V) received an investment of R$42 Million (approx. US$ 8 M) to generate clean fuel. It includes a solar plant with a capacity of 3 MW and a state-of-the-art electrolyser module for producing fuel guaranteed to be of renewable origin. These project and pilot plant will allow the analysis of the gas production chain, business models, strategic partnerships with industries and mobility adaptations using hydrogen. From there, regulatory issues will be defined to enable large-scale commercialization, mainly aimed at the foreign market.

GIZ, from Germany, is working together with SENAI from Natal (capital city from Rio Grande do Norte, a Northeast Brazilian State) to produce SAF (sustainable aviation fuel) in a small pilot plant (20,000 ton).

A list of the main initiatives for low carbon emission **hydrogen** production in Brazil. There are eight commercial plants and two pilot projects.

- **Unigel (State: Bahia):** Investment: US$ 1.5 billion; Production: Hydrogen (100’000 tons/year) and Ammonia (600’000 tons/year); Electrolysis capacity (first phase of the project): 60 MW; Expected start: 2024 (Italo 2024); Full operation: 2027
- **Qair (State: Pernambuco):** Investment: US$ 3.9 billion (according to (Jatobá 2024)); Production: low carbon emission hydrogen – electrolysis (488’000 tons/year) and blue hydrogen (198’000 tons/year); Electrolysis capacity: 2.2 GW; Expected start: 2025; Full operation: 2032
- **Qair (State: Ceará):** Investment: US$6.9 billion; Production of low carbon emission hydrogen: 488’000 tons/year; Electrolysis capacity: 2.2 GW; Offshore wind power capacity: 1.2 GW; Expected start: not disclosed
- **Casa dos Ventos and Commerce (State: Ceará):** Investment: US$4 billion; Production of low carbon emission hydrogen (365’000 tons/year) and low carbon emission ammonia (2.2 million tons/year); Electrolysis capacity: 2.4 GW; expected start: 2026; full operation: 2030
- **Fortescue (State: Ceará):** Investment: US$6 billion; Production of low carbon emission hydrogen – electrolysis (15 million tons/year; global target); Expected start: 2025; Full operation: 2027
- **AES (State: Ceará):** Investment: US$ 2 billion; Production of low carbon emission ammonia (800’000 tons/year); Electrolysis capacity: 2 GW; Expected start: not defined
- **White Martins (State: Pernambuco):** Investment: not disclosed; Production of low carbon emission hydrogen: 156 tons/year; Start of operation: 2022. In December 2022, the company received the low carbon emission Hydrogen Certification from TÜV Rheinland (White Martins 2022).

- **Green Hydrogen Pilot Projects Eletrobras Furnas (States: Goiás/Minas Gerais):** Investment: R$45 million; low carbon emission hydrogen production so far: approximately 5 tons; Power generation capacity: 1 MW; Start of operation: 2021. In November 2023, the Electricity Trading Chamber (CCEE) issued the first low carbon emission hydrogen certificates in Brazil (Gonçalves 2023).
- **EDP (State: Ceará):** Investment: R$42 million; low carbon emission hydrogen production: 250 m^3_{NTP}/h; Electrolysis capacity: 3MW; Start of operation: 2022; Full operation: 2024
- **Shell/Raízen/Hytron/Toyota (São Paulo):** Investment: R$50 million; Production of low carbon emission hydrogen: 390 tons/year; Expected start: 2024. This will be the first hydrogen produced from ethanol (Globo Rural 2024).

Chile

Haru Oni: The 'Haru Oni' pilot plant in Punta Arenas (Chile) was officially opened in December 2022. Haru Oni produces hydrogen via electrolysis using renewable energy from wind. The facility will also capture CO_2 from the atmosphere and use a process of synthesis to combine the CO_2 and hydrogen to produce e-fuels, including methanol, gasoline and liquefied gas.

Products: e-methanol, e-gasoline and e-liquified gas

China

Liquid Sunshine Project: The liquid sunshine project in Lanzhou is the world's first commercial-scale demonstration project of synthetic e-methanol production using solar-based renewable hydrogen. The CO_2 stems from nearby factories. The production of 1 t methanol uses 10'000 kWh electricity, which is generated from photovoltaics. In the project they use zinc (Zn) based catalysts instead of copper (Cu). According to available publications, the major research focus lies on improving catalysts and chemical processes.

Product: e-methanol

Methanol plant in Anyang: The Green Methanol Co-generated LNG Plant in Anyang produces green methanol and co-generated LNG by implementing the ETL (emissions to liquids) process invented by the Carbon Recycle International (CRI) corporation. Coke oven gas (COG) is the source for H_2 and CO (syngas). The world's first commercial scale CO_2-to-methanol plant has started production in Anyang, Henan Province, China. The cutting-edge facility is the first of its type in the world to produce methanol — a valuable fuel and chemical feedstock — at this scale from captured waste carbon dioxide and hydrogen gases. The plant's production process is based on the Emissions-to-Liquids (ETL) technology developed by Carbon Recycling International (CRI) and first demonstrated in Iceland. The new facility can capture 160'000 tonnes of carbon dioxide emissions a year, which is equivalent to taking more than 60'000 cars off the road. The captured carbon dioxide is then reacted with the recovered hydrogen in CRI's proprietary ETL reactor system with the capacity to produce 110'000 tonnes of methanol per year.

Product: e-methanol

Carbon Hydrogenated Gasoline: The Carbon Hydrogenated Gasoline Project in Zoucheng is the world's first plant of hydrogenation of CO_2 to gasoline products. COG is the source for H_2, the CO_2 is purchased externally. The life-cycle emissions of the produced e-gasoline is 0.58 t CO_2/t e-gasoline (with 18.4 t CO_2/t e-gasoline in the well-to-gate stage, minus 17.8 t CO_2/t e-gasoline purchased externally) and could reach zero emissions with cleaner grid and hydrogen. In the project a novel catalyst, Na-Fe3O4/HZSM-5, is developed to improve efficiency and reliability. The catalyst achieves 95% conversion of CO_2 and H_2, and the selectivity of gasoline is higher than 85 %, under quasi-industrial production conditions. The product can basically meet the China 6 standard on gasoline fuel quality. The catalyst has good stability and can be operated continuously for more than 1’000 hours.

Product: e-gasoline

E-Kerosene research: The production of aviation fuels is explored in a project from Tsinghua university. The current production capacity is 1’000 tons of kerosene-range aviation fuel per year and a scale up to over 10’000 tons per year is planned. In this project the educts H_2 and CO_2 stem from photovoltaic electrolysis and industrial CO_2 exhaust respectively.

Product: e-kerosene

Carbon hydrogenated methanol: There are two more projects that produce methanol: the carbon hydrogenated methanol project in Fudao, Hainan, that produces annually 5’000 t methanol since 2020; and a methanol production project between Wuhuan and Clariant, which is currently under development.

Product: e-methanol

MSW-to-H$_2$: Further research at Tsinghua University is done on municipal solid waste (MSW) to hydrogen (MSW-to-H_2) and further to e-fuels. Two demonstration plants are running: one at Guizhou with 100 t/d MWS gasification (MSW pellets as feed) and one at Suzhou with 10 t/d waste to H_2 (with sludge and biomass pellets as feed). Additionally, external carbon, H_2 and O_2 sources are needed to balance the variability of mass ratio of MSW.

Process: Waste-to-hydrogen
Products: hydrogen and e-fuels

Denmark

There are several ongoing projects in Denmark:

- HØST PtX, Esbjerg: 1 GW, 600 ktons NH_3
- H2ENERGY, Esbjerg: 1 GW H_2
- Idomlund, Holstebro: 150 MW H_2
- MEGATON, Ringkøbing: 2 GW, 1 Mton e-fuel
- Green Fuels for Denmark, Avedøre: 1.3 GW, 275 kton e-fuel
- Everfuel, Vestforsyning: 100 MW
- Green Hydrogen Hub, Viborg/Hobro: 1 GW
- HySynergy, Fredercia: 1 GW
- Reintegrate, European Energy, Aalborg: 120 MW
- Evida (pipelines): 5-24 TWh/yr

Finland

E-Fuel project VTT: «E-fuel project», which includes a power-to-liquid demonstration facility at VTT Bioruukki Pilot Centre for CO_2 capture, hydrogen and e-fuels production. The goal is to first demonstrate and afterwards to scale up the combination of high temperature electrolysis (SOEC) and Fischer-Tropsch synthesis to obtain drop-in paraffinic fuels with high efficiency.

Process: SOEC and Fischer-Tropsch

France

EMRhône e-Methanol production project on the Roches-Roussillon industrial platform. The plant would be located on the Roches Roussillon chemical platform, on a maximum land area of 5.5 ha, and would produce 150’000 tonnes of e-methanol per year.

The project would be connected to the electricity grid by a 5 km underground 225’000 Volt link provided by RTE.

Product: E-Methanol

Germany

There are many projects ongoing that are dealing with e-fuels. An overview on concrete plants is given in (PtXLab Lausitz 2023). With status July 2023 of these about 20 plants just 2 demo plants are starting the operational mode, e.g., Solarbelt FairFuel/atmosfair in Werlte, the former Audigas plant, using biogas for Fischer-Tropsch SAF with a capacity of 360 tons per year, and NextGate in Hamburg using the INERATEC technology for about 200 tons per year e-fuels for road and rail as well as 150 tons per year waxes, based on Fischer-Tropsch synthesis.

Japan

Several kind of national projects have just started (SOEC, FT, methanation).

Development of Technology for Producing Fuel Using CO_2, etc. It is a Green Innovation Fund Project, supported by the METI Ministry of Economy, Trade and Industry as well as NEDO, which is a Japanese funding agency. The project features are:

Development of technology for improving production yield and utilization technology of **synthetic fuels**: Develop integrated production process technologies to produce synthetic fuels from CO2 and hydrogen at high efficiency on a large scale and improve the liquid fuel yield rate. Achieve a liquid fuel yield rate of 80% on a pilot scale (planned 300 bbl/day) by 2030 with the goal of making the process independently commercialized by 2040.

Development of technology for producing **Sustainable Aviation Fuel (SAF)**: Develop Alcohol-to-JET(ATJ) technology to produce SAF from ethanol, which large production volumes (hundreds of thousands of kiloliters) are expected. Achieve a liquid fuel yield rate of 50% or higher and a production cost at the less than 200 yen/L (between 100-199 yen/L) with the aim of supplying the fuel to aircraft by 2030.

Development of innovative technology for the production of **synthetic methane**: Establish technology for methanation, a process that efficiently synthesizes methane using hydrogen produced from renewables and other energy sources, and CO2 captured at power plants and other facilities. Achieve an energy conversion efficiency rate of 60% or higher by 2030.

Development of technology for synthesizing **green liquefied petroleum (LP) gas** without fossil fuels: Establish technology for synthesizing LP gas (known as green LPG), which is not made from fossil fuels, but synthesized from hydrogen and carbon monoxide using methanol and dimethyl ether. Aim to establish synthesis technology with a production rate of 50% and commercialize it by 2030.

Project website: https://green-innovation.nedo.go.jp/en/project/development-fuel-manufacturing-technology-co2/

Products: SAF (ATJ), e-methane, liequefied petroleum gas

Methanation demonstration: INPEX and Osaka Gas will conduct the world's largest-scale methanation demonstration experiment from the latter half of FY2024 to FY2025. The synthetic methane production capacity of the methanation facility to be developed in the project will be approximately 400 m^3_{NTP}/h. In parallel, 10'000 m^3_{NTP}/h and 60'000 m^3_{NTP}/h will be considered.

Norway

Alpha plant by Norsk e-fuel with 25 to 50 million litres of e-crude oil annual production volume in 2025 to the Beta plant with 100 million litres annual production volume in 2028 to larger production plants from 2029.

Product: e-kerosene

Switzerland

In Switzerland, one larger power-to-methane plant is running. It belongs to Limeco and consists of a 2.5 MW PEM electrolyser and a biological methanation reactor. Further information: www.powertogas.ch

Product: e-methane

United States

Current e-fuel projects are mostly at the research stage. There are R&D projects funded by the U.S. Department of Energy. In particular, DOE's CO_2 Reduction and Upgrading for e-Fuels Consortium includes key national laboratories (Argonne National Laboratory, National Renewable Energy Laboratory [NREL], Lawrence Berkeley National Laboratory [LBNL], Lawrence Livermore National Laboratory [LLNL], and Oak Ridge National Laboratory [ORNL]) in the e-fuel production research field. The consortium develops advanced e-fuel production technologies and conduct TEA, LCA, and other analyses to help reduce GHG emissions, save water, and unlock social and economic opportunities of these conversion technologies. The consortium's research areas include thermochemical, biochemical, and electrocatalytic conversion routes into key intermediates and eventually to final products. The analysis teams evaluate cost, emission, siting, market, energy justice, and societal impacts of the e-fuel production pathways. Figure 4 shows the current consortium coverage, which is planned to be further refined and expanded during the next cycle.

