International PtX Hub

Agora Verkehrswende

DISCUSSION PAPER

E-fuels: Separating the substance from the hype

How electricity-based synthetic fuels can contribute to the energy transition in transport

Imprint

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Foreword

Dear readers,

In recent years, synthetic fuels based on renewable electricity – so-called e-fuels – have been garnering increased attention. Experts agree that e-fuels are likely to play an important role in global efforts to achieve net-zero transport systems. However, with a growing number of countries moving to adopt e-fuel regulations, vigorous debates have ensued, not least concerning the segments of the transport sector in which e-fuels should be used.

One prominent debate concerns the CO_2 emission standards that should apply to newly registered cars. In early 2023, after months of negotiations, the EU agreed to restrict new vehicle registrations to non-combustion zero-emission vehicles starting in 2035. Nevertheless, the German government questioned the agreement at the last moment, insisting on a special exemption that would allow the registration of new combustion vehicles provided they run exclusively on climate-neutral synthetic fuels. The fact that the EU regulation only applies to the first-time registration of a vehicle was often overlooked and fears arose that the "combustion phase-out" would soon mean that already registered combustion vehicles could no longer be driven. At the same time, e-fuels have raised hopes that driving can become climate-neutral without the need for significant change in the transport sector. These and related discussions have shined a prominent spotlight on e-fuels.

But can e-fuels really serve as a solution for climate protection in road transport? More broadly, what is the true promise of e-fuels – and where are hopes overblown? Ultimately, climate protection involves not just addressing climate change but also ensuring sustainable livelihoods and mobility for people around the world. If countries wish to comply with the Paris agreement and achieve climate neutrality, then the obligation to reduce greenhouse gas emissions cannot be post-poned to future generations. In Germany, the obligation to take action over the near term was recently affirmed by a landmark Federal Constitutional Court decision. To be sure, robust implementation plans are necessary now if meaningful change is to be achieved over the next two decades.

For some years now, experts have been intensively discussing the extent to which fossil fuels can be replaced by renewable synthetic fuels. Research has focused mainly on applications for which there are currently no battery-electric alternatives, i. e. primarily air and sea transport. This focus is necessary because e-fuels will remain an expensive and rare commodity for the foreseeable future. Furthermore, in the domain of road transport, electric vehicles are already significantly more energy-efficient than combustion cars, cost competitive, and widely available. Accordingly, while e-fuels can serve as a supplement to the direct use of renewable electricity, they are not an equivalent alternative. Even when e-fuel production in "sweet spot" regions with highly favourable production conditions is presumed, energy efficiency and sustainability will need to remain a top priority.

In this discussion paper, we summarize the current state of scientific knowledge regarding the potential offered by e-fuels. Compared to the German version of this paper that appeared in autumn 2023, we have added a new chapter on e-fuel policies in selected countries, and have generally expanded the paper's international perspective. Our aim is to provide an evidence-based foundation for current policy debates. If policymakers wish to ramp up global e-fuel production, then associated decisions must be made over the near term based on an internationally concerted strategy that is informed by clear priorities. To this end, it is crucial to distinguish between viable options and mere wishful thinking – that is, to separate the substance from the hype.

We hope you find this paper both useful and informative.

Best regards,

Wiebke Zimmer
Deputy Executive Director
On behalf of the Agora Verkehrswende Team
Berlin, May 2024

Key takeaways

1 **E-fuels will be indispensable for the foreseeable future to advance climate protection in aviation and maritime transport as well as in parts of the chemicals industry.** At the same time, they are expensive and less energy efficient, and, in all likelihood, will only be available in very limited quantities over the next few decades. Accordingly, e-fuels must be produced and used in a targeted manner. More specifically, they should be prioritized for segments of the transport sector that lack battery-electric alternatives, mainly aviation and maritime transport.

2 **Policymakers across the globe should facilitate a market ramp-up of e-fuels in transport by adopting suitable political and regulatory frameworks.** Far from relying on individual measures, policymakers should strive to adopt comprehensive regulatory packages that target actors throughout the fuel supply chain. The coordinated introduction of such measures in numerous countries would help to reduce the risk of market fragmentation and carbon leakage. Accordingly, international cooperation on e-fuel investment and regulatory policy is essential.

3 **The development of comprehensive sustainability criteria for e-fuels – and not just for hydrogen – is essential for their socially and environmentally sound production and use.** The following principles should apply to international cooperation, standards, and certification systems: (1) The supply of renewable electricity to the domestic economy and population should have priority over the production of e-fuels for export; (2) e-fuel projects should rely exclusively on additional renewable energy capacity that is developed as a supplement to domestic renewable needs; (3) such supplemental capacity should be developed in a manner that supports local infrastructure expansion and economic development; and (4) renewable electricity should be used as efficiently as possible in e-fuel production countries, with priority given to direct electric applications, such as electric vehicles.

4 **A sole focus on "sweet spot" regions that offer particularly beneficial conditions for e-fuel production is insufficient; rather, an overarching strategy that addresses all major dimensions of e-fuel production is needed.** An effective strategy for ramping up e-fuel production must consider not just the need to secure ample renewables generation but also the sustainable sourcing of carbon as well as viable models for project financing. Attention must also be given to steering the production and use of e-fuels in a manner that serves climate policy goals. The establishment of robust international standards will play an important role in this regard.

5 **Once the political frameworks for e-fuels are in place, it will fall to industry and investors to rapidly expand the supply of e-fuels for essential applications.** Projected global e-SAF production in 2030 correspond to around 3% of the EU's current jet fuel demand, while projected e-methanol production in 2030 is equivalent to 5% of European marine fuel demand. Accordingly, for meaningful decarbonization in the subsectors of aviation and maritime transport, it is necessary not only to realize all currently announced projects but also significantly expand the number of large-scale projects in the development pipeline.

Contents

List of abbreviations

AEL	Alkaline Electrolysis
ASTM	American Society for Testing and Materials
BEHG	German Fuel Emissions Trading Act, German: Brennstoffemissionshandelsgesetz
BtL	Biomass-to-Liquids
CBIO	Brazilian Decarbonization Credits
CapEx	Capital Expenditures
CCF	Carbon Correction Factor
CORSIA	Carbon Offsetting and Reduction Scheme for International Aviation
CHPS	Clean Hydrogen Production Standard
CtL	Coal-to-Liquids
CNG	Compressed Natural Gas
COP	Conference of the Parties
DAC	Direct Air Capture
EV	Electric Vehicle
EPA	Environmental Protection Agency
EU ETS	European Union Emission Trading System
FinEx	Financial Expenditures
GtL	Gas-to-Liquids
GHG	Greenhouse Gas Emissions
HDVs	Heavy-Duty Vehicles
HVO	Hydrotreated Vegetable Oils
IRA	Inflation Reduction Act
ICE	Internal Combustion Engine
ICAO	International Civil Aviation Organization
ICCT	International Council on Clean Transportation
LDV	Light Duty Vehicles
LNG	Liquified Natural Gas
MtG	Methanol-to-Gasoline
MtJ	Methanol-to-Jet
MtX	Methanol-to-X
OpEx	Operational Expenditures
PEMEL	Polymer Electrolyte Membrane Electrolysis
PtG	Power-to-Gas
PtL	Power-to-Liquid
PtX	Power-to-X
RED	Renewable Energy Directive
RFNBO	Renewable Fuels of Non-Biological Origin
RTFO	Renewable Transport Fuel Obligation
RWGS	Reverse Water Gas Shift
SOEL	Solid Oxide Electrolysis
ZAR	South African Rand
SAF	Sustainable Aviation Fuels
SDG	Sustainable Development Goals
UNGP	United Nations Guiding Principles on Business and Human Rights
UCO	Used Cooking Oil
WtL	Waste-to-Liquids
ZEV	Zero-Emission Vehicle

1 | Introduction: Climate neutrality and the transport sector

One major outcome of COP28 in Dubai was the pledge made by signatory parties to transition away from fossil fuels. This pledge was made against the backdrop of an ever-more pressing need to slash greenhouse gas emissions (GHG) and keep global warming below 1.5°C. The transport sector has special significance for GHG reduction efforts, as it is particularly reliant on petroleum products and has also shown particularly strong emissions growth. Indeed, between 1990 and 2022, transport emissions increased by 1.7% annually on average, surpassing all other end-use sectors, except for industry.[1] In order to achieve the climate targets set forth by the Paris Agreement, it is therefore crucial to promptly implement measures that set the transport sector on a path to climate neutrality.

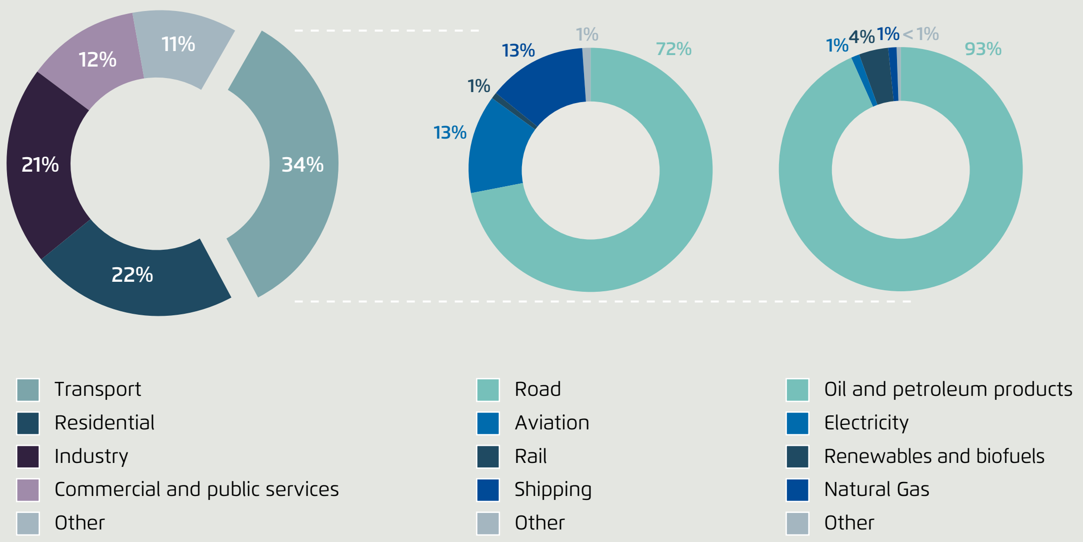
While each Paris signatory has unique starting conditions for transforming their transport sectors, an important foundation for tackling this challenge is to develop an overarching transformation strategy. Such strategies should exploit opportunities for increasing efficiency, including increased reliance on rail rather than road transport, as part of a broader "modal shift". In Germany, efficiency measures could reduce transport emissions by more than 25% by 2045.[2] An additional crucial aspect is to encourage an energy transition in transport so that remaining energy demand is covered with climate neutral energy, thus allowing transport emissions to be reduced to zero.

Policymakers around the globe have been devoting increased attention on the potential offered by e-fuels as a replacement for conventional fuels in the transport sector. However, numerous disagreements have emerged concerning the subsectors in which e-fuels should be used. At present, the EU's transport sector is 90% petroleum based, and 70% of petroleum consumption is attributable to road transport. In 2023 the EU passed more stringent CO_2 emission standards for new cars and light commercial vehicles, including a fleet-wide 100%

1 IEA (2024a).

2 Prognos, Öko-Institut, Wuppertal Institut (2021).

Final energy consumption by sector, mode of transport and energy source in the EU (2019) Figure 1



Agora Verkehrswende (2024) | Note: International aviation and maritime bunker fuels are included in the calculations. Source: Eurostat (2024).

CO_2 reduction target for new passenger and light commercial vehicles effective from 2035 onwards. However, mainly due to German pressure, an exemption for new vehicles that exclusively run on e-fuels was added at the last moment. This exemption encouraged the misplaced notion among the broader public that e-fuels can play a significant role in defossilizing road transport. Such misperceptions make it the more important to conduct an evidence-based assessment of how e-fuels can contribute to the energy transition in transport – and where hopes are misguided or overblown.

In this context, it is important to emphasize that road transport, aviation and maritime shipping have very different technical requirements with a view to propulsion technology. Reducing emissions in aviation is particularly challenging due to the high energy density required as well as space and weight constraints. Battery technology in maritime shipping poses its own challenges. Accordingly, aviation and maritime shipping are referred to as "hard-to-abate" sectors, because there are potentially insurmountable technical hurdles to direct electrification. For this reason, CO_2-neutral liquid fuels will be the only option for defossilization in aviation and maritime transport for the foreseeable future.[3]

In principle, liquid fossil fuels can be replaced by e-fuels or biofuels. Biofuels are potentially characterized by significantly lower greenhouse gas emissions than their fossil counterparts and can thus contribute to reducing the climate impact of the transport sector.[4] However, biofuels – and, in particular, conventional biofuels from cultivated biomass – have inherently high water and land requirements, and thus potentially compete with food cultivation. Accordingly, they are at best a temporary transitional solution (see infobox on Biofuels).