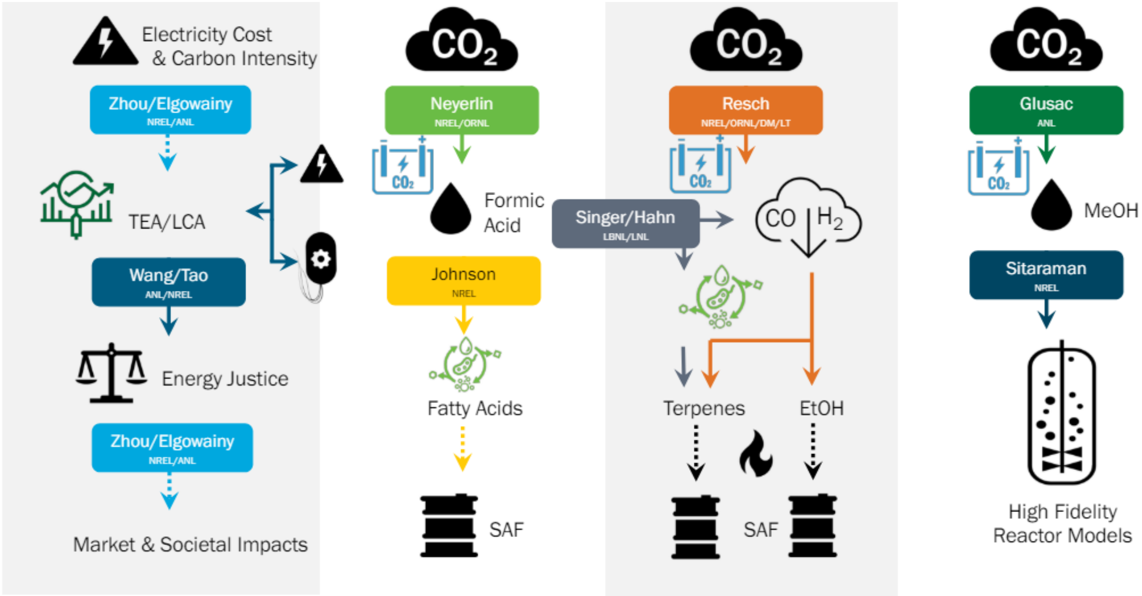

Figure 4. The research areas of DOE's CO_2 Reduction and Upgrading for e-Fuels Consortium. Source: (Resch 2023)

There are separate but relevant efforts on clean hydrogen production. DOE will fund about 8 regional clean hydrogen hubs to support clean hydrogen production demonstration projects. This includes all the hydrogen supply chains including the use of clean hydrogen.

The DOE will also support Direct Air Capture (DAC) hubs to demonstrate DAC technologies, with DAC CO_2 potentially used for e-fuel production.

Resources: CO_2 and H_2

Low carbon and net carbon-neutral fuels are either e-fuels or bio-fuels. The basis for e-fuel production is the availability of (renewable) power for low emission hydrogen production as well as CO_2 or N_2 for further processing.

The CO_2 can stem from industrial flue gas (e.g., steel, cement, ethanol), biogenic sources, or direct air capture (DAC). In chapter 3.8.3 of (Schröder 2023) different technologies for the supply of CO_2 are presented. Figure 5 shows the status quo of the resource potential of CO_2 point sources worldwide (Schröder 2023).

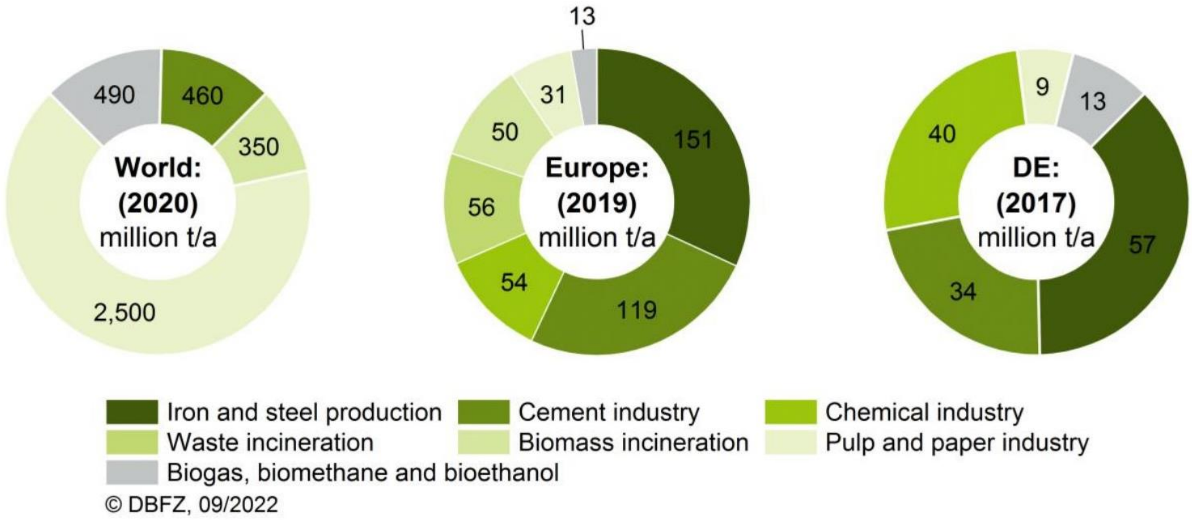

Figure 5: Status quo of the technical resource potential of CO_2 point sources worldwide, in Europe and in Germany. Note: cement industry incl. other mineral industries, chemical industry incl. other industrial point sources; with no claim to completeness and for Germany without data on waste and biomass incineration; illustration by (Schröder 2023), based on [(Kircher and Schwarz 2020); (Olsson et al. 2020); (Zitscher et al. 2020)].

Today, hydrogen is mainly produced from fossil-based fuel, i.e. coal, natural gas or oil. Additionally, it can be produced from biomass or by using electricity for water electrolysis (e-hydrogen). For electrolysis fresh water is required, therefore it must be remembered that there could be competition with drinking water and food production competences (Schröder 2023). In general, a substantial increase in the amount of e-hydrogen is expected, as well as a significant cost reduction. However, despite advances in technology development, renewably produced hydrogen from electrolysis will only be able to compete with the production costs of current fossil-based hydrogen production if CO_2 prices are set accordingly.

For the transport of hydrogen, the reuse of gas pipelines is economically most attractive, see Figure 6. According to (IEA International Energy Agency 2022), repurposing pipelines for hydrogen use can cut investment costs 50-80% relative to new pipelines. If new pipelines must be built, pipelines for short distances are economically more interesting, while transport with tankers only makes sense for a very long transport distance. However, in general, the costs for transport are not crucial compared to the total costs of hydrogen production.

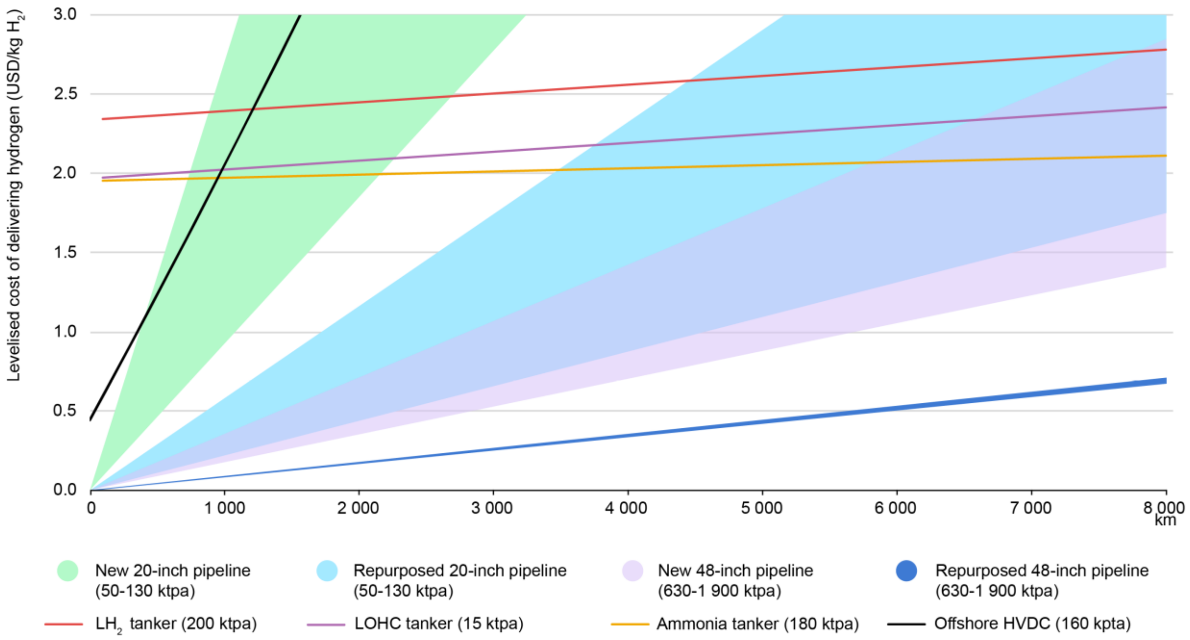

Figure 6: Levelised costs of delivering hydrogen by pipeline and by ship as LH_2, LOHC and ammonia carriers, and electricity transmission, 2030. Notes: ktpa = kilotons per year; LH_2 = liquefied hydrogen; LOHC = liquid organic hydrogen carrier. Includes conversion, export terminal, shipping, import terminal and reconversion costs for each carrier system (LH_2, LOHC and ammonia). The import and export terminals include storage costs at the port. Pipelines refer to onshore transmission pipelines operating at ranges between 25% and 75% of their design capacity during 5'000 full load hours. Electricity transmission reflects the transmission of the electricity required to obtain 1 kg H_2 in an electrolyser with a 69% efficiency located at the distance represented by the x-axis. Source: (IEA International Energy Agency 2022)

There are different possibilities to store hydrogen: compressed gaseous, liquid hydrogen and underground storage. Salt caverns for hydrogen storage have the highest technology readiness level compared to other underground storage possibilities like saline aquifers or depleted gas fields. Technology Monitor Report 2022 from Task 42

The European Hydrogen Backbone (EHB) initiative consists of a group of 31 European gas infrastructure companies and proposes a hydrogen network in Europe consisting of hydrogen pipelines and storages.

Availability of Resources in Different Countries

The availability of the resources required to produce e-fuels varies from country to country.

Table 4: Available resources for e-fuel production in the different countries.