3 The actual climate impact of air traffic is significantly greater, for in addition to the direct CO_2 emissions caused by fuel combustion, there are other, so-called non-CO_2 effects, such as the formation of contrails and the resulting cirrus clouds. These effects are responsible for around two thirds of the total climate impact of aviation and remain – at least in part – even when using e-SAF; see Lee et al. (2021).

4 IRENA (2022).

By contrast, electricity from renewables is by far the most important climate-neutral form of energy – and not just for transport, but for all sectors of the economy. However, as electricity from renewables will remain a scarce commodity around the globe for the foreseeable future it should be used as directly as possible, e.g. through batteries and overhead lines. Every conversion step (from electricity to hydrogen to e-fuels) significantly increases total energy demand. Nevertheless, select segments of the transport sector will need to rely on hydrogen and e-fuels in the coming decades.

This paper will focus on hard-to-abate segments of the transport sector while also devoting attention to hydrogen and e-fuel production processes, including the potential offered by "sweet spot" regions, in order to present an evidence-based picture of the role e-fuels can play in decarbonizing the transport sector.

Biofuels

Various biofuels are currently used in the transport sector. Globally, these are mainly conventional biofuels[5] such as biodiesel (primarily as an additive to fossil diesel) and bioethanol (primarily as an additive to fossil gasoline). In addition, HVO (hydrotreated vegetable oil) has been increasingly used as a substitute for fossil diesel in road and rail applications in recent years. In addition, biomethane has been used as a substitute for renewable CNG (compressed natural gas) or LNG (liquefied natural gas).

Of these biofuels, biodiesel and bioethanol in particular fall to large extent under the category of conventional biofuels, as they are predominantly produced from energy crops or cultivated biomass (e.g. rapeseed oil, palm oil, grains, sugarcane and sugar beet). This means that in most places they are potentially in direct competition with food and feed crops. HVO and biomethane, on the other hand, are mainly produced from residual and waste materials (e.g. used cooking oil (UCO), animal waste fats or liquid manure).

5 The term "conventional" refers to the biomass used here – namely, energy crops or plants that can also be used as food and animal feed.

Due to possible land competition in the cultivation of biomass for growing food and animal feed, the use case for conventional biofuels as a viable option for greenhouse gas emissions in the transport sector must be carefully evaluated based on local circumstances.[6]

So-called advanced biofuels, produced from residual and waste materials such as manure, straw, bagasse, waste and residual wood, and similar feedstocks, are a biogenic alternative.[7] Since these feedstocks are inevitably produced, at least to some degree, as by-products, their use is not associated with any additional climate impact, and the fuels entail correspondingly low greenhouse gas emissions. However, the provision of these raw materials, which usually occurs in a decentralized manner, is very costly, and their conversion into fuels is often technically complex and energy intensive.

In addition, the volume potential offered by biomass from waste and residues that do not lead to land-use competition is far too small to supply fuel for transport in sufficient quantities, other than for local demand.[8]

6 ifeu (2022); DBFZ (2023).
7 The raw materials permitted for the production of advanced biofuels are defined in Annex IX, Part A of the EU Renewable Energy Directive (EU RED).
8 ICCT (2018); ifeu (2020); NRW.Energy4Climate (2023).

2 | What are e-fuels and how are they produced?

"E-fuel" is a collective term for fuels typically produced from green hydrogen and CO_2 or, in the case of e-ammonia, from green hydrogen and nitrogen. Here, the "e" stands for the electricity used to produce the hydrogen. At the European level, they are also referred to – together with green hydrogen – as RFNBOs, i. e. "renewable liquid and gaseous transport fuels of non-biological origin". The process technologies used to produce e-fuels are generally referred to as power-to-X (PtX) processes. The "X" stands for the respective target product: If gaseous fuels such as synthetic methane are to be produced, one speaks of power-to-gas (PtG) processes; if the target product is liquid fuels such as gasoline, diesel or jet fuel, then one speaks of power-to-liquid (PtL) processes. In some cases, e-fuels are thus also referred to as PtX, PtG or PtL fuels.

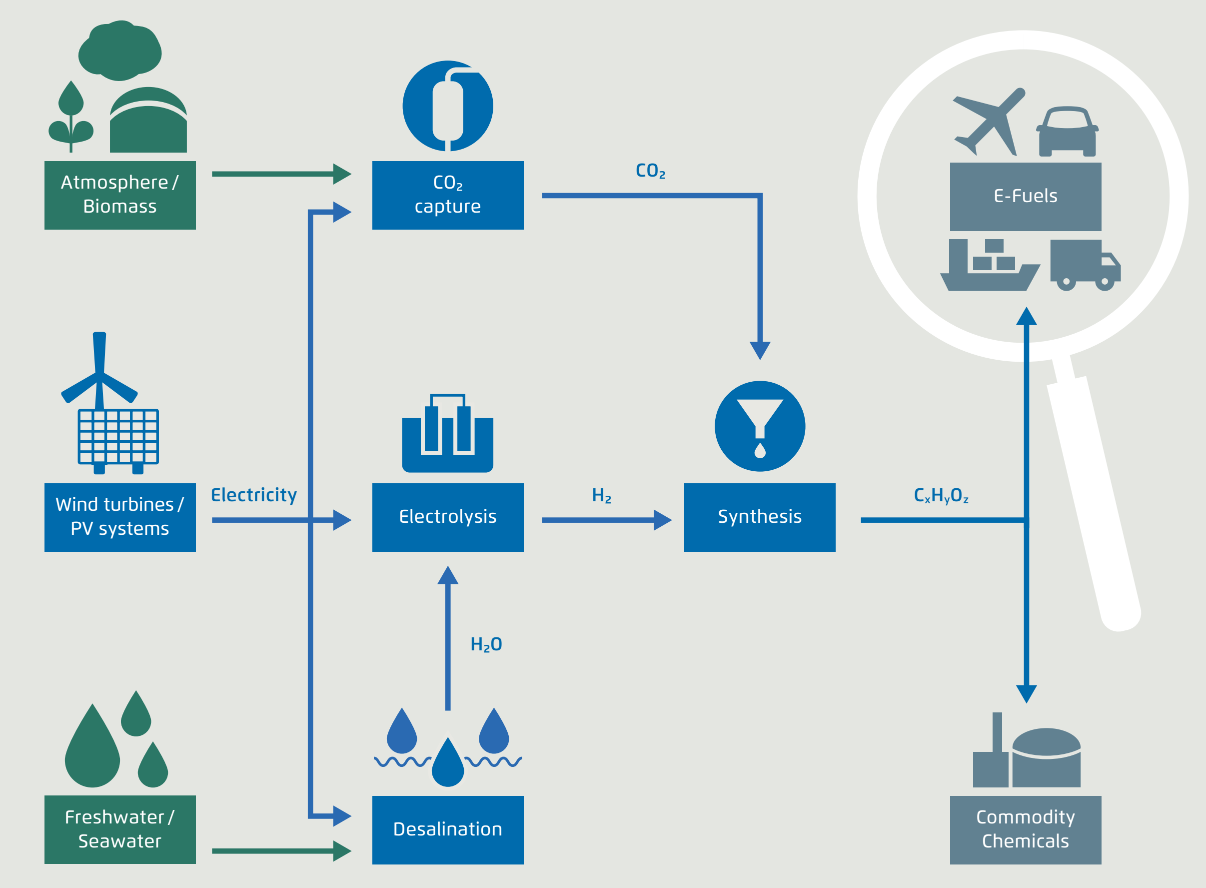
Since chemical synthesis processes are used to produce e-fuels, they are often also referred to as synthetic fuels. However, e-fuels are often misleadingly confused with synthetic fuels. Although they are produced using the same synthesis processes, the required synthesis gas may be generated from other sources (e. g., coal or biomass gasification or natural gas or biogas reforming). E-fuels are therefore always synthetic fuels, but synthetic fuels are not always e-fuels.

If the hydrogen required for this synthesis is produced by electrolysis using renewable electricity (so-called green hydrogen) and the CO_2 that is required is taken from the atmosphere,[9] these fuels are virtually CO_2-neutral. This

9 This is provided either technically with the help of so-called

E-fuel production steps and areas of application

Figure 2



Agora Verkehrswende (2024)

is not the case when the CO_2 is captured from industrial processes based on a fossil feedstock or energy carrier, such as cement production. Known as capture from an "industrial point source", this can be seen as cascade use of the fossil CO_2 from the original processes. The e-fuels produced in this manner could replace fossil transport fuels, but would emit additional CO_2 into the atmosphere. Thus, in the long term, they do not represent sustainable sources of CO_2 in a climate-neutral world.

Due to residual emissions that are difficult to avoid (e.g. from the construction of the required wind turbines and PV systems), e-fuels are not – as is often assumed – climate neutral, but they have a significantly lower impact on the climate. Since most e-fuels are still carbon-based (due to the CO_2 used for their production), they cannot contribute to transport-sector decarbonization (that is, the avoidance of CO_2 emissions), but rather only to transport-sector defossilization (that is, the avoidance of fossil feedstock/fuels). An exception to this is ammonia, which is discussed as a fuel for maritime shipping and is not based on carbon but on nitrogen.

In addition, "e-fuel" predominantly refers to fuels that are almost identical to conventional fossil fuels from a chemical point of view. This has the great advantage (at least in principle) of compatibility with existing infrastructure and systems, such as pipelines, filling stations and vehicles. Depending on the manufacturing process, different fuels can be produced for all conventional combustion engines, including aircraft turbines. The notation "e-" is often used as a designator in this case, e.g. e-gasoline, e-diesel and e-SAF (sustainable aviation fuel).

The green hydrogen needed for e-fuel production can also be used directly to power vehicles. However, this requires alternative drive/propulsion systems, such as fuel cells or hydrogen combustion engines, which in turn necessitate complex hydrogen storage systems. For this reason, green hydrogen is usually not referred to as e-fuel, but is instead considered to belong to the broader category of PtX fuels. Accordingly, the following discussion is concerned exclusively with liquid e-fuels.

direct air capture (DAC) systems or the CO_2 is first bound in biomass via photosynthesis, which is then converted to make the CO_2 usable again.

2.1 Feedstock supply

Various technical options are available to obtain the feedstocks required for e-fuel production (water, hydrogen, and nitrogen / CO_2).

Water: seawater desalination and treatment

The production of large quantities of green hydrogen requires correspondingly large quantities of water. Some 10 kilogrammes of water is required per kilogram of hydrogen produced using a stoichiometric reaction. Most electrolyzers require ultrapure water, such that even drinking water must be further purified to filter out salts and minerals. This purification usually takes place in a water treatment plant directly upstream from the electrolyzer. Research is also being conducted to directly use brackish water or seawater as feedstock. However, such technologies are still confined to the laboratory.[10]

In order to supply high volumes of water without adverse effects on the groundwater – especially in "sweet spots" for renewable power generation, which are often arid – seawater desalination plants are typically needed. Such plants are already used worldwide to supply drinking water to households and industry, and can thus be considered an established technology. The most widespread technology is "multi-stage flash evaporation", in which the seawater is evaporated by adding heat (often waste heat from nearby power plants) through several condensation stages to extract the salt. Due to the high energy requirements of this process, reverse osmosis plants are also increasingly being used as an alternative. In this process, seawater is forced through a membrane under high pressure, allowing separation of salt and other impurities. Seawater desalination plants require electricity to operate, although the associated power consumption is significantly lower than that of electrolysis. Additionally, special attention has to be paid to the leftover brine (highly concentrated salty runoff). This by-product has to be carefully reintroduced to the sea or completely evaporated to avoid damage to local marine life.[11]

10 Asghari et al. (2022).

11 Jones et al. (2019).

Hydrogen: electrolysis

In the context of green hydrogen production, electrolysis is generally understood as the splitting of water (H_2O) into hydrogen (H_2) and oxygen (O_2) using renewable electricity. Depending on the temperature level at which this process takes place, a distinction can be made between so-called low- and high-temperature electrolyzers. Currently, the most widely used technology in the first case is alkaline electrolysis (AEL), in which an alkaline solution is used as the electrolyte. Against the backdrop of increasing feed-in from fluctuating renewables, polymer electrolyte membrane electrolysis (PEMEL) has become established as another low-temperature electrolysis technology in recent years, due to its higher compatibility with fluctuating loads. Solid oxide electrolysis (SOEL), often referred to as high-temperature electrolysis, operates at significantly higher temperatures and requires water vapour (instead of liquid water) as an input, but is characterized by higher efficiencies than the low-temperature processes. A variant of SOEL is the co-electrolysis, in which CO_2 and water vapour are used simultaneously as a feedstock, directly producing a synthesis gas consisting of hydrogen and carbon monoxide (CO), which can be used for subsequent (fuel) synthesis. Compared to the low-temperature electrolyzers now established on the market, the high-temperature processes have only been realized in smaller demonstration plants.[12]

CO_2: biomass and direct air capture

There are essentially two different ways of capturing CO_2 from the atmosphere: either directly via direct air capture (DAC) or indirectly via biomass. In the latter case, CO_2 is absorbed during photosynthesis and released during subsequent conversion (e. g. in biomass combustion or in biogas/bioethanol production). In biogas and bioethanol production, CO_2 is produced as a by-product of the biological conversion processes in relatively high concentrations, requiring comparatively low additional purification. As a by-product of combustion processes, CO_2 is present in the exhaust gas in a considerably lower concentration and must be separated and purified with considerably higher effort.[13]

The DAC process is used to capture CO_2 directly from the atmosphere. This process follows three basic steps: first, by means of fans, large amounts of ambient air are directed through a device in which the air passes over a sorbent, which binds the CO_2 (and, depending on the sorbent, water molecules as well). In this way, the carbon dioxide can be separated from the other substances present in the air. In a second step, the air flow is interrupted and CO_2 as well as water are separated from the sorbent, usually by means of thermal energy, so that pure CO_2 is available at the end of the process chain.[14]

Nitrogen: air separation

In addition to hydrogen, pure nitrogen (N_2) is required as a feedstock in ammonia production. The provision of nitrogen can be realized by separating it directly from the atmosphere in an air separation plant using the so-called Linde process. In the Linde process, air is gradually liquefied and broken down into its main components, e. g. nitrogen (at very high purity levels) and oxygen. This process was developed at the end of the 19th century and has since been used on an industrial scale worldwide. Due to the significantly higher nitrogen content in the atmosphere compared to CO_2 (about 78% by volume compared to about 0.04% by volume), this process is characterized by significantly lower specific energy consumption, thus leading to significantly lower costs than CO_2 separation from the atmosphere using DAC. Nitrogen can also be provided from ambient air by means of pressure swing adsorption (PSA) if lower purities are sufficient.

2.2 Fuel synthesis

The generic term power-to-X (PtX) refers to various synthesis processes for the production of synthetic fuels. This includes Fischer–Tropsch synthesis for the production of synthetic hydrocarbons (e-kerosene, e-diesel), ammonia synthesis, methane or methanol synthesis, and processes for the further processing of methanol into synthetic hydrocarbons (i. e. methanol-to-X processes). Green hydrogen and the respective carrier molecules (nitrogen or CO_2) are required as feedstocks in all these processes.

12 IEA (2022).

13 ifeu (2019).

14 Viebahn et al. (2019).

Fischer–Tropsch synthesis

Fischer–Tropsch synthesis was originally developed in the early 20th century for the production of synthetic diesel from gasified coal. Fischer–Tropsch synthesis first requires a synthesis gas consisting mainly of hydrogen and carbon monoxide (CO). To produce e-fuels, this synthesis gas is obtained from the reduction of CO_2 in combination with green hydrogen. This is done via the above-mentioned co-electrolysis, or in a reverse water gas shift (RWGS) reaction. The technical implementation of the RWGS reaction currently represents the greatest technical challenge in e-fuel production. The product of the subsequent Fischer–Tropsch synthesis is a mixture of different hydrocarbons, often referred to as synthetic crude oil or syncrude for short.

Syncrude can be further processed in conventional refinery processes (including cracking, isomerization, distillation) to produce chemical feedstocks such as naphtha (crude gasoline) or standard-compliant fuels such as diesel or jet fuel. This further processing can take place either directly at the syncrude plant or at existing fossil feedstock (i. e. crude oil) processing refineries. If the syncrude is further processed together with crude oil (or intermediate crude oil products), this is referred to as co-processing. In principle, existing refinery plants can also be used exclusively for the further processing of syncrude after minor technical modifications. E-SAF produced by Fischer–Tropsch synthesis is approved as a blending component in civil aviation and may currently be blended with fossil jet fuel up to a 50% share.

Today, large-scale Fischer–Tropsch plants exist, but so far they are exclusively used for fossil feedstock conversion, such as coal (coal-to-liquids, CtL) or natural gas (gas-to-liquids, GtL). The world's two largest GtL plants, QatarEnergy and Shell's Pearl GtL plant and QatarEnergy and Sasol's ORYX GtL plant, both in Ras Laffas, Qatar, have a combined production capacity of 8.5 million tonnes per year.[15] Work has also been underway for several years to use biomass (biomass-to-liquids, BtL) or waste materials (waste-to-liquids, WtL) as feedstock for Fischer–Tropsch synthesis. The first such industrial plants are currently being built or have recently gone into operation in the USA and elsewhere.[16] They are significantly smaller than the aforementioned plants for processing fossil energy carriers (producing several 100,000 tonnes of synthetic products per year). The first demonstration plants for the production of e-fuels via Fischer–Tropsch synthesis (which are much smaller, with production capacities of about 350 tonnes per year) are currently being commissioned in Germany.[17] Additional larger PtL plants are currently being planned or already under construction.

Methanol synthesis

Methanol is one of the world's most widely produced and traded organic chemical feedstocks. Existing global production capacities are more than 100 million tonnes, and large-scale methanol production (up to 10,000 tonnes per day) is not uncommon. These conventional methanol production plants typically use natural gas or coal as a feedstock.

Renewable methanol can be produced by providing a non-fossil synthesis gas (similar to Fischer–Tropsch synthesis) without significant changes to the established synthesis process. There are several commercial biomass and municipal waste conversion plants currently planned or under construction. In addition to the use of synthesis gas, however, there are also synthesis processes that can convert hydrogen and CO_2 directly as feedstock, i. e. without prior reduction of CO_2 to CO. In addition to smaller demonstration plants for the production of e-methanol – for example, in Iceland (with a production capacity about 4,000 tonnes per year)[18] – much larger plants are planned.

Methanol-to-X

In addition to direct use as a fuel or chemical feedstock, methanol can be further processed into drop-in fuels such as gasoline or jet fuel via various process variants. Here, too, the processes are often named after the target product: Methanol-to-gasoline (MtG) refers to the production of gasoline and methanol-to-jet (MtJ) to the production of jet fuel. These processes are similar in terms of basic process technology and structure, but

15 Oxford Business Group (2023).

16 Cision PR Newswire (2022a).

17 Atmosfair (2023); P2X Europe (2022).

18 Carbon Recycling International (2023a).

are currently at different levels of technical maturity. For example, e-SAF via the MtJ route has not yet been approved for use in aviation; a corresponding certification process was initiated at the beginning of 2023.[19]

Plants for the synthesis of gasoline from methanol have been operating for the past century, and a first demonstration plant (with a production capacity of about 450 tonnes per year) for the production of e-fuels started operation in Chile at the end of 2022.[20] In contrast, the process for producing e-SAF from methanol is still at the research stage and only laboratory-scale plants exist to date.

Ammonia synthesis

Ammonia synthesis (usually using the Haber–Bosch process) is a process that has been known since the beginning of the 20th century and is now used on a large industrial scale in all regions of the world. In addition to hydrogen, ammonia synthesis requires nitrogen, which is usually separated from ambient air by processes that are deployable on an industrial scale. Green hydrogen is also needed to produce green ammonia, whereas current ammonia production plants today almost exclusively use grey hydrogen derived from natural gas. In addition, ammonia has so far not been used as a fuel, but as a bulk commodity in the chemicals industry – however, the maritime industry in particular sees great potential (especially economic) for ammonia as a fuel in oceanic shipping.[21]

19 Biofuels Central (2023a).

20 HIF (2022).

21 ABS; CE Delft; Arcsilea (2022).

3 | E-Fuel efficiency: Little bang for the buck

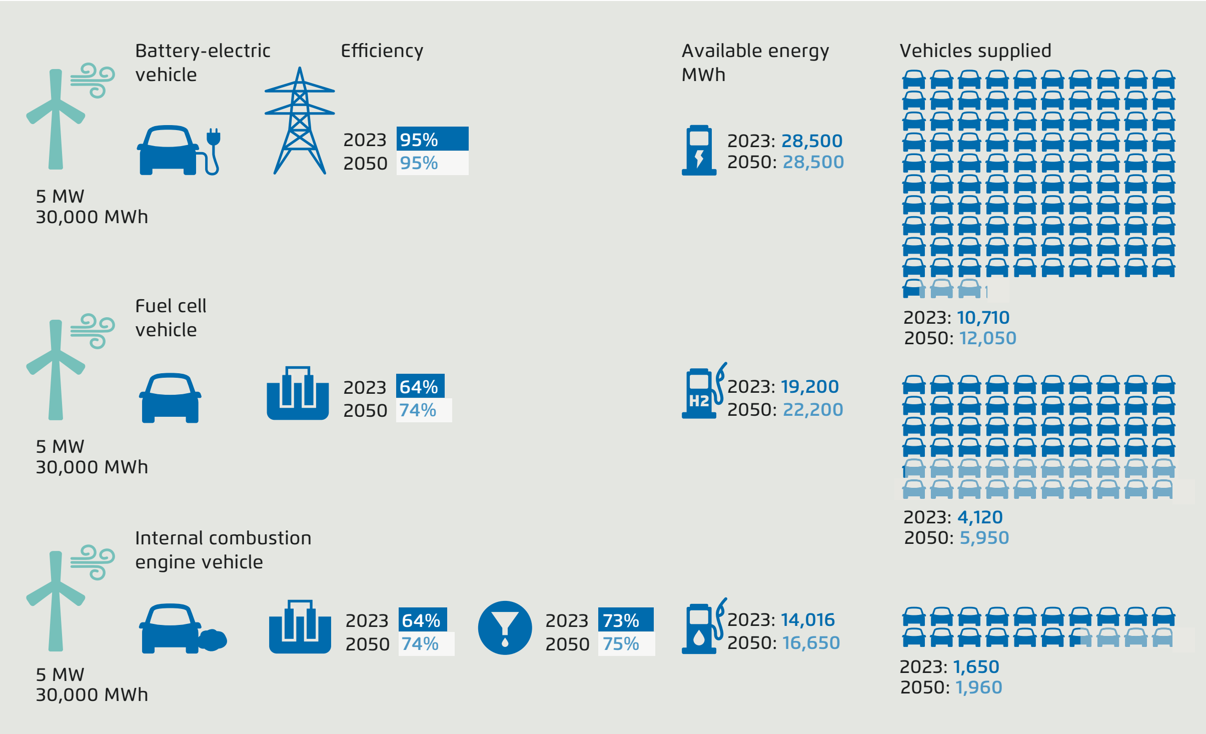
Compared to the direct use of electricity, e-fuel production involves high energy conversion losses. This is because green hydrogen must first be produced then processed with CO_2 to synthesize the fuel. This has two immediate consequences: First, the cost of e-fuels will always be significantly higher than the cost of using electricity directly. Second, reliance on e-fuels entails significantly higher renewables demand, and meeting this demand requires considerable financial, material, and land-use inputs for capacity development.[22] These expenses are incurred no matter where e-fuels are produced. Nevertheless, e-fuels can represent an energy storage solution, particularly in sweet spot regions with excellent wind or solar conditions, insofar as electricity grid connection is not economically feasible.

Figure 3 illustrates the conversion losses and efficiency levels associated with cars that rely on different propulsion systems, all of which are based on renewably generated electricity from a sweet spot region.[23] Specifically, the figure considers a battery-powered electric car, a fuel cell car, and a car with an internal combustion engine running on e-fuels. Here, a distinction is made between the energy required up to the fuel pump (in a "well-to-tank" analysis) and the total energy consumption of the vehicle (in a "tank-to-wheel" analysis). Energy consumption needs differ significantly between the three drive systems. The charging station for the electric vehicle is connected directly to the power grid, and the energy is transferred directly in the form of electrons. For the fuel cell and internal combustion vehicles, the fuels (in this case hydrogen and e-fuels,

22 Agora Verkehrswende, Agora Energiewende (2018).

23 Representative values without consideration of the upstream inputs.

Renewable energy in road transport: Comparison of drive system efficiency — Figure 3



Agora Verkehrswende (2024) | Note: The above figures are for a compact car that is driven 14,000 km/year. Future efficiency improvements result from expected efficiency gain in electrolysis and synthesis processes. Assumed average full load hours for a wind turbine in sweet spot region: 6,000 hours/year. Sources: acatech et al. (2017); dena (2021); iea (2021); Öko-Institut (2019).

respectively) are refuelled as molecules via a fuel pump, as is customary with combustion vehicles. The higher the number of conversion steps, the higher the associated energy losses. As the figure makes evident, a renewable source of electricity such as a wind turbine can supply more than six times as many battery-powered electric cars than internal combustion engines (ICE) cars running on e-fuels, given otherwise similar vehicles and annual mileage.