Country	Information concerning resources
Brazil	Considering the importance of flexible paths for the energy transition (avoiding technological locks), Brazil, given all its potential, has great opportunities in hydrogen economy. Brazil has a large potential for hydro, wind and solar electricity. And as the production grows in general (+ 30 % are expected until 2030) (https://www.epe.gov.br/pt/publicacoes-dados-abertos/publicacoes/plano-decenal-de-expansao-de-energia-2034), more biogenic waste is generated which can be used for energetic purposes. Especially wastes from soy, sugar

Country	Information concerning resources
	cane and corn production are available in a large amount. Currently, more than 25 % of the transport matrix in Brazil is renewable (mainly ethanol and biodiesel). Large-scale electrification is not necessarily needed, as it will be mainly applied in niches and for short distances. Otherwise, infrastructure investments would be too large.
China	Now, the sources of hydrogen and CO_2 are not necessarily in the context of low-emission energy (i.e., renewable H_2 and CCUS-CO_2). For example, COG-H_2 is seen as feedstock. However, CCUS has great prospects in China, since China's CO_2 capture demand might reach 20-408 million tons, 0.6-1.45 billion tons, and 1-1.82 billion tons in 2030, 2050, and 2060, respectively. Further information: CCUS Progress in China – A status report. https://www.globalccsinstitute.com/wp-content/uploads/2023/03/CCUS-Progress-in-China.pdf
Denmark	Largest project, BrintØ, Danish North Sea, will deliver 10 MW wind power corresponding to 6 GW electrolyzer capacity. Total 2040 Hydrogen production capacity forecast: High Case 16.3 GW, Mid Case 11.1 GW, Low Case 6.0 GW (DNV). CO_2 is available from cement factories, and from biogas upgrading.
Finland	News mapped 23 hydrogen projects in various development phases around Finland in 2023, of which 10 were planning to produce synthetic fuels. Fossil and biogenic CO_2 emissions (41.4 Mt CO2 in 2020) are available from large point sources such as power and heat production plants and other industrial facilities.
Germany	Hydrogen has been identified as one important renewable energy carrier by the Federal government. To assure availability, an import strategy for hydrogen and its derivatives is being developed. Green hydrogen is mostly being promoted under the National Hydrogen Strategy, and has to be used for the production of e-fuels as well (only green hydrogen is allowed for RFNBO production). A synthesis of estimations on CO_2 as resource and renewable electricity for e-fuels is done in (Schröder 2023).
Switzerland	Run-of-river power plants are currently regarded as the most promising plants for hydrogen production, as large electricity capacities are available at these locations. Ideally, the CO_2 for the processes stems from concentrated sources like cement plants, waste-incineration plants, biogas upgrading plants (e.g. combined with waste-water treatment plants), or alternatively from direct air capture.
United States	Several studies show the available CO_2 resources in the United States. In 2023 Billion-Ton Report: An Assessment of U.S. Renewable Carbon Resources, stationary CO_2 resources were evaluated along with the

Country	Information concerning resources
	estimated costs for CO_2 capture and purification. The Pathway To: Carbon Management Commercial Liftoff also presents U.S. CO_2 resources by types and regions along with the pipeline infrastructure needed to transport CO_2. This report also shows the ranges of the cost for capturing and transporting CO_2. Argonne also published papers discussing the potential of e-fuel production (FT-fuel and methanol) using stationary CO_2 sources (Zang et al. 2021b). Point sources in the U.S. include fermentation CO_2 from ethanol plants, CO_2 from ammonia and hydrogen plants, cement plants, and other sources such as electric power plants. They are more economical, as capture costs increase with decreasing concentrations. The price for the CO_2 is mainly defined by post-combustion technologies like capture, purification, compression and cooling. In particular, in the United States, the high purity CO_2 from industrial sources serve as low-cost feedstock for electro fuels production. With industrial CO_2, the potential e-fuels production volume can exceed the current U.S. jet fuel demand and meet over one third of diesel demand. All the high purity CO_2 sources in the U.S. can produce 39 billion gallons of jet (exceeding the current production of petroleum counterpart) and 23 billion gallons of diesel (about 38% of current distillate production). Argonne published a report (Elgowainy et al. 2020) regarding the hydrogen demand in the U.S., which is based on DOE's H2@Scale Initiative. One market/resource analysis project under the CO_2 Reduction and Upgrading for e-Fuels Consortium is currently evaluating the needed resources (CO_2, electricity, and H_2) for targeted e-fuel production in different US regions.
EU	In the EU, a proposal for the regulation of hydrogen production is being discussed. It includes low-emission hydrogen but not hydrogen from COG. The CO_2 source is not strictly regulated in Europe. Hydrogen must be renewable, CO_2 not (see chapter on regulations).

Furthermore, the Fraunhofer IEE has created an IEE PtX Atlas[7], which is a free WebGIS application and presents country-specific location analyses on the production characteristics and long-term production costs of electricity-based fuels.

Commonalities and Differences

Commonalities in the availability of resources for e-fuels across various regions include:

- **Renewable Energy Sources**: Many regions, including Brazil[8], China, Denmark, Finland, Germany, Switzerland, the United States, and the EU, recognize the importance of renewable energy sources such as solar, wind, and hydroelectric power for e-fuel production. Specifically for Brazil, with its long and robust history with hydropower, and

[7] See https://devkopsys.de/ptx-atlas/, accessed on 25.03.2024
[8] Brazil has a biofuels competitive advantage for e-fuels development.

the strongly growing solar and wind sources, the opportunities for e-fuel production have been unfolding.

- **CO_2 Capture and Utilization**: Several regions identify sources of CO_2 emissions from industrial processes like cement factories, waste incineration plants, ethanol and bioethanol or biogas upgrading plants for e-fuel production.
- **Hydrogen Production**: There is a widespread focus on hydrogen production through electrolysis, utilizing renewable energy sources to generate low carbon emission hydrogen.

Differences in the availability of resources for e-fuels across regions include:

- **Energy Mix**: The composition of renewable energy sources varies from region to region and is not always reflected in the current energy mix. For example, there are still some countries where the electricity supply is currently very CO_2-intensive.
- **CO_2 Sources**: The sources of CO_2 emissions vary from region to region and are, for example, industrial plants or biomass plants. The availability and accessibility of CO_2 for the production of e-fuels depends in particular on the local economy.
- **Policy Focus**: There are differences in policy focus and approach towards e-fuels, such as the inclusion or exclusion of certain hydrogen production methods (e.g., hydrogen from coal gasification) in regulations.

The European countries are very strict on a low-emission methanol and e-fuel production whereas other countries are more open to also include fossil methanol production. Therefore, the question is raised from the European side if it might be strategically better to be more tolerant regarding fossil produced e-fuels. Generally, this idea seemed to be approved by non-Europeans with the arguments that including fossil methanol production helps the development of the whole infrastructure and that it helps the cost competitiveness of the fuel.

Application Side

As e-fuel production facilities have not yet been scaled-up, only few experiences in the application of e-fuels could be gathered so far. The different e-fuels have each their advantages and disadvantages in application, depending also if they can be used as drop-in fuels or need a separate distribution infrastructure and end-use equipment. E-Fuels like kerosene, diesel and gasoline are compatible with existing infrastructure and can mostly be blended with their bio- or petroleum-based counterparts. For use in the transport sector, however, methanol and ammonia require new infrastructures and application technologies.

Shipping

In shipping, the energy density of the energy carrier is an important factor. If the storage space for the energy carrier increases, there is less space for cargo. If less cargo can be transported per ship, more ships are needed for the same amount of cargo, which leads to increased CO_2 emissions per transported ton. Therefore, the volumetric density (including the fuel storage installation) of the used fuel is very important. Methane, methanol and ammonia have a lower volumetric density than diesel and require more storage space. However, compared to other fuels, they are still a very good alternative.

Another requirement of the future marine fuels and their application are minimal costs. This also requires the retrofitting of engines to be as low-cost as possible.

There are two types of engines being used in the shipping industry:

- X-dual-fuel engines (otto principle)
- X-engines (diesel principle)

As ships are in operation for an average of 25 years, retrofitting current technologies is an important issue to significantly reduce greenhouse gas emissions.

Regulations for onboard use of methanol exist today and thus gives the broad implementation of methanol an advantage over the implementation of ammonia or hydrogen. The regulations for onboard use of ammonia and hydrogen are due to the higher complexity not expected to be fully developed before 2028 and 2032 respectively.

Hydrogen

The use of hydrogen for shipping purposes is expected to be limited to shorter distances, e.g., for ferries, because of the hydrogen's low energy density (which would increase the storage needs onboard a ship). Some projects with (liquid) hydrogen powered ships have been started. For example, in 2023, the MF Hydra, owned by one of Norway's leading ferry and express boat operators, Norled AS, was launched as the first commercial passenger and car ferry fueled by liquid hydrogen.[9] It is powered by 200 kW fuel cell modules, which was, according to their website, the first to achieve type approval from both DNV and Lloyd's Register for marine operations.

Also, in 2023, the application of hydrogen fuel cell technology in inland waterway vessels was accomplished in China, with the maiden voyage of the country's first hydrogen-powered

[9] Further information: https://blog.ballard.com/marine/worlds-first-liquid-powered-hydrogen-ship-mf-hydra-is-powered-by-ballards-fuel-cells, accessed on: 26.03.2024

ship, the Three Gorgers Hydrogen Boat No. 1. According to their website[10], the vessel has a steel-aluminium composite structure with a total length of 49.9 meters, a beam of 10.4 meters, and a draft of 3.2 meters. It is powered by a 500 kW hydrogen fuel cell in tandem with an 1'800 kWh lithium battery system, and has a maximum cruise range of 200 kilometres.

Another example for a hydrogen-powered vessel with a fuel cell propulsion is the *Antonie* in the Netherlands, which is a cargo vessel with approximately 443 feet in length with a cargo capacity of 3'700 tons. The sea trails were completed successfully, and the vessel will enter service soon.[11]

E-Methanol

Currently, the main driver for e-methanol production is the marine shipping sector due to a strong customer pull. In Maersk's case, the 200 largest customers asked for carbon neutral transport. This emerging purchaser of huge amounts of renewable methanol in the shipping industry opens the pathway for a large-scale e-methanol production.

In comparison to diesel, methanol shows shorter combustion and much lower soot emissions. The combustion flame of methanol is brighter compared to ammonia but shows much lower luminosity compared to classic diesel flames which burn noticeably brighter than the e-fuels, due to the high soot presence during combustion.

Maersk launched its first large methanol-enabled vessel, which entered service on an Asia - Europe trade lane in early 2024. The container vessel has a nominal capacity of 16'000 containers and is equipped with a dual-fuel engine enabling operations on methanol as well as biodiesel and conventional bunker fuel.[12]

E-Ammonia

Using ammonia as marine fuel, safety principles need to be considered, as ammonia has some challenging properties:

- Low combustibility; low energy density
- High solubility in water
- Corrosion
- Toxic vapours; toxicity to aquatic life when dissolved
- Segregation, etc.

In March 2024, the Australian mining company Fortescue has announced the world's first use of ammonia as a marine fuel in the Port of Singapore. The vessel, Fortescue Green Pioneer, was loaded with liquid ammonia for a seven-week fuel trial. Two of the vessel's four engines were converted to use ammonia and diesel for powering the ship, while the remaining two engines will use conventional fuels when necessary.[13]

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[10] Further information: https://www.offshore-energy.biz/chinas-first-hydrogen-powered-ship-embarks-on-maiden-voyage/, accessed on: 26.03.2024
[11] Further information: https://maritime-executive.com/article/first-newbuild-inland-hydrogen-cargo-vessel-prepares-to-enter-service, accessed on: 26.03.2024
[12] Further information: https://www.maersk.com/news/articles/2023/12/07/maersk-to-deploy-first-large-methanol-enabled-vessel-on-asia-europe-trade-lane, accessed on: 26.03.2024
[13] Further information: https://gcaptain.com/worlds-first-ammonia-powered-vessel-sets-sail-in-singapore/, accessed on: 26.03.2024

Liquefied Methane

Today, LNG tankers can generally be fuelled with methane. This technology is therefore already being used on a large scale and is on the market.

Aviation

Due to the expected rise in aviation, the goal to half the emissions by 2050 means that 80 % of the fuels in aviation need to be sustainable in 2050 (Hauptmeier 2023). If the reduction is to be higher, the amount increases accordingly. In the short term, biofuels will be used to cover the demand. They are cheaper in production than e-fuels. However, as it is a limited resource, it will become bottleneck. To avoid a lack of supply, sub-targets for e-fuels are set to build-up the infrastructure in due time. For example, a current draft of ReFuelEU Aviation proposes a blending mandate for hydrogen-based aviation fuels of 1.2 % (2030); up to 5 % in 2035.[14]

Currently, one path to produce jet fuels that is ASTM certified, is the production via Fischer-Tropsch-Synthesis. With this production path, 70-80% of products can be used directly for aviation, the rest are by-products that can be used in the chemical industry and shipping. In general, according to ASTM D7566, the following routes are alternatives for SAF production: HEFA, HC-HEFA, CHJ, SIF, ATJ, SPK-A and SPK-FT (synthesized paraffinic kerosine - Fischer-Tropsch).

Hydrogen

Hydrogen has a relatively low energy-density which makes the use for longer distances a challenge. Various concepts are currently being developed for bringing hydrogen-powered commercial aircrafts into the market. For example, Airbus has the ambition to bring hydrogen-powered aircraft to market by 2035.[15] They investigate the use of hydrogen combustion as well as hydrogen fuel cells. In early 2024, Airbus also started a project to investigate the feasibility of a hydrogen infrastructure in Scandinavian airports.[16]

Testing of small planes with hydrogen have already started (e.g., the Stuttgart-based H2Fly[17]), however, it is still on a demonstration level.