The lowest conversion losses from well-to-tank are incurred with the battery electric vehicle. Here, around 28,500 MWh (i. e. 95%) of the original energy (30,000 MWh) reaches the charging station. The fuel cell car comes in second place. Here, the losses associated with hydrogen generation by means of electrolysis as an intermediate step are clearly noticeable: only 19,200 MWh (i. e. 64%) of the original energy is available as hydrogen at the pump. The least efficient option is e-fuels, because in addition to electrolysis, further losses occur during fuel synthesis. In this case, only about 14,000 MWh (i. e. 47%) of the renewable electricity makes it way to the vehicle in the form of e-fuel.

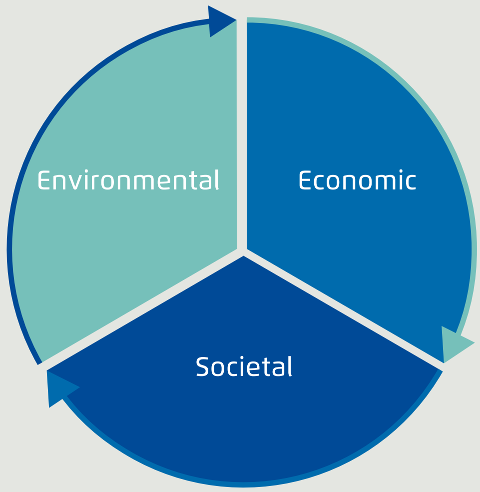
We find the same discrepancies in efficiency when considering the vehicle itself. The internal combustion engine incurs further losses, as around two thirds of the energy stored in the fuel is lost in the form of heat. Fuel cells are significantly more efficient – but here, too, some of the energy is lost through reconversion back into electricity. Battery electric vehicle incur the lowest losses. If all these effects are combined (well-to-wheel), we can obtain an accurate picture of the relative efficiency of each vehicle type.

In the future, efficiency improvements can be expected in almost all areas of the utilization chain, from renewable electricity production to vehicle propulsion. In the case of battery-powered electric vehicles, efficiencies are anticipated mainly "on the vehicle side", e. g. through more efficient charging systems and lower battery losses. Fuel cell vehicles, for their part, will benefit from significant efficiency improvements both in the electrolysis process and in vehicle technology. By contrast, combustion engines have already been optimized for decades, which is why only minor efficiency gains on the vehicle side can be anticipated. However, efficiency gains in both the electrolysis and synthesis process can be anticipated for e-fuel production. Nevertheless, improvements of just a few percentage points can be expected for the synthesis processes, as these processes are far from new discoveries.

The increases in the number of vehicles that can be supplied up to 2050 – as shown in the right hand column of the figure – are attributable to anticipated efficiency gains in the energy supply and vehicle technology. Overall, some 1,340 additional battery-powered electric cars (an increase of about 11%) can be supplied by 2050. The corresponding figures for e-fuel combustion and fuel cells cars are 310 and 1830, respectively (equivalent to an increase of 16% and 31%). This means that electric vehicles will remain the most efficient drive technology long into the future. In other words, given identical driving distances, an ICE car running on e-fuels requires many multiples of the renewable electricity consumed by a comparable battery electric vehicle. Running any significant share of the combustion fleet on e-fuels would thus require enormous additional renewable power capacity in combination with expensive facilities for fuel production, all of which would be associated with significant additional resource inputs and land use requirements.

4 | Sustainability: Complex, yet imperative

Enabling a virtuous circle: The three dimensions of e-fuel sustainability and their requirements — Figure 4



Environmental

- Additional power generation capacities
- Closed carbon loop
- Ecological seawater desalination
- Avoidance of land use competition
- Circular raw material use

Economic

- Long-term economic development
- Energy transition at the local level
- Opportunities for use in local transport

Societal

- Capacity building to advance the energy transition
- Electricity and drinking water supply for the local population
- Land use rights and stakeholder participation
- Human rights and labor standards

Agora Verkehrswende (2024)

Currently, e-fuels are mainly discussed in connection with their potential to reduce CO_2 emissions in transport. However, in addition to furthering climate protection, the development of e-fuel production capacities will have various social and economic impacts. For this reason, we advocate a holistic view of e-fuel sustainability based on the UN's Sustainable Development Goals (SDGs). In this connection, it is necessary to consider the environmental, economic and social dimensions of e-fuel production and use (see figure 4).[24]

At the same time, sustainability measures must always be developed in collaboration with local communities and adapted to their living realities, rather than merely imposed in a top–down manner. In the following, we briefly highlight important aspects that should be taken into consideration and discuss their interrelationships.

24 See also the "EESG Framework" by the International PtX Hub (2022).

The environmental dimension: The sustainable use of feedstocks, land and materials

New renewables capacity ("additionality"): The production of hydrogen via electrolysis is responsible for a large share of the electricity required to manufacture e-fuels. To keep greenhouse gas emissions from hydrogen production as low as possible, the electricity required in the e-fuel production process must come from renewable sources. Yet merely relying on the electricity provided by the existing power supply system is problematic in many localities, due to the high share of generation from fossil fuels. Furthermore, as renewable power is scarce, it should be used directly and in the most efficient manner possible in order to avoid conversion losses and minimize fossil-based power demand. Accordingly, it is necessary to develop additional renewable electricity generation capacities that are dedicated to hydrogen production (thus fulfilling the criterion of "additionality"), as this will prevent hydrogen production from competing with renewables expansion in the existing grid.[25]

25 Agora Energiewende; Agora Industrie (2022).

Closed CO_2 cycle: In addition to hydrogen, the synthesis of nearly climate-neutral e-fuels requires CO_2 from a closed cycle. This means that only carbon from DAC or biogenic sources, preferably residues, should be used. DAC is site-independent and promises to make CO_2 from the atmosphere directly available for e-fuel synthesis. However, the technology has significant space and energy requirements, due to the low concentration of CO_2 in the atmosphere, and it is not yet deployable at scale. Accordingly, only a limited amount of CO_2 is available using DAC at present, and the method remains very expensive.

By contrast, biogenic CO_2 (e. g. from biogas or bioethanol plants) is available today, and is relatively inexpensive. However, there are various risks to sustainable deployment at scale, due to land-use competition with the food industry and indirect land-use changes. Overall, the availability of sustainable biogenic CO_2 at scale is sharply limited.[26]

Ecological seawater desalination: One litre of e-SAF requires 3.6 litres of purified water, mainly for hydrogen electrolysis. Geographically there are few locations that offer both good conditions for renewables production as well as sufficient volumes of sweet water. While many regions may initially seem attractive for the production of e-fuels due to their high solar energy potential, such regions often lack sufficient (surplus) water resources. Large-scale seawater desalination represents a possible solution moving forward. However, the energy required to run such desalinisation plants must come from renewables, in order to maintain the positive CO_2 balance of e-fuels. In addition, desalination creates brine (i. e. hypersaline water), the disposal of which must be regulated.[27]

Avoiding land-use competition: The production of e-fuels requires less land than the production of biofuels based on energy crops such as soy, corn or canola. Nevertheless, the land-use requirements for all associated systems (including DAC plants, PV systems and wind turbines) are significant. These land-use requirements can be minimized through various approaches, such as wind-turbine placement amid pastures, or the dual use of land for solar energy production and agriculture ("agrophotovoltaics").[28]

Circular raw material use: Various metals, including platinum and iridium, are required for e-fuel production technologies (e. g. as catalysts in the synthesis process, and to manufacture electrodes for electrolysis). Platinum and iridium are rare metals and currently only mined in a few global locations. For this reason, further research is required not only with a view to reducing the volume of metals required from a technical perspective, but also concerning the potentials for substitution and recycling, which is currently only carried out to a limited extent.[29]

The economic dimension: Local value creation and use cases

Long-term economic development: To ensure that the benefits of future e-fuel projects are not limited to additional tax revenues or profit streams for the state, strong linkages to local economic structures should be encouraged. Insofar as local economic actors can be successfully integrated into the e-fuel value creation chain (both upstream and downstream), this promises to create positive impulses for the formation of new companies as well as for investment and innovation. This, in turn, can support sustainable economic development and the creation of high-quality jobs over the long term.[30]

Forward and Backward Linkages

The production of e-fuels presents various opportunities to create forward and backward linkages to the domestic economy and thus for contributing to sustainable socioeconomic development. Moving up the supply chain, local suppliers can provide finished systems, components and other inputs to the e-fuel plants (e. g. solar panels, wind turbines, electrolyzers and other necessary services and technologies). Insofar as local production capacities are lacking, targeted investment and capacity building measures could be promoted

26 Viebahn et al. (2019); ifeu (2019).
27 BHL; LBST (2022); WIRED (2019).
28 Jeswani et al. (2020); Fraunhofer ISE (2022).
29 Fraunhofer ISE, E4tech, Fraunhofer IPA (2018); Bahadur et al. (2018).
30 Altenburg et al. (2023).

(see below). Further, synergies can be created between e-fuels production and the agricultural sector (in which CO_2 from biomass is produced). In some arid locations, the shade provided by the solar panels combined with smart irrigation and fertilization measures could potentially create new fertile land. Moving down the supply chain, the produced e-fuels have a higher commercial value than the hydrogen itself and can generate significant export revenues. However, e-fuels also offer significant opportunities for the defossilization of domestic aviation and shipping which could create local demand.

Lastly, other industries stand to benefit indirectly from foreign direct investment in e-fuel production and associated renewable capacities. Prior agreements between domestic policy makers and investing companies could stipulate that additional renewable capacity must be built; this would benefit local companies and the population at large. In this way, e-fuel production can encourage a just transition with wide-ranging benefits for economic development, innovation, job creation and human capital formation.

The domestic energy transition: Electricity supply re-mains inadequate in many countries that have good preconditions for e-fuel production or they rely on fossil-fuel power plants with poor efficiency. On the one hand, there is a risk that focusing on e-fuel production will run at cross purposes with the efficient development of domestic renewables or the decarbonization of the power supply mix, particularly in "sweet spot" locations with favourable conditions for renewables. On the other hand, improving power infrastructure comes with high costs that may be difficult to afford, especially in low-income countries. The investments made in connection with e-fuel projects to provide additional power generation could offer an opportunity to advance the development of infrastructure that serves local needs, and not just that of the e-fuel project. Accordingly, e-fuel projects should strive to overbuild infrastructure capacities, including that of the power grid, in the countries in which they take place.[31]

31 Afful-Dadzie et al. (2020); United Nations (2023).

Domestic transport: E-fuels production is also of relevance for the domestic transition to sustainable transport technologies. In many countries, transport fleets are comprised of older vehicles that are particularly polluting. This applies not only to road vehicles, but also to ships and aircraft (which should have priority for e-fuel use). In this context, a key question is whether a country should produce e-fuels primarily for export or rather for domestic consumption.

The societal dimension: Supporting a just transition

Occupational training: The ramp-up of e-fuel production can have significant impacts on the labour market. By way of example, if jobs in fossil fuel extraction are lost or if parts of the economy migrate to regions with better conditions for renewables, this can create socioeconomic dislocation. Occupational training programmes, including programs to retrain workers, are thus essential to minimize negative impacts to the workforce. Cooperation between countries in the domain of technology transfer can strengthen local economic capacities. A related but no less important issue is to ensure domestic officials have the expertise required to formulate and enact effective regulatory and industrial policy.

Access to electricity and drinking water for the population: E-fuel production creates significant demand for electricity and drinking water that can potentially threaten security of supply for local populations, especially in precarious regions. Therefore, e-fuel production could trigger or intensify resource conflicts. The construction of additional renewable generation and desalination capacities can mitigate this risk and help to ensure water and electricity access for local populations.[32] One possible model is to undertake such additional investment using public–private partnerships that are structured to produce benefits for both local communities and investors.

Land use rights: Large-scale projects in the energy sector require considerable amounts of land and historically such projects have sometimes resulted in violations of land-use rights. To ensure that such rights are upheld, governance procedures should be established by the project principles (both public and private) that enable

32 Pacific Institute (2023).

the genuine participation of local peoples. This should include the creation of platforms for soliciting opinions from civil society. In addition, transparent complaint mechanisms (e. g. based on the principle of Free, Prior and Informed Consent, or FPIC) should be established.[33]

Human rights and labour standards: It is important to ensure that the operators of e-fuel plants adhere to relevant human rights and labour standards, including those set forth in the UN Guiding Principles on Business and Human Rights (UNGP), the ILO Core Labour Standards, and the OECD Guidelines for International Enterprises, including the OECD's Due Diligence Guidance.[34] These requirements and standards include the prohibition of forced child labour and of discrimination against women. Monitoring mechanisms are also needed to ensure health and safety compliance.