Trains

Hydrogen

In 2018, the Coradia iLint™ by Alstom entered into commercial service in Germany. It is a passenger train powered by a hydrogen fuel cell, being used for a local train service. It is

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[14] See press release by IATA: Statement on Refuel EU Proposals, 26.04.2023; https://www.iata.org/en/pressroom/2023-releases/2023-04-26-02/

[15] Further information: https://www.airbus.com/en/innovation/low-carbon-aviation/hydrogen/zeroe, accessed on 26.03.2024

[16] Further information: https://www.airbus.com/en/newsroom/press-releases/2024-01-airbus-avinor-sas-swedavia-and-vattenfall-pave-the-way-for-hydrogen, accessed on 26.03.2024

[17] Further information: https://www.hydrogeninsight.com/transport/world-first-german-aviators-fly-liquid-hydrogen-powered-plane-for-three-hours/2-1-1514524, accessed on 26.03.2024

specifically designed to non- or partially electrified lines up to 1’000 km.[18]

Stadler has also developed a hydrogen-powered train model for routes where diesel trains are still in use today. The first vehicle was sold in the United States in 2019, delivering the first hydrogen-powered train for American passenger rail transport.[19]

Methane

There are already trains that run on biogas[20], albeit in small numbers. If available, biogas can be replaced by e-methane.

Road Transport and other Purposes

Further growing application areas for the use of e-methanol are heavy-duty transport and cars but also heat and power generation. In China for instance, 27’600 methanol fuelled vehicles are in operation and in Shanxi Province a total of 50’000 households are heated with methanol. The use of methanol and ethanol for vehicles was promoted in China.

Ammonia is also being considered for use as a fuel, but this is not as widespread yet. Research is being carried out in this area. Toyota, for example, is also investigating the use of ammonia in an internal combustion engine.[21]

In addition, e-fuels in general could play a role in heavy off-road applications, e.g. in agriculture, forestry, construction, mining, etc.

Overview on Different Applications of E-Fuels in Transport

The following table gives an overview on the different e-fuels and their application in different transport sectors. The technologies in the application are not specific to the e-fuel production pathways, as it is not relevant in the application if the e-fuels are chemically identical to the fossil or biogenic fuels. This is why established fuels such as diesel are considered directly marketable, while methanol, for example, requires a reorganisation of the infrastructure.

[18] Further information: https://www.alstom.com/solutions/rolling-stock/alstom-coradia-ilint-worlds-1st-hydrogen-powered-passenger-train, accessed on 26.03.2024
[19] Further information: https://www.stadlerrail.com/en/flirt-h2/details/, accessed on 26.03.2024
[20] For example, the train “Amanda” in Sweden, https://www.renewableenergymagazine.com/biogas/scandinavia-boasts-world-s-first-biogaspowered-train, accessed on 26.03.2024.
[21] Further information: https://www.21stcentech.com/toyota-develops-internal-combustion-engine-runs-ammonia/, accessed on 06.10.2024.

Table 5: Different areas of application in transport for e-fuels and their marketability, according to the authors' own assessment. Off-road and industrial applications are not included in the overview.
Dark green: is already in use or can be replaced easily (e.g., replacement of fossil diesel with renewable diesel).
Light green: is in use, but only in small numbers, and a significant number of orders have been placed.
Orange: could become relevant; currently either certification is missing, or technology is still in development and not yet available on the market.
Grey: combination is not relevant.

	Ships	**Planes / Helicopters**	**Trains**	**Trucks / Busses**	**Cars / motor cycles**
Hydrogen	Is already in use in small numbers; only suitable for small distances.	Technologies in development.	First vehicles are on the market.	Trucks and refuelling stations are available in small numbers.	Cars and refuelling stations are available in small numbers.
Methane	Liquefied methane is being uses in maritime applications.		First vehicles are being used.	Trucks and refuelling stations are on the market (liquid and compressed methane).	Cars and refuelling stations are on the market (compressed methane).
Methanol	Suitable for large distances		Technologies in development, incl. methanol as a hydrogen storage medium.	There have been trials with methanol for buses and trucks for some time.	A large number of methanol vehicles are operated in China.
Ammonia	Suitable for large distances.		Technologies in development, incl. ammonia as a hydrogen storage medium.	Technologies in development, incl. ammonia as a hydrogen storage medium.	Technologies in development.
Gasoline					Cars and refuelling stations are on the market.
FT Diesel	Marine diesel oil (MDO) is a type of distillate diesel oil and widely used.		Diesel locomotives are in widespread use.	Many trucks and busses currently run on diesel.	Cars and refuelling stations are on the market.
Jet fuel (ATJ and FT)		Blending is possible, FT and ATJ jet fuels are on the market and certified, but not as e-fuels.			

Experiences in the Application of E-Fuels

As the technologies for producing e-fuels are only just starting up, there is still little experience with the use of e-fuels.

Table 6: Experience in the application of e-fuels in the different countries.

Country	Experiences
Brazil	Demonstration and pilot-scale e-fuel projects have been built and developed in Brazil, although there is no large-scale production units available until now. As an example, in the Pecém Complex, in Ceará, there is a low-emission hydrogen pilot plant. It includes a solar plant with a capacity of 3 MW and a state-of-the-art electrolyser module for producing fuel guaranteed to be of renewable origin. GIZ, from Germany, is working together with SENAI from Natal (a city from a Brazilian State) to produce SAF (sustainable aviation fuel) in a small pilot plant (20'000 ton)
China	Demonstration and polit-scale e-fuel projects have been operated in China. However, first-hand operational data are rarely available for detailed sustainability and economic accounting.
Denmark	In 2022, the Danish company Møller-Maersk made an agreement with Spain to produce up to two million tons of e-methanol per year by 2030 to supply its fleet of cargo ships. The development is planned in three phases, with an initial 200'000 tons of low-emission methanol being reached in 2025, increasing production to 1 million tons in 2027 and ultimately 2 million tons by 2030. The project will require and investment of about 10 billion euros partly financed with EU recovery funds, according to Spanish government calculations, and Spain may enter as a strategic investor. Maersk launched the world's first container vessel operating on dual-fuel methanol in September 2023, and by 2025 they want to have a total of 19 dual-fuel methanol vessels in operation. In 2021 a limited fleet of modified gasoline vehicles was approved for road use with methanol (EUDP 64020-1047).
Finland	Demonstration of e-diesel in a tractor from R&D project (www.e-fuel.fi).
Germany	Examples: Car trips with FT diesel from the Sunfire pilot plant in Dresden in joint venture with Audi. HaruOni project is a joint venture with German companies and co-financed by Germany in Patagonia, Chile. The e-methanol is to be made from hydrogen produced using wind power and the CO_2 captured from the air. The fuel application is demonstrated with Porsche cars.[22]

[22] For further information: https://www.bmwk.de/Redaktion/EN/Hydrogen/Examples/haru-oni-chile.html or https://hifglobal.com/haru-oni or https://www.man-es.com/discover/haru-oni-e-fuels

Switzerland	In Switzerland, 18 hydrogen refuelling stations for trucks are in operation and more are under construction. There are currently around 50 hydrogen trucks on the road; a total of 1'600 hydrogen trucks have been ordered (Hyundai) by 2025. The H2 Mobility Switzerland association was founded so that the infrastructure for hydrogen refuelling stations and the operation of hydrogen trucks can be ramped up at the same time. The association plays a coordinating role.
United States	Although e-fuel production in the U.S. is mostly at the R&D stage, there are some commercial scale activities. LanzaTech uses the gas fermentation process to convert waste gases mainly CO_2 or CO into ethanol, further upgraded to SAF, which has been operating at commercial scale since 2018. Twelve is building its first commercial scale plant in Washington. It will begin operations by mid-2024 with 40'000 gallons of SAF a year, which will be increased to 1 million gallons of SAF annually. Twelve also signed an agreement with the International Airlines Group (IAG for a long-term SAF offtake. Highly Innovative Fuels USA (HIF USA) got permission to build an e-fuel facility in Texas, which expects to produce 200 million gallons per year from 2027.

Regulations

In order to implement e-fuels effectively, regulations are put into force. They help to achieve an environmental benefit compared to fossil fuels and enable cross-border trade. The approach to how e-fuels are promoted and how their use is regulated in different countries varies.

European Union

According to the website of the European Commission[23], the Delegated Act on a methodology for renewable fuels on non-biological origin, defines under which conditions hydrogen, hydrogen-based fuels, or other energy carriers can be considered as renewable fuels of non-biological origin (RFNBO).

The website states further (European Commission 2024):

> *"The additionality delegated act includes 2 types of criteria to ensure that hydrogen is renewable:*
>
> - ***The additionality requirement:*** *The idea of additionality is to ensure that the increased hydrogen production goes hand in hand with new renewable electricity generation capacities. To this end, the rules require hydrogen producers to conclude power purchase agreements with new and [financially] unsupported renewable electricity generation capacity.*
> - ***The criteria on temporal and geographic correlation***
>   *These criteria ensure that hydrogen is produced when and where renewable electricity is available. The criteria aim to avoid that the demand for renewable electricity used for hydrogen production is incentivising more fossil electricity generation as this would have negative consequences for greenhouse gas emissions, fossil fuel demand, and related gas and electricity prices.*
>
> *To support the early scale-up of electrolysers, renewable hydrogen producers will have the possibility to sign long-term renewable power purchase agreements with existing installations (until 1 January 2028).*
>
> *Further, it is allowed to match the production of renewable power generation with its associated renewable hydrogen production on a monthly basis (until January 2030).*
>
> *This delegated act is subject to a review in July 2028."*

Renewable Energy Directive III: On 16 June 2023, the European Council adopted RED III, making it binding.

- In comparison to RED II, the EU is doubling its ambition for the expansion of renewable energies.
- The European target for renewable energies is thus significantly increased to 42.5 percent in 2030, with binding targets for the respective sectors. [24]
- In the industrial sector, a new binding target is set for the use of hydrogen and other electricity-based fuels (RFNBO). 42 percent of the hydrogen consumed in industry in 2030 must come from renewable energy sources of non-biological origin, and in 2035 this figure should already be 60 percent. A new indicative target is that the share of renewable energies in total energy consumption in industry should increase by 1.6

[23] See Renewable hydrogen - European Commission (europa.eu), last accessed on 25.03.2024
[24] Source: https://equota.de/red-iii/

percent each year. [25]

- A new binding sub-target for the transport transition includes a combination of electricity-based renewable fuels (RFNBOs) and advanced biofuels. This sub-target is 5.5 percent, of which 1 percent is to be covered by RFNBOs. [26]

"ReFuelEU Aviation": The EU is introducing a quota for the market ramp-up of e-fuels ("RFNBOs") in the aviation sector, from 1.2% e-fuels in 2030 to 35% e-fuels in 2050. Overall, 70% of aviation fuels must then be renewable in 2050. In aviation, e-fuels are particularly important because direct electrification is only possible to a limited extent.[27]

Regulations by Country

Table 7: Existing or planned regulations for e-fuel production and / or application in each country.

Country	Regulation
Brazil	Law – Fuels of Future. Recently, President Lula sanctioned this law which brings a set of initiatives to promote sustainable low-carbon mobility and it aims to help Brazil achieve international targets for reducing greenhouse gas (GHG) emissions. Concerning Synthetic fuels, for example, the law establishes that ANP (regulation entity) will also regulate the production and distribution of e-Fuel, as well as their quality and use.
China	In China, there are no specific regulations on e-fuels and it is not expected that they will emerge in the near future. But there are separate regulations on various products contained in e-fuels: • Existing standards are ready for methanol used as industrial materials, pure or blended fuels (M85). • China 6 standards on gasoline fuel quality. • Appendix B of Jet fuel Standard regulates the non-fossil based syntenic fuel as a portion of jet fuel blending.
Denmark	A binding political agreement of March 15th, 2022, places a goal of 4-6 GW electrolyser capacity by 2023, 167 MEUR as fixed price subsidy for e-fuel produced during a period of 10 years, possibility of direct power lines to PtX-producers, lower rates for electricity in areas with generous supply, framework for a national hydrogen pipeline grid and other initiatives.
Germany	Due to the national implementation of RED II (GHG quota; revision expected until 2025) fuel suppliers must ensure a minimum share of sustainable aviation fuel produced as Power-to-Liquid (RFNBOs): 0.5 % (2026), 1 % (2028) and 2 % (2030). Green hydrogen at refineries are allowed and multi-counted like also Power-to-Liquid. Moreover, the delegated acts for RFNBOs are relevant as well.
Japan	Regulations on carbon management: There was a communique by G7 Climate Energy and Environment Ministers in April 2023 addressing the need to

[25] Source: RED III – so will die EU den Ausbau der erneuerbaren Energien beschleunigen | eQuota
[26] Source: RED III – so will die EU den Ausbau der erneuerbaren Energien beschleunigen | eQuota
[27] Source: BMWK - Durchbruch für ambitionierten Ausbau der erneuerbaren Energien in der EU

Country	Regulation
	develop export and import mechanisms for CO2 as well as to enhance utilization of CO2. Digital platform for GHG tracking covering the entire e-methane supply chain is being developed by a group of volunteer Japanese leading companies from different industries. This platform is called «CO_2NNEX digital platform». Japan is to make it mandatory that 10% of aviation fuel for international flights using Japanese airports be sustainable. Source: https://asia.nikkei.com/Business/Transportation/Japan-to-require-overseas-flights-use-10-sustainable-fuel Japan's Energy White Paper 2022: The Annual Report on Energy in Japan (Japan's Energy White Paper) summarizes the measures on energy supply and demand that the Government of Japan conducted in 2021 fiscal year. It is submitted to the Diet pursuant to Article 11 of the Basic Act on Energy Policy (Act No. 71 of 2002). Link: https://www.meti.go.jp/english/press/2022/0607_002.html
Switzerland	The Climate Protection Regulation («Klimaschutz-Verordnung») includes funding for novel technologies and processes (Article 6). It offers financial aid until 2030 for measures for the application of novel technologies and processes in companies (application, transport and storage of CO_2). One criteria for the support is that the measures must reduce greenhouse gas emissions or achieve negative emissions. In Switzerland, there is a performance-related heavy vehicle charge, which means that trucks have to pay a fee. This fee depends on the emission level of the vehicle as well as the number of driven kilometres. To support more environmentally friendly drive systems (e.g., battery-electric and hydrogen trucks), these are exempt from the fee. A national hydrogen strategy will be published at the end of 2024.
United States	The U.S. government passed the Inflation Reduction Act (IRA), which includes significant incentives for a mix of transportation sector decarbonization technologies and strategies in August 2022. It starts in 2024 and lasts for 10 years. With the IRA, low carbon hydrogen production is incentivized with tax credits. The U.S. IRA provides maximum \$3/kg tax credit for clean H_2 production (depending on GHG emissions), providing a significant economic incentive to produce e-fuels. The cost reduction of clean H_2, aided by CO_2 credit, can reach cost parity with conventional hydrogen. The e-methanol production cost varies with H_2 cost and CO_2 cost. The breakeven cost to match high-bound market price is about \$1.5/kg for H_2, which is in the ballpark of current H_2 production cost after IRA credit. By using low-cost CO_2 and clean H_2, about 319 billion gal, or 957 million MT/year of methanol can be produced. Using CO_2 from ammonia plant, the e-methanol can reach 12 million MT/year, exceeding the current U.S. market supply. Opportunities exist to produce low-cost e-methanol in the U.S. Gulf

Country	Regulation
	Coast Region, by using nearby high purity CO_2 source and local clean H_2. In 2023, a credit will start for SAF (until 2027), for which an emission reduction for SAF of minimum 50 % needs to be shown to get the incentive. The IRA supports the production of SAF with $1.25 to $1.75 per gallon, based on CO_2 reduction potential. Source: https://crsreports.congress.gov/product/pdf/IN/IN12003 https://www.catf.us/2022/08/on-the-road-inflation-reduction-act-jumpstarts-us-transportation-sector-decarbonization/ *(from AMF-Newsletter February 2023)*

Furthermore, in Europe:

- The European Parliament has resolved to allow the sale of new internal combustion engine vehicles after 2035, on the condition that they are limited to only synthetic fuels that emit no greenhouse gases.
- RFNBOs (Renewable fuels of non-biological origin) defined in the EU Renewable Energy Directive (RED II) is eligible fuel.
- By 2025, the EU Commission is supposed to develop a common methodology for assessing the life cycle CO 2 and energy consumption of synthetic fuels.

Commonalities and Differences

The regulations in the various countries have the following common features:

1. **Government Initiatives:** All the mentioned countries have introduced government initiatives or regulations aimed at promoting the use of sustainable fuels or reducing greenhouse gas emissions in the transportation sector. These initiatives vary from setting targets for renewable energy adoption to providing subsidies and tax credits for the production and adoption of alternative fuels and low carbon emission vehicles.
2. **Regulation:** Several countries have introduced or plan to introduce regulations to guarantee the governance of the production, distribution, and use of alternative fuels like e-fuels. This ensures quality control and safety standards in the adoption of these fuels.

Some of the differences between the countries are shown below:

1. **Specific Targets and Policies:** While there is a common goal of reducing greenhouse gas emissions and promoting sustainable transportation, each country has its specific targets, policies, and approaches to achieve these goals. For example, Denmark focuses on electrolyser capacity and subsidies for e-fuels, while the U.S. emphasizes tax credits and funding for low carbon emission vehicle manufacturing and infrastructure.
2. **Regional Context:** The regulations of each country are influenced by their unique regional contexts, including available resources, infrastructure, and economic priorities.
3. **Technological Focus:** There are differences in the technologies and fuels being prioritized by each country. For example, Japan is focusing on e-methane and

developing a digital platform for GHG tracking, while the U.S. is supporting sustainable aviation fuel (SAF) production and low carbon emission vehicle manufacturing; or Germany focusses on Power-to-Liquid for aviation.

Techno-Economic Assessments (TEA)

The economic viability of e-fuels hinges on specific framework conditions. Generally, the production of e-fuels is more expensive than of biofuels. A primary cost driver in e-fuel production is hydrogen, with production costs heavily reliant on electricity prices and capital investment. Achieving economical e-fuels necessitates significant reductions in both electricity costs and electrolyser capital costs, as well as increase in efficiency and higher load hours supplied by low-carbon electricity (IRENA 2020). This requires ambitious learning curves, high operating capacities, and poses a substantial challenge.

Efforts to lower e-fuel production costs include enhancing production technology efficiencies, scaling up production plants, and reducing expenses for resources like CO_2 and nitrogen. The cost of CO_2 primarily depends on post-combustion technologies, with capture, purification, compression, and cooling defining its price. Point sources are economically favourable due to increased capture costs with decreasing concentrations. Pure, low-cost biogenic CO_2 can for example be found in ethanol biorefineries and biomethane plants.

Carbon pricing and low renewable power costs are pivotal in bolstering the economic competitiveness of e-fuels. Analysing price sensitivity reveals that a 5 to 10 €/MWh increase in electricity costs could inflate jet fuel costs by approximately 250 €/tonne. Similarly, a 400 million € increase in plant CAPEX or a 75 €/tonne rise in CO_2 capture costs would yield the same cost escalation. Consequently, electricity costs emerge as the primary driver of jet fuel production expenses, with geographical location significantly influencing them.

Techno-Economic Model

When analysing e-fuels, data from the public GREET tool was used in this report. The GREET model (https://greet.es.anl.gov) of Argonne National Laboratory, United States, includes techno-economic assessments (TEA) (using the H2A model) and life cycle assessments (LCA). Both TEA and LCA studies are based on the results of process modelling carried out with Aspen Plus and Aspen Economic Analyzer. They focus on high TRL technologies or mature technologies that are compatible with end-user infrastructure and equipment (e.g. vehicle engines).

E-Fuel Cost Projections

It is currently still difficult to make statements about the costs of producing or using e-fuels. There are only a few plants and an industrial roll-out is still pending. There is therefore little experience and hardly any upscaling yet.

Influence Parameters

Production costs are highly dependent on energy prices, which are subject to market fluctuations. Low electricity costs are therefore crucial for economical e-fuel production. The IEA published a report on "The Role of E-Fuels in Decarbonising Transport" at the beginning of 2024. In their cost analyses, they show that the capacity utilisation of the electrolyser also has an influence on the production costs of e-fuels. At a constant electricity price, the levelised costs of e-fuels increase very sharply if the plant's load factor falls below 40%. (IEA International Energy Agency 2024)

Research as part of the EU Store&Go project[28], in which three power-to-methane plants were built and investigated, has shown similar results. One key message was that the full load hours have a major influence on the economic efficiency of a plant in addition to the electricity costs. (Gorre et al. 2019) If the plant cannot be operated at full capacity, the investment costs outweigh the fuel production costs. The annual load of an e-fuel production plant is therefore an important factor.

The price for the CO_2 source depends on the capture process itself and on availability, but also on the development of CO_2 pricing in the context of emissions trading systems and B2B contracts (who charges for emissions avoidance, as all industries must become climate-neutral and CO_2 is only counted once in the overall balance).

Cost Projections

Cost projections depend on several parameters and the data and literature, on which studies are currently relied on, usually expect a substantial cost reduction for all plant components due to technological progress and large-scale production (Ueckerdt et al. 2021). The largest uncertainties are hereby associated with direct air capture (DAC), one of the possibilities to acquire CO_2 to the process, electrolysis and costs of transporting hydrogen (Ueckerdt et al. 2021).

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[28] Further information on the Store&Go project can be found here: https://www.storeandgo.info/index.html, last accessed on 06.10.2024.

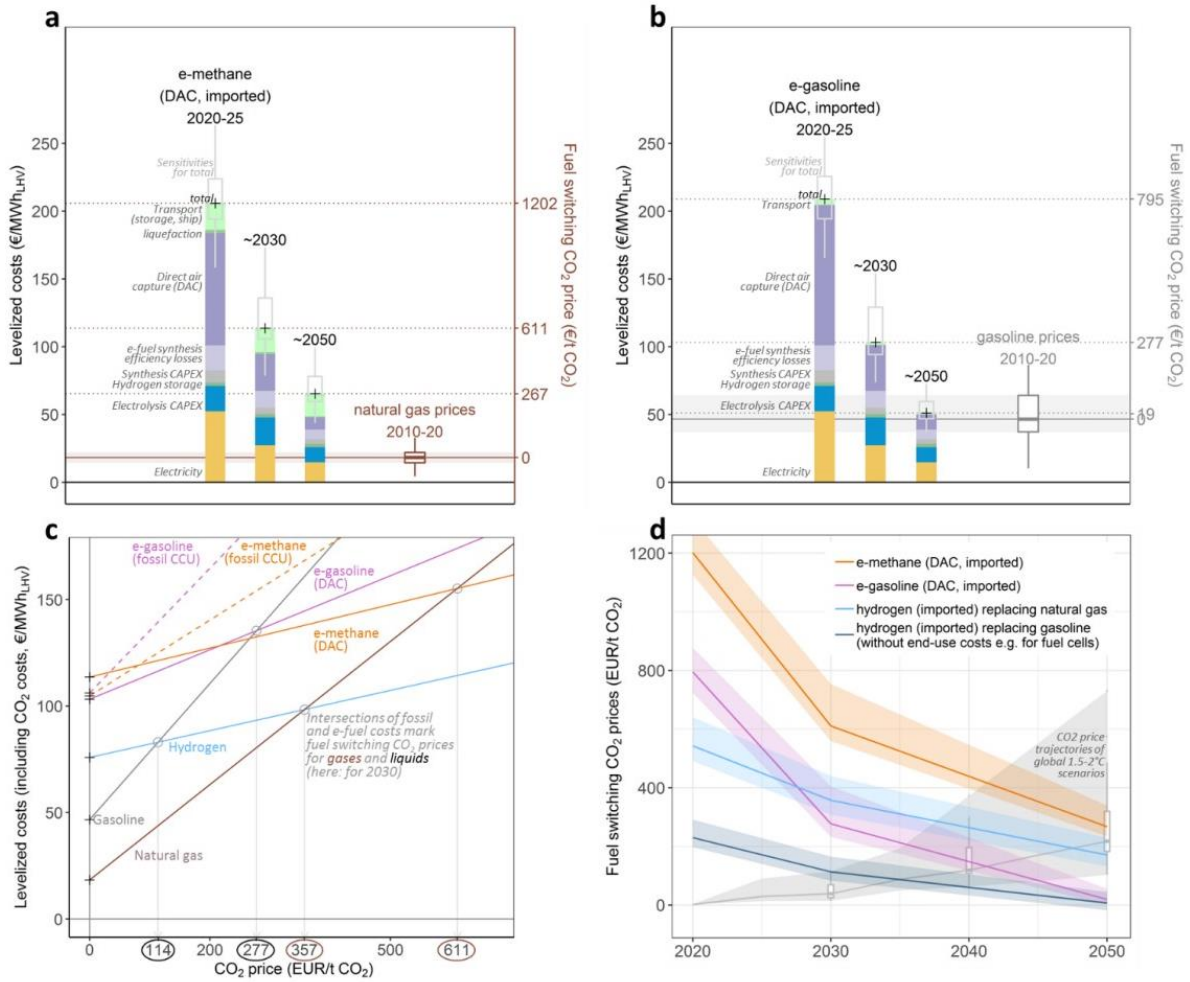

Figure 7: Study by (Ueckerdt et al. 2021) on levelized costs and fuel switching CO_2 prices of e-fuels. a, Levelized cost (and its components) and fuel switching CO_2 prices for e-methane (shipped from Northwest Africa to North-western European ports, based on DAC) for 2020-25, 2030 and 2050, in comparison to European whole-sale market natural gas prices for 2010-20. The + shows total costs. The box plots indicate uncertainties based on a sensitivity study. b, same as 'a', but for e-gasoline compared to wholesale gasoline prices. c, Levelized costs (including CO_2 costs) of e-fuels and fossil fuels for 2030 as a function of CO_2 prices. The + on y-axis are the direct costs (without CO_2) shown in panel a and b. The slopes represent the life-cycle carbon intensities of the respective fuels. The circles mark the intersections of fossil and e-fuel costs, which are the break-even points that determine fuel switching CO_2 prices (shown on the 2nd y-axis in a and b). d, Fuel switching CO_2 prices in time, for e-fuels and hydrogen, in comparison to CO2 price trajectories of global 1.5-2°C climate mitigation scenarios63. Uncertainty ribbons of the e-fuels lines represent 25th -75th percentiles. Source: (Ueckerdt et al. 2021)

The study (Galimova et al. 2023) analysed which countries could become exporters and which could become importers of e-fuels in the future. Its analysis is based on the assumption that countries with lower production costs are more likely to become exporters and countries with high production costs are more likely to become importers. To this end, they analysed the development of prices for various e-fuels, which is shown in Figure 8.