In light of the above, we find that the development of e-fuels may be accompanied by various positive and negative impacts for people, the economy and the environment. Policymakers have the responsibility to encourage regulatory and investment conditions across all of these dimensions that maximize the benefits of e-fuels production while minimizing potential downsides. One important factor is the need to establish international standards and associated certifications for sustainable e-fuels. The implementation of such standards is a complex issue that should be tackled globally to avoid market fragmentation. To be sure, trusting international cooperation is an essential prerequisite, not just for devising and adopting such standards and certifications, but also for ensuring that e-fuels contribute to a just transition in the transport sector.

33 Backhouse (2019); International PtX Hub (2024).

34 OECD (2018).

5 | Production costs: Anticipated to remain very high for the forseeable future

How costly will e-fuels be in future – both for the individual user and for the economy as a whole? While the answer to this question is subject to numerous uncertainties, it is possible to develop some preliminary estimates. E-fuel production costs are generally driven by three categories of costs:

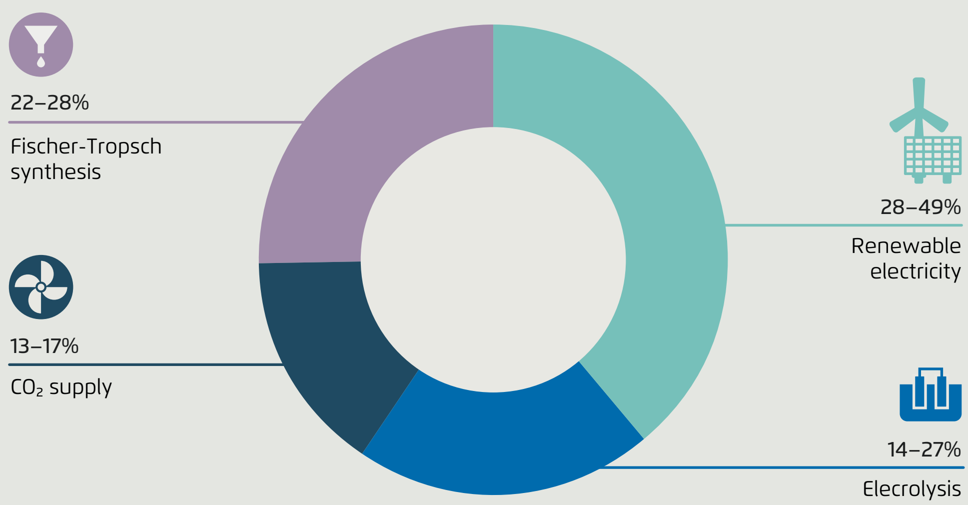
- Operational expenditures (OpEx): Describes all cost associated with the operation of the production facility.
- Capital expenditures (CapEx): Describes the capital required to construct the production plant.
- Financial expenditures (FinEx): Describes cost of capital, including costs that accrue to service debt and pay dividends.

The relative weight of each of these cost categories will vary from project to project. Whether expenditures primarily take the form of OpEx or CapEx will depend on the specific merchant model used. In this regard, we can differentiate between an "integrated" and "segregated" merchant model". In an integrated merchant model, the costs associated with the production of all feedstocks (electricity, CO_2, water, etc.) are integrated in the project and thus fall under CapEx. In a fully segregated merchant model, by contrast, the operator does not generate its own feedstocks and therefore enters into purchase agreements for feedstock supply. In this case, the costs for purchasing the feedstocks fall under OpEx. However, mixed variants of these two models are also possible. The following example illustrates the key differences between the integrated and segregated merchant models.

The chart below shows CapEx components for an integrated merchant model. According to relevant studies, under this model electrolysis and renewable power generation account for more than 50% of e-fuel production costs.

Electricity costs account for 28–49% of overall e-fuel production costs. The lower end of this electricity cost range reflects production in geographical sweet spots with favourable weather conditions. Many of these locations are in the southern hemisphere. However, in

Capital expenditures and operating costs as an averaged share of e-fuel production costs — Figure 5



Agora Verkehrswende (2024) | Note: The cost ranges result from different assumed production locations. Source: dena (2022).

these regions sustainable CO_2 point sources for large-scale e-fuel production are scarce, making large-scale DAC inevitable. What is more, according to a recent study, CO_2 supply via DAC is likely to cost significantly more than estimated in the past.

Financial expenditures (FinEx) also have a significant impact on production costs. High cost of capital in developing countries can more than offset the production advantages associated with favourable wind and solar conditions. Country-specific credit risk is one main component of cost of capital; the sovereign credit rating is thus strong indication of the cost of capital spread to similar projects in developed countries. Credit ratings agencies will take a range of factors into account when assigning a country sovereign credit rating.[35] Obtaining a good sovereign credit rating is usually essential for developing countries to access funding in international bond markets. The following table shows the current rating of selected countries, including the basis-point spread to German government bonds, also known as "bunds".

While most e-fuel projects are funded in a hard currency (euros or US dollars) the risk premium for financing a project in a developing country can be significant. Various mechanisms have been explored to overcome this cost of capital disadvantage and enable green investment in developing countries, including guarantees, grants and concessional loans provided by multilateral development banks (MDBs) and development finance institutions (DFIs).

35 Two of the three biggest rating agencies (S&P and Fitch) assign rankings from AAA to D (for "default"). Moody's, the third major rating agency, has a similar scale that ranges from Aaa to C.

Since no commercial e-fuel production plants are yet in operation, there are also no reliable figures for market prices or future costs. In recent years, various studies have sought to estimate the market costs for e-fuels. These studies generally conclude that e-fuels are five to ten times as expensive as comparable conventional fuels. However, as is always the case with projections, these estimates are subject to considerable uncertainties.

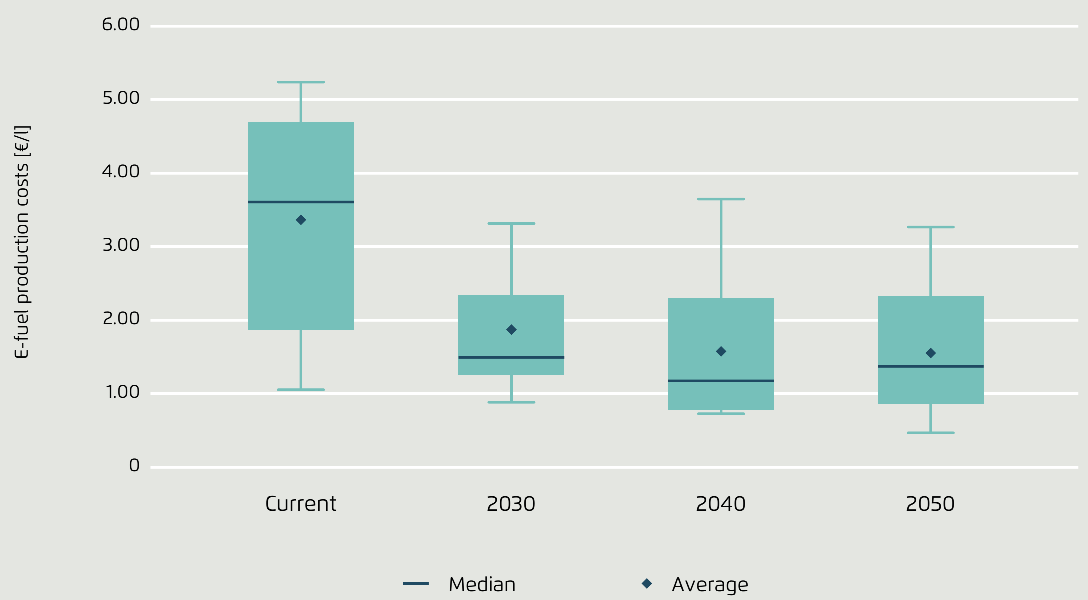
The following figure showcases the results of various studies on the current and future cost of e-SAF production using Fischer–Tropsch synthesis. The projections are subject to wide variation depending on the assumptions made regarding plant location, the cost of renewable electricity, and plant efficiency. On average, the estimates foresee current production costs of about 3.85 euros per litre. However, past studies have yielded widely divergent estimates ranging from 2.05 to 4.70 euros per litre. At the lower end of this cost range we find the studies that assume cheap renewable supply with high full-load hours, such as hydropower, in combination with CO_2 from point sources. However, in the real world, few locations can satisfy both of these factors, meaning these estimates are not reflective of the conditions that would govern large-scale production. Mid-range costs result for a combination of low-cost power with high full-load hours and an expensive CO_2 source such as DAC or, alternatively, low full-load power generation in less favourable regions with a cheaper CO_2 point source. Very high costs result when production

Rating of selected countries and the traded credit spread to German bunds in August 2023 — Table 1

Country	Rating (S&P, 08/23)	Basis point spread to German bunds (08/23)
Kenya	B-	1,398
Nigeria	B-	1,180
South Africa	BB-	772
Brazil	BB-	870
India	BBB-	457

Agora Verkehrswende (2024)

Hydrocarbon-based e-fuel production costs: Projected ranges including median values — Figure 6



Agora Verkehrswende (2024) | Sources: Becattini et al. (2021); BHL, LBST (2022); DECHEMA (2023); dena (2022); E4tech (2021); iea (2022); ifeu, DLR, Johaneum Research (2020); Öko-Institut (2021); Sherwin (2021); Ueckerdt et al. (2021); WEF (2020).

takes place regions with low renewable potential in combination with CO_2 from DAC plants.

Looking forward, production costs are estimated to fall to 0.90 to 2.35 euros per litre by 2050 given robust market deployment and associated learning-curve effects and economies of scale. On average, manufacturing costs in 2050 are estimated at 1.40 euros per litre. However, such studies generally only consider "minimum" production costs. Specifically, they do not consider additional costs for fuel transportation, certification, taxes and levies, or commercial profits. By way of comparison, fossil fuel production costs are currently between 60 and 70 euro cents per litre. However, the end consumer price in Germany is over twice that – namely, between 1.50 and 1.70 euros per litre. In any event, the retail prices paid by consumers of e-fuels are likely to be significantly higher than their production costs.

Although the forecasts and estimates for e-fuel production costs vary widely, the additional macroeconomic costs that will result from their use can be estimated by considering the fuel volumes that will be required – for example, to meet the ReFuelEU Aviation RFNBO sub-quota.[36] According to the aforementioned studies on e-fuel production costs, e-SAF can be produced at a cost of about 1,900 euros per tonne in 2030.[37] Assuming current prices for fossil-based Jet A-1 of around 850 euros per tonne, this would result in additional costs of at least 1,000 euros per tonne for e-SAF. Thus, to supply the approximately 570,000 tonnes of e-SAF required to meet the 2030 quota of 1.2 percent, additional costs of over 570 million euros would be incurred.

As a rule of thumb, the expected costs increase with the complexity of the production process and the feedstocks required in addition to hydrogen. Thus, e-methanol promises to be the cheapest option with a view to ease of production up to e-SAF. The Fischer–Tropsch route

36 For additional background on this quota, please see the following section on e-fuel policies.

37 Median of the analyzed studies for 2030 is 1.51 euros per litre; assumed SAF density: 0.8 kg/l.

might lead to slightly higher costs, but is also a very compelling technical option, as it currently represents the only certified pathway for producing e-SAF. Furthermore, its by-products can be sold, which improves its cost effectiveness. Indeed, capital investment and production costs for Fischer–Tropsch synthesis are expected to fall considerable in coming years due to economics of scale, standardization and learning-curve effects.

Ultimately it is important to stress that no hard data are available concerning the costs that will result for e-fuel production. The unit costs achieved by pilot plants are not representative of the costs achievable under large-scale deployment. Accordingly, unit cost expectations over the near term should not be the decisive factor for vanguard investments that seek to further develop e-fuel technology, given the cost efficiencies that will naturally result during a large-scale production ramp-up.

6 | E-fuel policies: Different countries, different approaches

Targeted and effective policy will be essential for overcoming the challenges described in the previous section and for steering the market ramp-up of e-fuels in the transport sector. Against the backdrop of efforts to identify appropriate policy tools, one key question is whether and how countries are currently addressing this topic, and, if so, which transport segments are being targeted.

As part of our research, we have closely analyzed eight jurisdictions with a view to the regulatory policies and market-based measures that have been adopted to encourage e-fuel adoption in the transport sector. Specifically, we consider two of the biggest consumers of fossil fuels (USA, EU); three countries with announced ambitions to become major e-fuel demand centres (Germany, Japan, UK); as well as three countries with rapidly rising fuel consumption and beneficial conditions for e-fuel production (Brazil, India, South Africa) (see table 2).[38] The results of this analysis are presented in the following and summarized in table 3 at the end of the section.

38 To obtain information on the policy landscape of the here referred to countries, desktop research was conducted. Public policy databases by IEA (2024b) and New Climate Institute (2024) as well as primary resources on ministerial landing pages or secondary sources by news agencies were used. In order to verify and elaborate on the retrieved data, expert interviews with representatives from domestic think tanks and private companies were carried out.