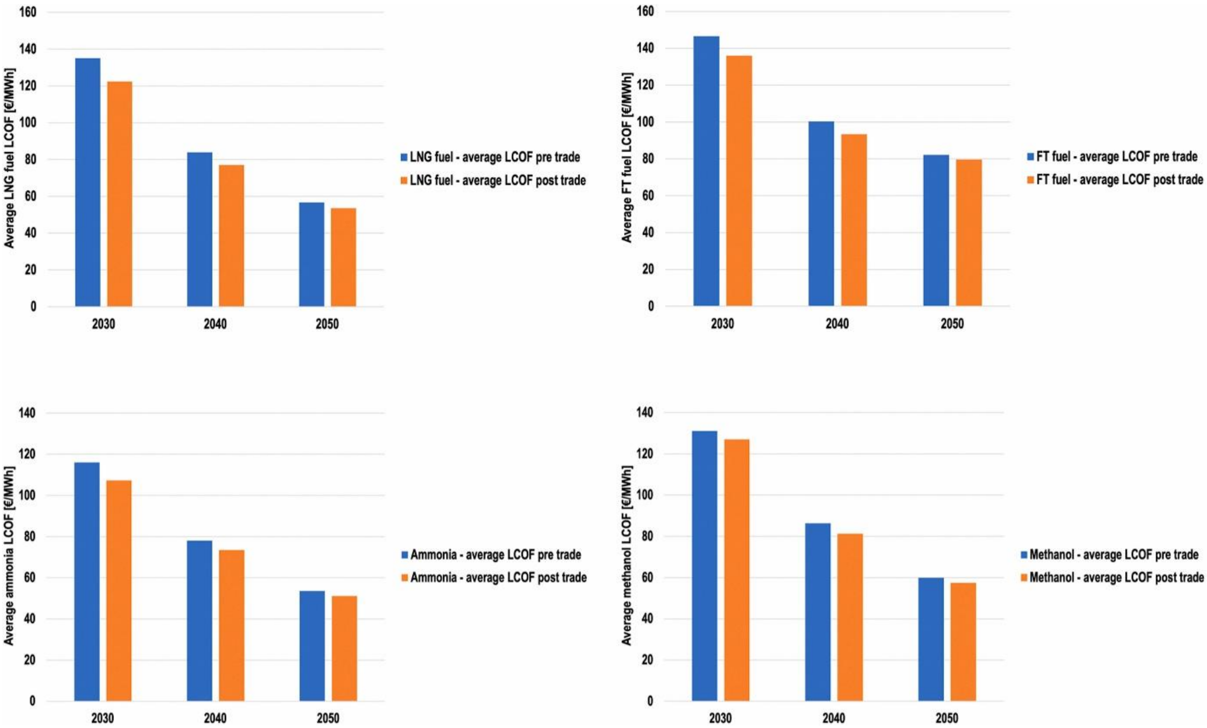

Figure 8: Global average levelised cost of e-fuels and e-chemicals before and after trading for e-LNG (top left), e-FTL fuels (top right), e-ammonia (bottom left), and e-methanol (bottom right) during the transition period from 2030 to 2050. (Galimova et al. 2023)

A reduction in production costs is expected for all e-fuels by 2050.

Cost-Related Information on Activities by Country

Table 8: Country specific information of incentives for a market uptake of e-fuel technologies.

Country	Activities / Point of views
Brazil	Considering low-carbon emission hydrogen, according to an IEA study (IEA International Energy Agency 2023), currently, the production cost of H2V per kilogram, on the international market, using renewable sources, is between US$ 3 and US$ 8. In this study, Brazil is pointed as a country where this value would be in the range of US$ 2.2 and US$ 5.2, considering the use of energy generated in wind or solar plants, which are increasingly abundant in the country. For Brazil, the high proportion of renewable energies in electricity generation and the high potential to offer pure biogenic CO_2 from ethanol and biomethane production and the cellulose industry should be emphasised. In another research job, Clean Energy Latin America (CELA)[29], a consulting company, created an index, whose value currently ranges for producing low-emission H2V becomes between 2.87 and 3.56 dollars per kilogram of hydrogen, depending on the state where it is produced. According to them, with the right policy and incentives, however, these values could fall to $1.69 to

[29] Further information: see https://cela.com.br/wp-content/uploads/2023/08/LCOH-en-1.pdf, last accessed on 19.08.2024; and: https://cela.com.br/en/lcox-en/

Country	Activities / Point of views
	\$1.86 per kilogram, which would be in a highly competitive range in the world. At the end of 2023, a new Project of Law (PL 2,308/2023) was approved on the Brazil Chamber of Deputies. This PL withdrew the subsidies package and included tax incentives for production of hydrogen[30].
China	E-fuels are expensive but often compatible with existing infrastructure or end-use technologies (as in the case of synthetic kerosene for aviation), lowering overall costs. Low-cost renewables in western regions in China is expected to drive down production costs. High cost of e-fuels is still a challenge faced by the hydrogenation of CO_2 to methanol. Appropriate carbon pricing and low renewable power cost are critical to enhance the economic competitiveness of e-fuels in China. For example, a CO_2 price of USD 200 to USD 345 (CNY 1’380 to CNY 2’380) per ton CO_2 is needed to make synthetic kerosene competitive with conventional jet kerosene. In the Liquid Sunshine project, the overall costs of coal-to-methanol and e-methanol (with power from solar electricity generation) were compared. The analysis shows that a price-parity could be achieved if the solar electricity generation cost could be reduced to 0.2 CNY/kWh (which corresponds to 0.027 EUR/kWh or 0.028 USD/kWh)[31] and if the coal price is over 1’000 CNY/t (which equals 133.1 EUR/t or 138.9 USD/t).
Denmark	A tender based subsidy of 167 MEUR for hydrogen produced with PtX-technology during next 10 years.
EU	The European Commission supports a number of hydrogen projects as IPCEIs (Important Project of Common European Interest). They approved 5.4 billion euro of public support for IPCEI Hy2Tech (2022), 5.2 billion euro for IPCEI Hy2Use (2022) and 6.9 billion euro for Hy2Infra (2024).
Germany	An indirect incentive is given as e-fuel/PTL or low-emission hydrogen is counted twice within the German GHG quota. Moreover, there might be a hard to quantify-impact connected with the so called quota prices[32].
Japan	Currently, there are many efforts to commercialize e-methane, including technological projects. Especially, the cost of procuring hydrogen as feedstock has a significant impact on production costs. The target production cost of e-methane in 2050 is as the same as fossil based natural gas by selecting suitable production sites where electricity costs can be minimized, and by

[30] For further information: https://eixos.com.br/hidrogenio/novo-texto-do-marco-do-hidrogenio-amplia-incentivos-em-r-5-bi/, last accessed on 06.10.2024
[31] with 0.1331 EUR/CNY and 0.1389 USD/CNY (28.11.22)
[32] For further information (in German): https://www.dbfz.de/fileadmin/user_upload/Referenzen/Broschueren/Fokusheft-Marktanalyse-und-Treibhausgasquote-Pilot-SBG-Oktober2023.pdf, last accessed on 06.10.2024

Country	Activities / Point of views
	scaling-up methanation plants. There are four measures identified to reduce e-methane production costs: • Suitable production sites: Reduction of hydrogen production costs due to lower electricity costs depending on the location of the plant. • High efficiency of methanation (Increased conversion efficiency through innovative technologies) • CO_2 Lower collection costs, etc. • Large-scale methanation plant: Increased volume flow of the produced methane.
Switzerland	Low-emission hydrogen and Power-to-X products still have difficulties on the market in competition with to their biomass-based or fossil counterparts. In general, H_2 and synthetic fuels need support and price signals. Substantial quantities will probably have to be imported to Switzerland, as it is a small country with a large energy demand. With massive expansion of PV systems in Switzerland, hydrogen might become important as a long-term energy storage.
United States	The USDRIVE Net Zero Carbon Fuel Tech Team conducted TEA of various e-fuel production pathways (Dees et al. 2021) (Report 2). One project of DOE's CO_2 Reduction and Upgrading for e-Fuels Consortium evaluates the economics of the conversion technologies that are being developed. The consortium published a study (Grim et al. 2023), which presents the feasibility of viable direct CO_2 conversion technologies. Argonne published several TEA papers discussing the potential of e-fuel production (FT-fuel and methanol) using stationary CO_2 sources (Zang et al. 2021b); (Zang et al. 2021a) (Delgado et al. 2023). Although The Pathway To: Carbon Management Commercial Liftoff does not include detailed TEA of e-fuel production pathways, the report discusses key economic aspects such as cost and revenues (incentives). Lastly, Global CO_2 Initiative led by University of Michigan makes efforts in harmonizing TEA/LCA through the International CCU Assessment Harmonization Group. The group discusses TEA/LCA methodologies and datasets to develop a common framework for consistent and transparent TEA/LCA when evaluating e-fuel pathways.

Commonalities and Differences

The importance of carbon pricing for improving the economic competitiveness of low-emission hydrogen and e-fuels is recognised by most countries. They support the need for appropriate carbon pricing mechanisms to incentivise the transition to low-carbon fuel production.

In order to reduce the costs of e-fuel production, the countries use various political instruments to promote e-fuel production. According to Table 8, Denmark offers subsidies for low-emission hydrogen production, Germany provides indirect incentives within the GHG quota, while the United States incentivizes production through tax credits. Brazil included tax incentives for production of hydrogen.

Life-Cycle Assessments (LCA)

To determine whether and what ecological benefits e-fuels have compared to fossil fuels, life-cycle assessments (LCA) must be carried out. When setting up a LCA, consistent system boundaries are important to be able to compare the results for different fuels, especially when comparing renewable fuels to their fossil counterparts.

Results of LCAs show that using renewable electricity and hydrogen is key to having low-carbon e-fuels. Usually, using electricity grid mix for producing e-fuels does not provide greenhouse gas (GHG) emission reduction benefits compared to the fossil baseline fuels. The analysis shows that e-FT fuels and e-methanol present significant GHG reduction benefit coupled with renewable electricity and/or H_2 compared to their fossil counterparts.

As the amount of freshwater needed as a renewable source of hydrogen from electrolysis for e-fuel production is significant, regional and seasonal variations in water availability and scarcity should be considered when siting CCU facilities to avoid water-scarce areas. Nevertheless, is worth saying that other sources of hydrogen are possible, not only from electrolysis process.

Results from Different Studies

Carbon Intensities of Hydrogen depending on Hydrogen Production Technology

When analysing e-fuels, data from the public GREET tool was used in this report. The GREET model (https://greet.es.anl.gov) of Argonne National Laboratory, United States, includes techno-economic assessments (TEA) (using the H2A model) and life cycle assessments (LCA). Both TEA and LCA studies are based on the results of process modelling carried out with Aspen Plus and Aspen Economic Analyzer. They focus on high TRL technologies or mature technologies that are compatible with end-user infrastructure and equipment (e.g. vehicle engines).