The transport segments targeted by hydrogen strategies

All of the above jurisdictions have published strategies and roadmaps that include a role for hydrogen and its derivatives in the effort to achieve GHG emission reductions, enhance energy security and encourage sustainable development.[39] Transport is universally addressed as a potential end-use sector within these strategies. Most strategies foresee the use of e-fuels in the hard-to-abate segments of aviation and maritime shipping; Japan is the only country that does not explicitly include aviation. Heavy-duty road transport is also uniformly identified as an off-taking segment; in addition, Japan and the US mention possible use in passenger cars and light duty vehicles. Notably, only Japan and India explicitly mention the possibility of supplying the existing passenger vehicle fleet with e-fuels. With the exception of Germany, most countries also consider rail as a potential end-use segment, especially as a solution for hard-to-electrify routes. In terms of hydrogen availability and production, the EU has set the highest adoption target: namely, 20 million tonnes by 2030 (of which 10 million tonnes will be imported, and 10 million tonnes produced domestically).

Frameworks for sustainable e-fuels production

The EU and UK have published regulatory frameworks for the sustainable production of hydrogen and e-fuels.

39 The analysis is based on the latest version of the respective countries' hydrogen strategy.

Fossil fuel consumption in transport in 2019 and associated growth between 2000 and 2019 — Table 2

Country	Fossil fuel consumption in transport, 2019 (in Terajoule (TJ) millions)	Growth in consumption between 2000 and 2019
Brazil	2.8	50%
European Union	14.6	7%
Germany	2.6	-4%
India	4.2	212%
Japan	3.2	-21%
South Africa	0.9	42%
United Kingdom	2.2	<1%
United States	24.8	1%

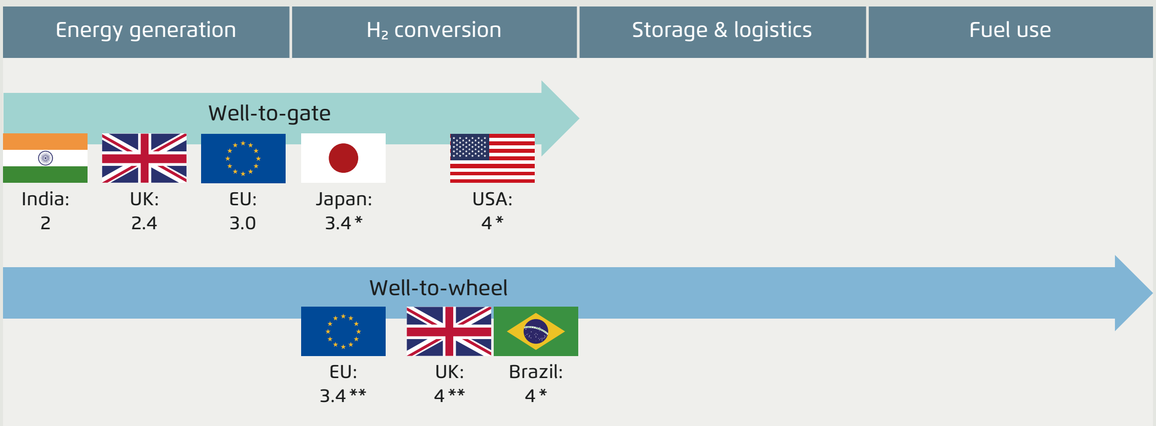
Agora Verkehrswende (2024) | Source: IEA (2024a)

Both the European EU RED (RED II)[40] as well as the British Renewable Transport Fuel Obligation (RTFO)[41] introduce standards for RFNBO and define associated production requirements.[42,43] According to these standards, the renewable hydrogen that is produced to obtain RFNBOs must be based on electrolysis powered by renewable electricity. Both standards also specify criteria with a view to additional renewable capacity for electrolysis and permissible CO_2 sources for e-fuel synthesis.

India has established standards for eligible GHG-emission intensity for hydrogen but not for its derivatives.[44] India specifies "green" hydrogen to be produced with renewable electricity or from biomass conversion. In the United States, the Department of Energy published updated guidance regarding its clean hydrogen production standard (CHPS) in June 2023; however, CHPS is not a regulatory standard. The US approach is to remain open to all production pathways as long as the respective emission intensity requirements are fulfilled.[45,46] Brazil and Japan recently announced they will introduce hydrogen standards and have indicated they will remain open to all production pathways, like the US.[47,48] South Africa has not yet presented any plans regarding the implementation of such standards.[49]

40 The second recast (RED II) was supplemented through respective delegated acts to article 27 and 28 by the European Commission in July 2023.
41 The RTFO was last updated in January 2021, and supplemented by the RTFO Guidance for Renewable Fuels of on-biological origin in January 2024.
42 European Commission (2023a).
43 Department for Transport (2023a).
44 Ministry of New and Renewable Energy (2023a).
45 Department of Energy (2023a).
46 Additionally, a tiered model is supposed to be introduced to the 45V Clean Hydrogen Production Tax Credit as part of the Inflation Reduction Act (IRA). This model will be based on emission intensity of the produced hydrogen, with only the top tier receiving the full credit (0–0.45 kg CO_2eq/kg H2 for receiving the full $3.00 and 2.5–4 kg CO_2eq/kg H2 as the lowest threshold to receive a tax credit of $0.60/kg H2). As of the writing of this paper, the timeline for finalizing the guidelines remains uncertain (The White House, 2023a).
47 Special Commission for Study, Evaluation and Monitoring of Initiatives and Adopted Measures for Energy Transition - Renewable Sources and Green Hydrogen Production in Brazil (2023).
48 Ministry of Economy, Trade and Industry (2023).
49 For a comprehensive overview of the examined countries' hydrogen standards see figure 7.

Overview of maximum GHG-emission intensity standards for hydrogen (in kg CO_2eq / kg H_2) Figure 7



* The GHG-emission standard for hydrogen has been announced but remains to be translated into binding national law.
** For hydrogen and its derivatives the same GHG-emission reduction target applies compared to a standard value for fossil fuels.

Agora Verkehrswende (2024) | Source: Government documents of the countries listed.

Obligations for fuel producers to introduce e-fuels

The EU and UK already have already adopted blending mandates and GHG-reduction obligations for fuel suppliers as a means of encouraging e-fuel adoption. In the EU, the third recast of the RED (RED III)[50] obligates fuel suppliers to ensure a 29% share of renewable energy in the final energy demand of transport by 2030 or at least a 14.5% GHG reduction in supplied fuels compared to a benchmark of 94g CO_{2eq}/MJ by that year. RED III requires fuel suppliers to ensure a minimum RFNBO share of 1% in total final energy consumption in transport by 2030, and also foresees a 5.5% target for advanced biofuels and RFNBOs.[51,52] Germany translated the RED targets into national law by introducing a "greenhouse gas reduction quota", which requires a consistent increase in GHG reduction, with targets rising from 6.0% in 2020 to 10.5% in 2025 and 25.0% in 2030. This policy and the associated targets are likely sufficient for fulfilling the revised RED III obligations.[53] The UK, for its part, requires fuel suppliers to feed-in non-fossil fuels[54] as part of the RTFO regulatory framework mentioned above.

In 2023 the EU also introduced specific blending targets for aviation sector. Aviation fuel suppliers will be required to adopt sustainable aviation fuel (starting at a 2% share in 2025, and increasing in 5-year steps to 70% by 2050).[55] A specific sub-mandate applies to the supply of RFNBOs, which is to start at 1.2% in 2030, reach 2% by 2032 and increase to 35% by 2050.[56] Germany had already established a (more ambitious) blending mandate for e-SAF of 2% by 2030 and a quantitative goal of 200,000 tonnes by 2030 in 2021. Given the EU-level requirement that blending mandates must be identical within the EU to avoid distortions to the internal market, it may be necessary to scale back Germany's more ambitious e-SAF quota.[57] In 2022, the UK government committed to introducing a SAF mandate by 2025 that would require at least 10% of jet fuel to originate from sustainable feedstocks by 2030.[58] While the UK has acknowledged that an e-SAF sub-mandate is needed to ensure a faster ramp-up of this technology, which promises high GHG-savings with low risks to land-use change, the precise scope of such a mandate and its timeframe for implementation remain to be determined.

Both India and Japan have also recently announced plans to introduce blending mandates for SAF. However, they have not specified whether they intend to adopt a sub-target for e-SAF.[59,60] Similarly, the US has announced the goal of supplying 3 billion gallons (11.3 billion litres) of SAF annually by 2030, but has not specified e-SAF goals.[61]

Brazil, for its part, has adopted CO_2 emission reduction targets for fuel suppliers, but links them to the purchase of biofuels specifically.[62]

Carbon pricing

In addition to e-fuel adoption mandates for the transport sector, market-based mechanisms such as CO_2 pricing can support the uptake of e-fuels in the transport sector due to the incentive effects created by higher fossil fuel prices. In this connection, special allowances for e-fuels usage can provide additional incentives for companies

50 RED III entered into force in November 2023.
51 European Parliament and Council of the European Union (2023a).
52 A multiplier of 2 applies for RFNBO towards the overall policy target (5.5%). Further, a 1.5 multiplier is added for RFNBO supplied to the maritime and aviation sector.
53 Bundesministerium der Justiz (2024a).
54 The obligation comprises two components: the 'primary obligation' and the 'development fuel target.' For 2024 the primary obligation requires a 13.563% share of the respective fuel suppliers supplied fuel to come from renewable sources, as well as an additional 1.379% share of 'development fuels' (i. e., RFNBO as well as those derived from biowaste or residues, excluding segregated oil and fat such as UCO). For RFNBO a multiplier of 2 applies. This share is set to increase to 17.676% primary obligation and 3.390% development fuel share by 2032.
55 European Parliament and Council of the European Union (2023b).
56 The sub-mandate is also considered complied with if renewable hydrogen or low carbon aviation fuels are supplied. "Low-carbon aviation fuels" is defined as aviation fuels sourced from non-biological origin, with their energy content derived from non-fossil low-carbon hydrogen (e. g. produced with nuclear energy).
57 Bundesministerium für Digitales und Verkehr (2021).
58 Department for Transport (2023b).
59 Reuters (2023).
60 Nikkei Asia (2023).
61 Department of Energy (2022).
62 Ministry of Mines and Energy (2021b).

that are subject to the carbon price system. Four of the eight countries considered in our analysis have already introduced carbon pricing.

In the EU, aviation falls under the EU Emission Trading System (EU ETS), which operates on a cap-and-trade principle and targets downstream polluters. The EU ETS was extended to maritime shipping in January 2024.[63,64] In 2027 a separate emission trading system will be introduced to cover road transport (EU ETS II). Currently, Germany has its own emission trading system in place to target this segment of the transport sector. However, unlike the EU ETS, the *Brennstoffemissionshandelsgesetz* (BEHG) is an upstream system that targets fuel distributors. This regulatory model was chosen due to the multitude of actors in road transport that would have to be charged under a downstream system (i. e. individual cars).[65] It remains to be clarified how the BEHG and EU ETS II will interact. The UK has introduced an emission trading system (UK ETS) that operates in a similar manner. For now, it only includes the aviation sector. The UK government has declared plans to extend the UK ETS to domestic maritime transport.[66] However, no plans to include road transport have been announced yet. South Africa's approach to carbon pricing does not rely on a tradable certificate system but rather on a carbon fuel levy.[67] The levy rate is scheduled to rise incrementally on an annual basis, from $20 per tonne by 2025 up to a minimum of $30 per tonne by 2030.

Japan recently announced plans to introduce a carbon levy on fossil fuel importers beginning in 2028, initially at an affordable level but gradually increasing on an annual basis. In addition, an Emission Trading Scheme (GX ETS) will be phased in for high-emission sectors, starting with voluntary trading amongst the GX League (a group of Japanese companies). From 2033 onwards allowances will be auctioned to electric power companies to expedite the decarbonization of the power sector. The Japanese transport sector will likely be affected by the carbon fuel levy.[68]

In September 2023 a bill proposing a domestic GHG trading system was introduced to the Brazilian congress.[69] As of March 2024, the proposal is still being negotiated, and it remains uncertain whether the system will encompass (parts of) the transport sector.

Obligations on manufacturers and consumers

Lastly, we also studied CO_2 emission reduction obligations for vehicle manufacturers and consumers with a view to their potential impact on the use of e-fuels in transport. A 100% CO_2 reduction target for manufacturers would entail the need to switch to a different drivetrain technology altogether (e. g. battery-electric power, fuel cells, or combustion based on hydrogen). As hydrogen can be considered an e-fuel (see Section 2), this type of policy measure is included in our analysis. Furthermore, as described below, the EU plans to exempt combustion vehicles running on e-fuels from the ICE registration ban. In six of the eight jurisdictions considered, mandatory CO_2 reduction obligations have been introduced for manufacturers in the road transport sector. Two jurisdictions also impose CO_2 reduction obligations on consumers.

Manufacturers: In April 2023, the EU amended its CO_2 emission performance standards for new cars and light commercial vehicles (LDVs), setting more ambitious targets:[70] By 2035, all new vehicles are mandated to have zero emissions. The amendment also includes plans for a registration framework for vehicles exclusively powered by e-fuels after 2035, though as of January 2024, no final agreement on this classification has been reached. In February 2024, negotiators from the Council of the EU and the European Parliament reached a provisional political agreement on an amendment proposal by the European Commission on CO_2 emission standards for heavy-

63 The revised EU ETS Directive foresees that 20 million allowances out of the total quantity of allowances for aviation are reserved for the usage of SAF between 2024 and 2030. Generally, usage of SAF compliant with RED is accounted with an emission factor of zero, which reduces the emissions aircraft operators have to account for. The additional allowances shall thus provide an additional incentive to use SAF.

64 European Parliament and Council of the European Union (2023c).

65 Bundesministerium der Justiz (2024b).

66 Department for Energy Security and Net Zero (2023).

67 National Treasury (2010).

68 Agency for Natural Resources and Energy (2023).

69 International Carbon Action Partnership (2023).

70 European Parliament and Council of the European Union (2023d).

duty vehicles (HDVs).[71] The agreement expands the scope to include urban buses, coaches, trailers, and other lorries besides trucks (>5 tonnes). The targets for HDVs entail a 45% reduction in average CO_2 emissions from 2030, a 65% reduction from 2035, and a 90% reduction from 2040 onwards (in relation to 2019 levels). However, the Commission will have to evaluate the possibility of developing a common methodology for assessing and reporting the full lifecycle CO_2 emissions of new HDVs and assess the role of a carbon correction factor (CCF)[72] in the transition towards zero-emission mobility in the sector in 2027. Also, similar to the standards for cars and LDVs, the methodology for registering HDVs exclusively running on CO_2-neutral fuels will be assessed within a year from entry into force of the regulation.

In January 2024 a zero-emission vehicle (ZEV) mandate for cars and vans came into force in the UK. It specifies the annual percentage of new zero-emission cars and vans that manufacturers must produce up to 2030.[73] By 2030, 80% of new cars and 70% of new vans sold in the United Kingdom must be zero-emission vehicles, and the target will increase to 100% for both categories in 2035. The ZEV mandate thus sets a target for vehicle manufacturers' annual sale percentages as a means of transitioning to zero tailpipe emissions. For each non-ZEV sold the manufacturer must have a ZEV allowance, which can be traded if the target is exceeded. For HDVs no intensified policy for non-ZEVs has been published yet, despite confirmation that the UK intends to end the sale of fossil HDVs less than or equal to 26 tonnes from 2035 onwards and required all new HDVs to be zero emission vehicles from 2040.[74] Following Brexit, the CO_2 emission performance standards for new HDVs from 2019 were transferred into UK law at the end of the transition period in December 2020 without major modification. The regulation sets targets to reduce the average CO_2 emissions from new HDVs by 15% in 2025 and by 30% in 2030. Similar to the British approach of setting sales targets, in 2021 the Biden administration in the United States announced the goal of having electric vehicles constitute 50% of new vehicle sales by 2030; to this end, the US launched the *EV Acceleration Challenge*.[75] At the federal level, the US government has not yet committed to a phase-out of conventional combustion engines. In March 2024 the Environmental Protection Agency (EPA) adopted revised multi-pollutant emissions standards for light-duty and medium-duty vehicles for model years 2027 and later. The EPA has introduced standards for light-duty vehicles that become more stringent annually over a span of six years, from model years 2027 to 2032.[76] According to EPA projections, the standards aim to achieve an average fleet target of 85 g CO_2/mile (53 g CO_2/km) for the light-duty fleet by model year 2032. The corresponding figure for cars is 73 g CO_2/mile (46 g CO_2/km). This represents a 49% reduction in the projected fleet average greenhouse gas (GHG) emissions target levels compared to the current standards set for model year 2026 (168 g CO_2/mile or 105 g CO_2/km). For medium-duty vehicles the standards foresee a target of 274 g CO_2/mile (171 g CO_2/km) by model year 2032 for the total average fleet, a reduction of 44% from 2026 model year standards (246 g CO_2/km). For HDVs the EPA has also adopted stronger CO_2 standards for model year 2027 and later in March 2024. These standards are supposed to become stricter up to 2032 and later. For example, for heavy-duty vehicles with compression-ignition engines that fall under the urban subcategory the standard will go from 269 g CO_2/mile (168 g CO_2/km) in model year 2027 to 188 g CO_2/mile (117 g CO_2/km) in model year 2032.[77]

Both India and South Africa have introduced CO_2 reduction obligations for light-duty vehicles.[78,79] Furthermore, at COP26, India signed the Zero-Emission Vehicle Declaration, which aims to make all new car and van sales zero-emission across the globe by 2040, and to have leading markets achieve this goal by 2035. In India, the standards are set in terms of gasoline-equivalent litres per 100 kilometres (l/100 km) and are adjusted based on vehicle curb weight. Accordingly, from 2022 onwards gasoline equivalent fuel consumption should be less than 4.76l/100km at an average curb weight of 1,082 kg. During vehicle type approval, fuel consumption for compliance is assessed in grams of CO_2 emissions per

71 Council of the European Union (2024).
72 A carbon correction factor would reduce the GHG-emission profile of HDVs based on emission intensity of the fuel mix.
73 Department for Transport (2024).
74 Department for Transport (2022).
75 The White House (2023b).
76 Environmental Protection Agency (2024a).
77 Environmental Protection Agency (2024b).
78 Bureau of Energy Efficiency (2024).
79 PWC (2023).

kilometre (g CO_2/km). The regulation specifies the factors required for converting the consumption of various fuel types into gasoline-equivalent fuel consumption, as well as for converting from gasoline-equivalent fuel consumption to CO_2 emissions. International Council on Clean Transportation (ICCT) India thus calculates the average CO_2 target to be equivalent to 113.1 g CO_2/km. In South Africa the standard is set at 120 g CO_2/km and the levy applies at ZAR 132 ($7.16) per gram of additional CO_2 produced per kilometre. For double cab passenger vehicles, the rate is ZAR 176 ($9.55) per gram of CO_2 produced per kilometre beyond the initial 175 g CO_2/km.

Japan has set the goal of making 100% of new passenger vehicle sales "electrified vehicles" by 2035 (a category encompassing both non-plug-in hybrids, hybrid vehicles, and plug-in hybrid vehicles).[80] Japan foresees e-fuels playing a potential role in the decarbonization of the existing car fleet from the early 2030s onwards. Japan has pollution and fuel efficiency standards in place, but no CO_2 reduction standards for manufacturers.

Brazil is set to introduce a target based on the GHG-intensity of the fuel mix and vehicle efficiency, as measured in g CO_2/km.[81] Rather than regulating different segments of the emissions chain, this policy takes a holistic approach, and is highly dependent on the share of low carbon fuels in the energy mix.

Consumers: In Brazil, the Fuel of the Future Program foresees the introduction of CO_2 reduction targets for airlines in their domestic operations, rather than blending mandates; international flights will be exempt. The reduction obligations will start at 1% in 2027 and increase progressively to 10% in 2037. The reference year for emissions is not specifically mentioned, but given the policy's orientation to the Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA) by the International Civil Aviation Organisation (ICAO), average emissions in 2019–20 are likely to be the baseline. The obligations must be met through the consumption of SAF, and not via technological or operational improvements. A legal framework for SAF is included in the bill and supplemented with specifications regarding "aviation biokerosene". Here, the term "bio" does not mean "limited to biogenic", but rather denotes "alternative to fossil". This becomes evident through the details of the bill, which state all technological routes for the production of SAF are allowed as long as they are approved by the American Society for Testing and Materials (ASTM) (thus paving the way for e-SAF compliance with production based on Fischer–Tropsch synthesis).

The FuelEU Maritime regulation requires all ships with a gross tonnage (GT) above 5,000 that call at European ports to gradually reduce the GHG-intensity of the energy used onboard. The reduction target will incrementally increase from 2% in 2025 to 80% in 2050. A conditional blending mandate has also been established for maritime shipping. This mandate foresees a 2% RFNBO blending share from 2034 onward if the share of RFNBO in the maritime bunker fuels used by ships is less than 1% by 2031.[82] The 2034 target may not be enforced in case of issues related to the availability, cost, or distribution of RFNBOs. Also, under this mandate, RFNBOs may be substituted with any fuel meeting a 70% GHG reduction threshold.[83] Other than the blending mandate for aviation, the obligations may apply directly to consumers (meaning maritime shipping companies), rather than to fuel suppliers.

Overall, two main conclusions emerge with a view to whether and how e-fuels are currently regulated in various markets:

- First, while more and more jurisdictions are adopting standards for hydrogen production and all countries investigated have in fact introduced a strategy or roadmap for hydrogen use, comprehensive frameworks that encompass e-fuels have only been adopted in a few jurisdictions, such as the EU and UK. Furthermore, we conclude that such policy frameworks are important for reducing market fragmentation and for ensuring e-fuel usage effectively serves climate reduction targets.
- Second, the strategic implementation of blending mandates and greenhouse gas reduction obligations both upstream (e. g. for fuel suppliers) and downstream (e. g. for vehicle manufacturers) emerge as key policy tools being used to increase alternative fuel uptake in the transport sector, as multiple governments have

80 Climate Action Tracker (2024).
81 Ministry of Mines and Energy (2023).
82 European Parliament and Council of the European Union (2023e).
83 ICCT (2023).

implemented or plan to implement similar measures (e. g. with regard to SAF). In their hydrogen strategy documents all countries observed recognize aviation and shipping as pivotal sectors for e-fuel usage, which underscores the urgent need to integrate e-fuels in these transport segments. However, to date, only the EU (and Germany) have adopted specific targets for e-fuels as part of blending mandates.

It is important to acknowledge that countries are subject to divergent local opportunities and constraints, and that domestic factors must be taken into consideration when evaluating national ambition. Not least given the disparate status of policy efforts, concerted global action and international cooperation will be essential to drive the adoption of effective policy and facilitate the ramp-up of e-fuels in transport.

Overview of policies in place of relevance to e-fuel ramp-up in the transport sector in selected jurisdictions — Table 3

	Upstream				Downstream		
Country	Framework for sustainable e-fuel production	Blending mandate for e-fuels for fuel suppliers	CO_2 emission reduction obligation for fuel suppliers	Carbon pricing	Carbon pricing	CO_2 emission reduction obligations on manufacturers [e]	CO_2 emission reduction obligations on fuel consumers
Brazil			Not sector specific [c]				
European Union	Hydrogen, E-fuels	Not sector specific [a]	Not sector specific	Road Transport [d]	Aviation, Shipping	Road Transport	Shipping
Germany	Hydrogen, E-fuels	Aviation	Not sector specific	Road Transport	Aviation, Shipping	Road Transport	
India	Hydrogen					Cars & light duty vehicles	
Japan							
South Africa				Not sector specific		Cars & light duty vehicles	
United Kingdom	Hydrogen, E-fuels	Not sector specific [b]			Aviation	Road Transport	
United States						Road Transport	

Hydrogen · E-fuels · Aviation · Shipping · Road Transport · Cars & light duty vehicles · Not sector specific

The term "upstream" in the upper line of the table refers to measures that are targeted at fuel producers for certain transport segments. The term "downstream" refers to measures targeted at energy consumers within the transport sector. The list refers only to binding law at the federal level already in force by the writing of this paper (March 2024). Announced policies are mentioned in the text.

a The third recast of the Renewable Energy Directive (RED III) foresees a minimum share of 1% RFNBO in transport (road, rail, aviation and maritime) by 2030. Sub-targets apply to aviation and maritime shipping (RefuelEU Aviation and FuelEU Maritime)

b The Renewable Transport Fuel Obligation (RTFO) includes an obligation to provide "development fuels", which, in addition to advanced biofuels, includes e-fuels (or RFNBO).

c The RenovaBio mandates an emissions reduction target for fuel suppliers which must be met through the purchase of CBIO Decarbonization Credits. Biofuel producers obtain credits for their production and sell them to fuel distributors to allow the latter to meet their targets. This aims to increase the share of biofuels in the energy matrix.

d The revised version of the EU Emissions Trading System directive, which entered into force on 16 May 2023, foresees the introduction of a separate emission trading system for road transport by 2027.

e This refers to CO_2 reduction standards at the tailpipe and not fuel efficiency standards. While for India, the measure technically refers to fuel efficiency standards, this is included as a policy measure as it specifically includes CO_2 reduction targets.

Agora Verkehrswende (2024) | Source: Government documents of the countries listed. Information current to March 2024.