The carbon intensity of hydrogen varies greatly depending on the hydrogen production technology. Figure 9 shows the differences in the carbon intensity of hydrogen being produced by steam methane reforming, as a by-product or by water electrolysis.

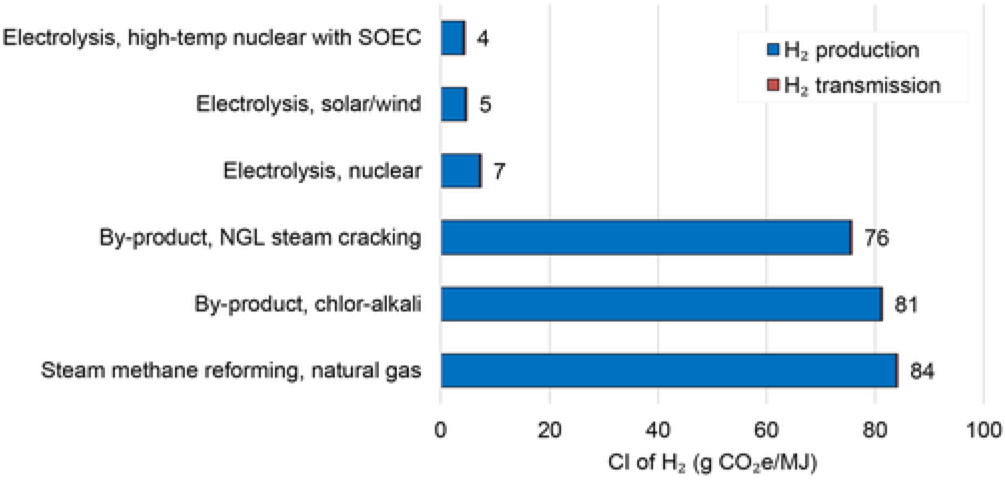

Figure 9: Carbon intensities (CI) (in g CO_{2e}/MJ H_2) of H_2 used for CO_2-to-ethanol, including H_2 production and transmission (80 km). Source: (Lee et al. 2021)

Life-Cycle GHG Emissions Intensities for Transport Applications

The study (Ueckerdt et al. 2021) shows that e-fuels can be low-emission alternatives to fossil fuels. However, their climate mitigation effectiveness critically depends upon the carbon intensity of the input electricity and the source of CO_2. In Figure 10 a range of applications in the transport sector is shown: light-duty vehicle (LDV, easy-to-abate), heavy-duty trucks (hard-to-abate) and long-distance aviation (hard-to-abate and inaccessible to electrification). GHG emissions for these transportation modes from a full cradle-to-grave life cycle assessment are shown as a function of the life-cycle carbon intensity of electricity used for battery charging, hydrogen production (electrolysis) and e-fuel production as well as for two different sources of CO_2 (DAC and fossil CCU) (Ueckerdt et al. 2021).

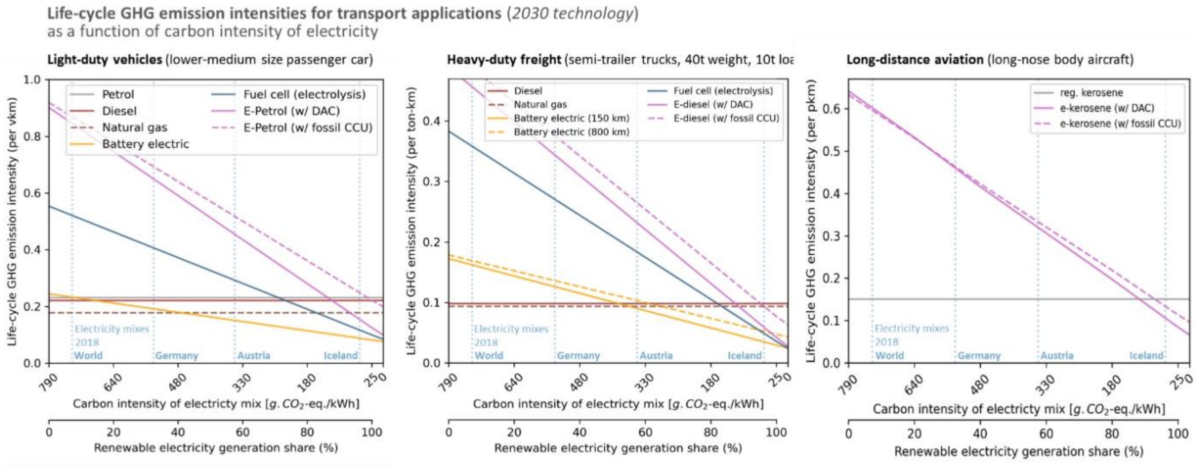

Figure 10: Life-cycle GHG emissions for different fuels and transport applications, as a function of the life-cycle carbon intensities of electricity used for battery charging, hydrogen and e-fuel production. Note different functional units on y-axis across light-duty vehicles (left), heavy-duty trucks (middle), and planes (right). Comparing e-fuel options (CO_2 from DAC or fossil CCU), hydrogen fuel cells (H_2 from electrolysis), direct electrification with batteries and fossil options, all of which is based on anticipated technological progress in 2030 using the life cycle assessment model carculator50 and carculator_truck51. Vertical lines show life-cycle carbon intensities of electricity for selected geographies for 2018. The secondary x-axis (bottom) translates the carbon intensity of electricity into an equivalent share of renewable electricity generation (equal shares of wind and solar PV electricity, where the remaining non-renewable generation is natural gas and coal electricity in equal shares). Source: (Ueckerdt et al. 2021)

As the production of e-fuels is very energy-intensive, their use in vehicles is only better for the environment than fossil fuels if the electricity mix has a very low carbon intensity. In most cases, battery-electric drive systems make more sense than e-fuels from an environmental perspective for lightweight vehicles.

Country Specific Information

LCA studies are being carried out in various countries to ensure the additional ecological benefits of e-fuels. The aim is to avoid a situation where renewable fuels are supposedly favoured but ultimately cause as much or even more environmental damage. The following table shows findings from country-specific studies on LCA studies on e-fuels. The main differences between countries are likely to be the electricity mix used for electrolysis, the source of CO_2 and possible water shortages depending on the geographic area.

Table 9: Information on environmental impacts of e-fuel production and use in different countries.

Country	Information concerning life cycle assessments
Brazil	Study from Brazil: Technical Report Comparison of Biofuel Life Cycle Analysis Tools Phase 2, Part 2: biochemical 2G ethanol production and distribution - Task-39-Phase-2.2-Ethanol-2G-Comparison-of-Biofuel-Life-Cycle-Analysis-Tools.pdf (ubc.ca) Brazil also has a specific public policy for biofuels (RenovaBio) that could be adapted to include e-fuels as low carbon emission fuel (Brazil 2017).
China	Carbon flow of E-fuel production is calculated in China based on actual production data. The emission of the feedstock (hydrogen and carbon) production and of electricity has a huge impact on the life cycle emission of E-fuel. In China, low-emission hydrogen paths are being explored, although the current hydrogen production structure is dominated by fossil-based hydrogen. China's demand for carbon dioxide capture from the industrial sector may be high enough to provide carbon source for E-fuel production. There're abundant solar and wind energy resources in western China that can be used for clean power production.
Germany	Usually study-based, cf. some examples in (Schröder 2023).
Switzerland	Hydrogen and e-fuels must be part of decarbonisation if the goal is net-zero CO_2 emissions. A prerequisite for this goal is a massive expansion of renewable electricity production. As power-to-X processes are very energy-intensive, a targeted use of H_2 and e-fuels would be advantageous (e.g., for aviation, industry and heavy-duty transport), because low-emission hydrogen will be a scarce commodity for the foreseeable future. (Kober et al. 2019)
United States	The USDRIVE Net Zero Carbon Fuel Tech Team conducted LCA of various e-fuel production pathways (Dees et al. 2021; Chen et al. 2023). One project of DOE's CO_2 Reduction and Upgrading for e-Fuels Consortium also evaluates the environmental metrics of the conversion technologies that are being developed under the consortium. Separately, Argonne has evaluated multiple e-fuel production pathways of various CO_2 feedstocks and conversion technologies using Argonne's GREET model with the support of the DOE, which are documented in journal articles (Zang et al. 2021b; Zang et al. 2021a; Yoo et al. 2022; Lee et al. 2021; Delgado et al. 2023). Global CO_2 Initiative led by University of Michigan makes efforts in harmonizing TEA/LCA through the International CCU Assessment Harmonization Group. The group discusses TEA/LCA methodologies and datasets to develop a common framework for consistent and transparent TEA/LCA when evaluating e-fuel pathways. There are several outstanding LCA issues when analyzing e-fuel pathways. First, the impact of embodied emissions becomes important in the e-fuel pathways. Argonne evaluated the impacts of embodied emissions of solar PV, wind turbines, nuclear power plants, batteries, and hydrogen electrolyzers,

Country	Information concerning life cycle assessments
	which are available in GREET 2023 (Gan et al. 2023; Wang et al. 2023). Second, handling of different CO_2 sources (biogenic, fossil, and CO_2 from direct air capture) with different fates is an important carbon accounting issue to ensure avoiding omission or double counting of carbon emissions. Third, due to the intermittency nature of renewable electricity, handling of the intermittency issue can impact the LCA results. Depending on how this is addressed, grid electricity may need to be used when renewable electricity is unavailable; or, embodied emissions of energy storage may need to be considered. The issues are related to temporal matching between electricity generation and e-fuel production. Lastly, there are regional dimensions to be considered. As major resources (CO_2, renewable or low-carbon electricity, and hydrogen [or water]) are widely distributed, LCA results may vary depending on the regional parameters. In addition, unlike greenhouse gas emissions, some LCA metrics such as air quality, water quality/stress, employment, and environmental justice may have significant regional implications.

Stakeholders

There are many players in the e-fuel market: from research to development, production, distribution, application, associations and interest groups. The following section provides an insight into the different stakeholders.

Global Organisations / Initiatives

Various organisations have formed in international bodies that focus on e-fuels. Next to IEA Advanced Motor Fuels TCP, the following should be mentioned in particular with special regard to hydrogen:

- IEA Hydrogen TCP (intergovernmental body) created in 1977 focussed on R&D and analysis, the oldest organization in the field of international hydrogen collaboration
- IPHE International Partnership for Hydrogen and Fuel Cells in the Economy, created in 2003 in Washington, intergovernmental body, more focused on policy (IPHE is very similar to CSLF initiative)
- Carbon Sequestration Leadership Forum (CSLF): Ministerial-level international initiative that is focused on the development of technologies for the separation and capture of carbon dioxide (CCS) for its transport and long-term storage
- Clean Energy Ministerial: Clean Energy Ministerial | Advancing Clean Energy Together
- Mission Innovation (MI) is a global initiative of 23 countries and the European Commission (on behalf of the European Union). Mission Innovation – Catalysing Clean Energy Solutions for All (mission-innovation.net)
- World Economic Forum/ Hydrogen mission and First Movers Coalition
- Hydrogen Council (private initative): Homepage | Hydrogen Council
- Green Hydrogen Organization (Swiss non-profit Foundation): Home | Green Hydrogen Organisation (gh2.org)
- UN/ UNDPP Hydrogen programme
- UN/UNECE Hydrogen Action
- UN/UNIDO Hydrogen center
- IRENA/ Hydrogen programme
- Methanol Institute
- International Maritime Organization (IMO)
- RE100 is a global corporate renewable energy initiative bringing together hundreds of large and ambitious businesses committed to 100% renewable electricity. https://www.there100.org/

Stakeholders in Brazil

- Government entities: MME, MCTI, ANEEL, ANP
- Government entities of funding: BNDES, FNDCT, FINEP, FAPESP, CNPq and FAPERJ
- Academy and Research institution: EPE, UNICAMP, USP, IPEN, COPPE/UFRJ, PTI, CENEH, CPPHV, UFC
- Local Flying Companies: Gol, LATAM, Azul
- Aircraft manufacturer: Embraer, Airbus, Boeing

Stakeholders in China

Several categories of stakeholders are involved in the e-fuel production chain for increasingly stringent regulatory measures under carbon neutrality. Educational institutions, chemical and energy enterprises, and automotive companies have participated in the track of e-fuel demonstration as well as H_2 equipment and CO_2 producers. Some examples are shown in the table below:

Table 10: Stakeholders in China

Production side	Application side
<u>CO_2 production</u> • Shanghai Electric Power Station Group • Henan Shuncheng Group Energy Technology • Jining Bao steel Gas Co., LTD. <u>H_2 production</u> • Suzhou Jingli Hydrogen Production Equipment <u>Chemical enterprise</u> • Iceland Carbon Recycle International Corporation • Clariant, Germany <u>Research</u> • Dalian Institute of Chemical Physics • Shanghai Institute of Advanced Science • Tsinghua University	<u>Conventional Petrochemical</u> • China National Offshore Oil Co., LTD • Jikuang Minsheng Coal Chemical Co., LTD • Yankuang Klankemet Chemical Co., LTD <u>Energy & environment related enterprises</u> • Zhuhai Futian Energy Technology Co., LTD • Suzhou Komai New Energy Co., LTD • Anyang Shunli Environmental Protection Technology Co., LTD. <u>Automotive enterprises</u> • Zhejiang Geely Holding Group

Stakeholders in Denmark

Table 11: Start-ups in Denmark

E-Fuel	Start-ups
E-Kerosene	Arcadia eFuels, https://arcadiaefuels.com/ First e-fuel Facility in Vordingborg, Denmark Arcadia eFuels selects Sasol and Topsoe as technology providers for the first commercial e-fuels plant in Denmark. The plant will be located in Vordingborg, Denmark, and will produce approximately 100 million litres per year of e-fuels.

Stakeholders in Germany

Along the value chain there are lots of stakeholders with academic and industry background as well as initiatives dedicated to single technologies for e-fuels and accompanying aspects. Despite e-fuels have been foreseen as compliance option within the German greenhouse gas quota by means of a SAF/PTL quota and consideration of low-emission hydrogen based on renewable electricity e-fuels are seen as future fuel for future combustion engines for road application and were forced esp. by some automotive and fuels industries and have been controversial discussed in context of the CO_2 fleet regulations and emission regulations in the EU.

Many stakeholders are organised e.g. in the eFuel alliance (eFuel Alliance 2023) which is an initiative especially made up of various industries which will promote the establishment of e-fuels. In addition, the Power to X Allianz (Power to X Allianz 2023) see themselves as cross-sector action alliance of companies and associations that unite various competencies around e-fuel technologies along the value chain. To support international activities from a governmental background the International PtX Hub (International PtX Hub 2023) was implemented to provide a knowledge and exchange platform on a global scale.

Moreover, many start-ups are considering e-fuels.

Table 12: Examples for Start-ups in Germany

E-Fuel	Start-ups
E-Methane	Turn2X, Turn2X - Making green energy transportable
	Electrochaea, Electrochaea GmbH - Power-to-Gas Energy Storage, biological methanation
	Microbenergy (part of Schmack by Hitachi Zosen Inova), microbEnergy - microbEnergy; Power-to-Methane Plant Limeco in Dietikon, Switzerland
E-Methanol	Circular Carbon Chemistry, C1 Green Chemicals AG (carbon.one)
	enaDyne, enaDyne | Profitable CO2 Recycling (also different alcohols)
	Ico dos, ICODOS - changing the green methanol market
	refuel green, https://www.refuel.green/
E-Kerosene	Ineratec, www.ineratec.de Impower2X, Impower2X - a pathfinder for the e-Fuel pioneer plant | INERATEC Caphenia, https://caphenia.tech/ Spark efuels, https://www.sparkefuels.com/

Stakeholders in Japan

Various efforts are underway on the supply and demand sides to commercialize e-methane, including technological development, demonstrations, and feasibility studies of international projects.

Table 13: Japanese Stakeholders within Japan

Production side	Application side

• INPEX
• Osaka Gas: INPEX and Osaka Gas will conduct the world's largest-scale methanation demonstration experiment from the latter half of FY2024 to FY2025.
• KEPCO
• Tokyo Gas: Started Methanation Demonstration Test in Yokohama City in March 2022
    ○ Tokyo Gas aims to create a model of carbon neutral local production for local consumption in the region through regional collaboration with the City of Yokohama and neighboring companies, and by applying the latest water electrolysis equipment and methanation technology.
    ○ The CO2 stems from neighboring districts.
• Hitachi Zosen: Successful Demonstration Operation of Methanation
    ○ Methanation test equipment installed at the Nagaoka Mine (8 Nm 3 /h). CO2 was derived from natural gas fields.
• Scaled-up plant was tested at City of Odawara incineration plant (125 Nm 3 /h). CO2 was derived from point source of flue gas.
	<u>Demand side (methanation)</u>
	• Taiheiyo Cement
	• Mitsubishi Material
	• Asahi group HD
	• JFE steel
	• AISIN
	• DENSO
	<u>Demand side (combustion)</u>
	• Asahi-Kasei
	• Daio Paper Corp.

Internationally active Japanese Stakeholders:

- Tokyo Gas Sumitomo Corp. PETRONAS
- Osaka Gas City Energy Local Singaporean Company
- Osaka Gas Marubeni Corp Peru LNG S.A.
- JERA
- Tokyo Gas Osaka Gas Mitsubishi corp.
- INPEX Osaka Gas
- Osaka Gas ATCO Australia
- Tokyo Gas Mitsubishi Corp.

Stakeholders in Switzerland

Table 14: E-fuel stakeholders in Switzerland

Sector	Stakeholders
Public authorities	• Swiss Federal Office of Energy • Federal Office for the Environment • Federal Office of Civil Aviation
Research	• Bern University of Applied Sciences BFH: Laboratory for vehicle emissions and drive systems; Laboratory for hydrogen systems • Swiss Federal Laboratories for Materials Testing and Research EMPA: co-lead of reFuel.ch (together with ZHAW; SWEET consortium): Renewable Fuels and Chemicals for Switzerland; «Move-MEGA» research platform: post-fossil mobility including fuel supply, storage and refuelling; Initiative «SynFuels»: focus on renewable kerosene • Federal Institute of Technology Lausanne EPFL: Group of Energy Materials; Industrial Process and Energy Systems Engineering • Swiss Federal Institute of Technology ETH Zurich: Sun-to-liquid • OST Eastern Switzerland University of Applied Sciences: Research platform for renewable energy carriers power-to-X • Paul Scherrer Institute PSI: ESI-Platform („Energy System Integration“) • University of Lucerne: Competence center for Energy Law Lucerne, CELL • University of Geneva: Chair for Energy Efficiency • ZHAW Zurich University of Applied Sciences: Electrical energy systems and smart grids
Networks, associations and initiatives	• Airbornfuels • Association of H2 producers Switzerland • Niederurnen CO_2 Competence Centre • Swiss H_2 Mobility Association • SVGW Association for Water, Gas and Heat; work group on hydrogen • Swisspower • Swiss Liquid Future • Swiss Power-to-X Innovation Network (SPIN) • VSE, Association of Swiss Electricity Companies • VSG, Association of the Swiss Gas Industry
Companies	• Alphasynt: Power-to-Methane technologies, start-up • Climeworks: direct air capture technologies, start-up • GreenGT: High performance hydrogen powertrains • H2Energy: Hydrogen production • Hydrospider: Production and distribution of low-emission hydrogen to decarbonise heavy goods transport • HZ Inova: Globally active clean-tech company in the fields of Energy from Waste (EfW) and Renewable Gas. • Limeco: first commercial power-to-methane plant in Switzerland • Methanology AG: Power-to-liquid systems for the home • Osterwalder: Mineral oil, petrol stations, low-emission hydrogen refuelling stations • Synhelion: sun-to-liquid, start-up, production of e-kerosene • WinGD: Future Fuels Lab

Stakeholders in the United States

Table 15: E-fuel stakeholders in the United States.

Sectors	Stakeholders
Federal agencies	DOE, Federal Aviation Administration (FAA), U.S. Department of Agriculture (USDA), Environmental Protection Agency (EPA)
States	California, Washington, Oregon, Illinois, Nebraska, New Mexico
Research organizations	DOE national labs (Argonne, NREL, LBNL, LLNL, ORNL, National Energy Technology Laboratory [NETL]), Universities (University of Michigan, Washington State University, Princeton University, Columbia University, Harvard University, Massachusetts Institute of Technology [MIT], Medical University of South Carolina [MUSC], North Carolina State University [NC State], Pennsylvania State University, The Ohio State University, University of California at Los Angeles [UCLA], University of Massachusetts at Amherst)
Trade associations	Renewable Fuels Association (RFA), Growth Energy, Clean Fuels Alliance America, Commercial Aviation Alternative Fuels Initiative (CAAFI), U.S. Grains Council (USGC)
Companies	LanzaTech, Marquis, Twelve, Highly Innovative Fuels USA, Carbon Engineering, 1PointFive, Boeing

Conclusions and Outlook

To reach a net zero target in the energy and mobility system, e-fuels will play an important role together with biofuels. Both types of renewable fuels have their advantages and challenges, and both are needed for a successful energy transition. E-fuels are an important complement to biofuels, and countries can combine the synergies and benefits of e-fuels and biofuels. The opportunities that arise with the energy transition will lead to an increase in the global technology diversity. Several new technologies are being developed and there is a global technological race, with several routes and alternatives capable of assuming a relevant role in the energy transition. In the new future, there will be several emerging industries coexisting and eventually replacing the traditional technologies. Energy systems will follow a process of carbon intensity reduction, as the climate agenda will increasingly influence international trade and international relations.

In general, biofuels production technologies have a higher technology readiness level (TRL) than e-fuels. Some e-fuels, such as FT fuels, or methanol, can be produced as well from high TRL or mature technologies. However, it needs to be pointed out, that although some single technologies might have a high TRL, the overall TRL in the combination of several technologies in an overall plant can be lower.

In the strategies of most countries, e-fuels are regarded as important for different applications in the future. To support technology development and to increase e-fuel production, strategic programmes in several countries were implemented. Depending on the country, they consist of incentives for e-fuel production, of support for research projects or of regulations that make a certain percentage of the use of e-fuel mandatory, or a combination of these three. Next to political programmes, also companies are enforcing the use of sustainable fuels, in order to reduce their carbon footprint.

The production of e-fuels is very energy-intensive if based on water electrolysis, which is why it is being discussed whether these processes should be used primarily for applications that are difficult to electrify. These so-called hard-to-abate sectors are the aviation industry, maritime applications and industrial processes. For international aviation, fuels need to be ASTM certified. According to ASTM D7566, the following routes are suitable for SAF production: HEFA, HC-HEFA, CHJ, SIF, ATJ, SPK-A and SPK-FT (synthesized paraffinic kerosene; Fischer-Tropsch). In the shipping industry, e-methanol, e-ammonia, e-methane and hydrogen are considered interesting for the use. Regulations for onboard use of methanol and liquefied methane exist today and thus gives their implementation an advantage over the implementation of ammonia or hydrogen.

When producing e-fuels, the water electrolysis is a key technology. It is necessary for all e-fuel production pathways and has the largest impact on e-fuel production cost as well as the carbon intensity of the product. LCA results show that using renewable electricity and hydrogen is key to having low-carbon e-fuels. Usually, using electricity grid mix for producing e-fuels does not provide greenhouse gas (GHG) emission reduction benefits compared to the fossil baseline fuels. It is therefore crucial to use low-emission electricity sources in order to obtain an ecological benefit. The analysis shows that e-FT fuels and e-methanol present significant GHG reduction benefit coupled with renewable electricity and/or H_2 compared to their fossil counterparts. Regional distribution of CO_2 sources and the available freshwater need to be considered further. As the amount of freshwater needed as a renewable source of hydrogen for e-fuel production is significant, regional and seasonal variations in water availability and scarcity should be considered when siting CCU facilities to avoid water-scarce areas.

The key cost driver of e-fuel production is hydrogen, of which the production cost mainly depends on electricity prices and capital cost. Since electricity costs depend on the geographical area, the location of a production facility has a major influence. To achieve low-cost hydrogen for economical e-fuels production, both electricity cost and electrolyser capital cost needs to decrease greatly. There are ambitious learning curves assumed and high operating capacities are needed (and a challenge). The costs of e-fuel production can additionally be lowered by increasing the efficiencies of e-fuel production technologies, by increasing the sizes of the production plants and by lowering costs for other resources like CO_2 and nitrogen. The price for the CO_2 is mainly defined by post-combustion technologies like capture, purification, compression and cooling. Point sources are more economical, as capture costs increase with decreasing concentrations. However, e-fuels are generally more expensive than biofuels. Appropriate carbon pricing and low renewable power cost are critical to enhance the economic competitiveness of e-fuels.

Despite economic challenges, projects for the production of e-fuels are announced frequently and worldwide. Political programmes and customer demand are the main drivers of this development and a major expansion of production facilities is expected. It remains to be seen which technologies will prevail and which countries will be the main producers and exporters.

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Appendix: Further reading

E-Fuel Technology Routes

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