7 | Availability: Significant production volumes are a long way off

E-fuel production levels in the coming years are difficult to forecast. At present, just a few plants produce e-fuels, and the number of new facilities under construction is very low. While various projects with large production capacities have been announced, most of these projects are at an early stage (e. g. general feasibility study; basic engineering; final investment decision made). Nevertheless, various regulatory measures are in place to ensure a market ramp-up of e-fuels, especially on the demand side, in order to achieve climate protection goals. Specifically, as discussed in the prior section, the EU has adopted quota obligations for the use of e-fuels in air and sea transport. Furthermore, numerous countries have enacted CO_2 reduction obligations for fuel suppliers and manufacturers, as well as market-based measures such as carbon pricing systems. Last but not least, various jurisdictions have targeted incentives to support the development of the e-fuel market (such as the tax breaks and subsidies provided under the IRA).

Despite the attendant uncertainties, e-fuel production levels up to 2030 can be roughly estimated based on current project announcements and other public data. Some three to four years are required for the design, permitting, and construction of an e-fuel plant.[84] Accordingly, only few projects that foresee completion after 2030 have been announced to date.

In the following, we draw a distinction between e-fuel production for aviation and for shipping. Fischer–Tropsch plants, for example, are often designed for the production of e-SAF, and thus have a clear focus on fuel production for aviation. Methanol, by contrast, is a basic chemical required by industry worldwide, and can also be used as a fuel in shipping, or refined into e-gasoline or e-SAF. E-methanol thus provides a means of defossilizing the chemicals industry, while also competing directly with the transport sector in terms of use. While some e-methanol projects are specifically focused on fuel production, this is not always clearly communicated. Therefore, it cannot be assumed that all of the e-methanol produced in the future will be available to the transport sector. This is even more true with regards to ammonia. Despite beeing seen as alternative marine fuel, it is also discussed as a carbon-free energy carrier in the energy sector and is a base chemical for fertilizer production. Thus, nearly all announced e-ammonia projects focus on the energy sector or fertilizer production. In addition, apart from a few demonstration projects, there are no commercially available marine engines that can directly run on ammonia. Due to the challenging properties of ammonia – including in particular its toxicity to humans and aquatic organisms – it is not clear when (or even if) it will be used as a marine fuel.[85]

7.1 E-SAF for aviation

Nearly all Fischer–Tropsch plants (whether announced or in operation) are geared to the production of sustainable aviation fuel and thus to maximize e-kerosene yield. E-naphtha (raw gasoline) and e-diesel are still produced as by-products. If further processing takes place directly in the e-fuel plant, the e-kerosene content can be between 50% and 70% – and is expected to rise to 80% in future with improvements to process design, operating conditions and catalysts.[86]

While no significant production capacities for e-SAF exist at present, large-scale industrial plants are in various stages of planning. To date, only three smaller demonstration plants have been built: In Werlte, Germany, Atmosfair operates a plant that primarily produces e-kerosene for further co-processing to jet fuel, and in Hamburg, Germany, P2X Europe operates a plant that primarily produces e-diesel and e-waxes for the chemicals industry. These plants each have a production capacity of around 350 tonnes per year. Lastly, at the beginning of 2024 an e-SAF plant built and operated by Infinium went into operation in Texas. The first industrial plants are scheduled to come on line between 2025 and 2027 and are being developed mainly in Europe (see figure 8).

However, due primarily to uncertainties surrounding EU regulatory provisions, including the sustainability criteria for green hydrogen contained in RED II (Delegated Acts on Articles 27 and 28), final investment decisions for these plants are still largely pending.[87] The first sig-

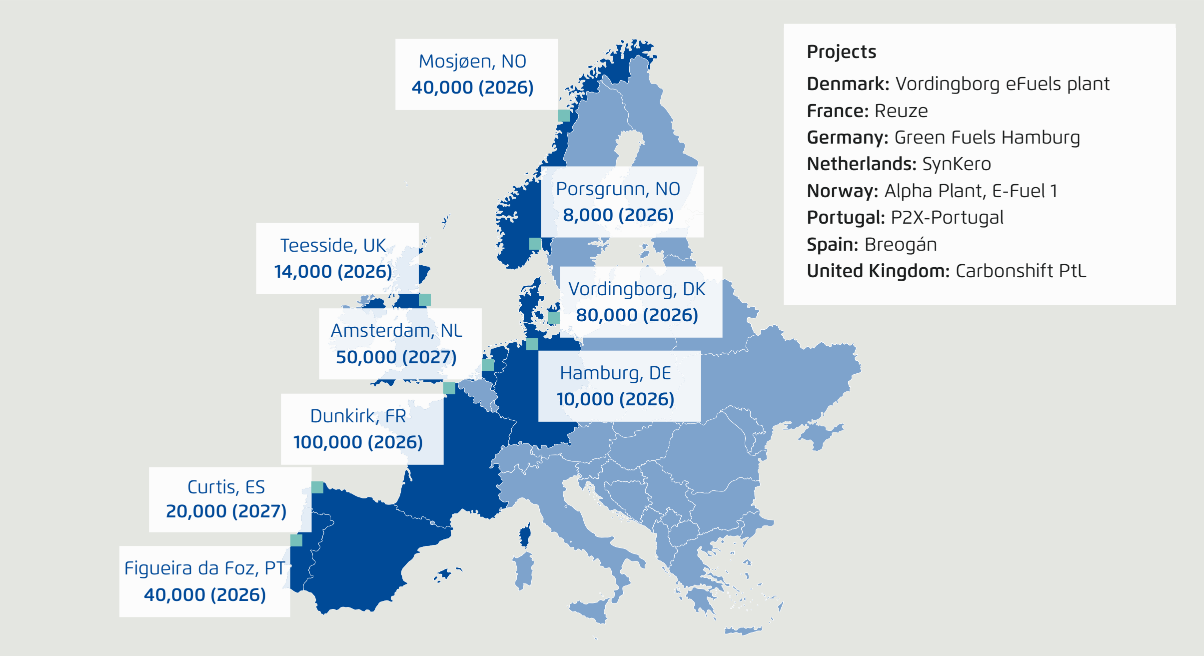
84 This may even take longer for first of its kind projects, especially regarding preceding engineering and approval processes.

85 European Maritime Safety Agency (2023).

86 Schär (2022).

87 T&E (2024); Ueckerdt, Odenweller (2023).

Overview of industrial e-SAF projects with planned start-up by 2027 — Figure 8



Agora Verkehrswende (2024) | Note: Total planned capacity in t/a based on public announcements as of March 2024; the year refers to announced commissioning or expansion. References in appendix.

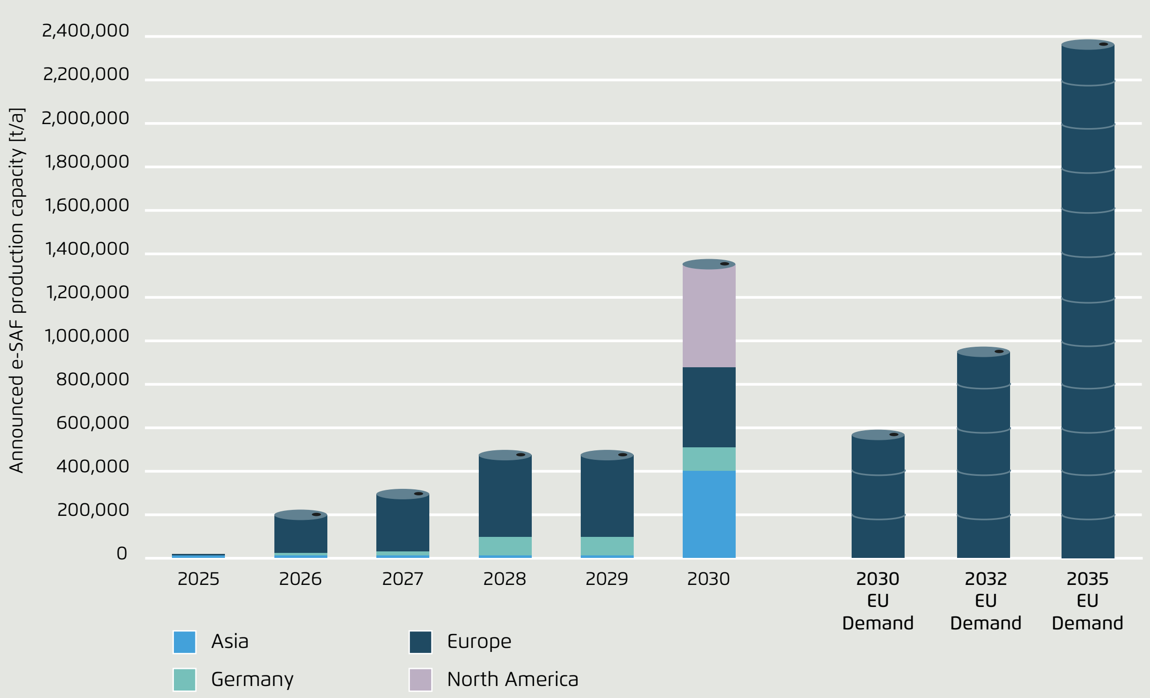
nificant quantities of e-SAF could be produced as early as 2026 if the announced plants are realized on schedule (see figure 9). Cumulative global production capacity would then amount to about 200,000 tonnes per year. In the following years, further plants with an additional production capacity of roughly 270,000 tonnes per year could in all likelihood come on line, followed by further large plants that are scheduled to go into operation in 2030. This could lead to a maximum expected e-SAF production capacity of around 1,360,000 tonnes per year. Depending on the final process layout and associated product spectrum, additional amounts of naphtha and diesel may be produced, which could be used as feedstock in the chemicals industry or as a transport fuel (e.g. in shipping). However, since hardly any of these projects are currently under construction, commissioning prior to 2030 to contribute to the EU quota obligations is unlikely.

The Europe-wide RFNBO sub-quota implemented within the ReFuelEU Aviation regulation will by itself create demand that would consume most of the foreseeable global production. As early as 2030, fulfilling the EU obligation will generate demand for some 570,000 tonnes of e-SAF, almost half of the announced worldwide production capacity. This demand will increase to 950,000 tonnes in 2032 and up to 2.4 million tonnes in 2035. For Europe alone, this would require significantly larger production capacities than currently planned. By comparison, EU jet fuel consumption represents only about 14% of global consumption.[88] Therefore, an even more ambitious market ramp-up for e-SAF is necessary. These back-of-the-envelope calculation shows that ambitious quotas have not been sufficient to trigger the production ramp-up that is necessary. Accordingly, there is a clear need for supplemental supply-side measures.

Meeting future quota-based e-SAF demand needs will require not just the construction of the synthesis plants but also an ample supply of renewable electricity,

88 Jet fuel consumption in 2019 (pre-pandemic levels) – EU: 47.39 million tonnes, worldwide: 331.56 tonnes (U.S. Energy Information Administration, 2023).

Anticipated global e-SAF production capacity up to 2030 and ReFuelEU Aviation demand — Figure 9



Agora Verkehrswende (2024) | Note: Authors' projection based on public announcements, data in appendix; where no kerosene production figures were available, a 60% product split was assumed for Fischer-Tropsch projects.

sustainable sources of carbon, and electrolyzers for hydrogen production. Since renewable electricity will be a scarce resource over the coming decades as we move to decarbonize all sectors of our economy, the electricity needed for e-fuel production should come from additionally installed renewables capacity that is expressly built to cover the power needs of e-fuel production.

In concrete terms, this means that if the volumes required to meet the ReFuelEU Aviation subquota were to be produced in the EU, additional electrolysis capacities of 2.5 to 5.1 gigawatts would be needed (see figure 10). Furthermore, fulfilling the 2035 quota would necessitate 10.5 to 21.1 gigawatts.[89] By comparison, global installed electrolysis capacity stood at approximately 0.7 gigawatts at the end of 2022 and was anticipated to have tripled to 2 gigawatts by the end of 2023.[90] Although a rapid ramp-up of electrolysis capacity is expected, announced projects primarily aim to decarbonize industry (e. g. steel andchemicals, including fertilizers). The EU's hydrogen strategy, which aims to install 40 GW electrolyzer capacity by 2030, is also focused on these areas of application.[91]

A total of roughly 21 terawatt hours of renewable electricity would be needed to produce sufficient e-SAF. If the renewable electricity required in this regard were to be generated exclusively by photovoltaic systems in Central Europe, around 16.6 gigawatts of additional capacity would have to be installed. This corresponds to roughly ten percent of current aggregate PV capacity in Europe. The installation of this capacity would require fairly significant land resources; for ground-mounted PV,

89 The range results from the assumed full load hours of the electrolysers (4,000 to 8,000 hours per year); required storage capacities were not taken into account, as these would mainly be reflected in the production costs.

90 IEA (2023b).

91 European Commission (2020).

some 543 square kilometers (200 square miles) would be needed – roughly the area of Lake Constance.

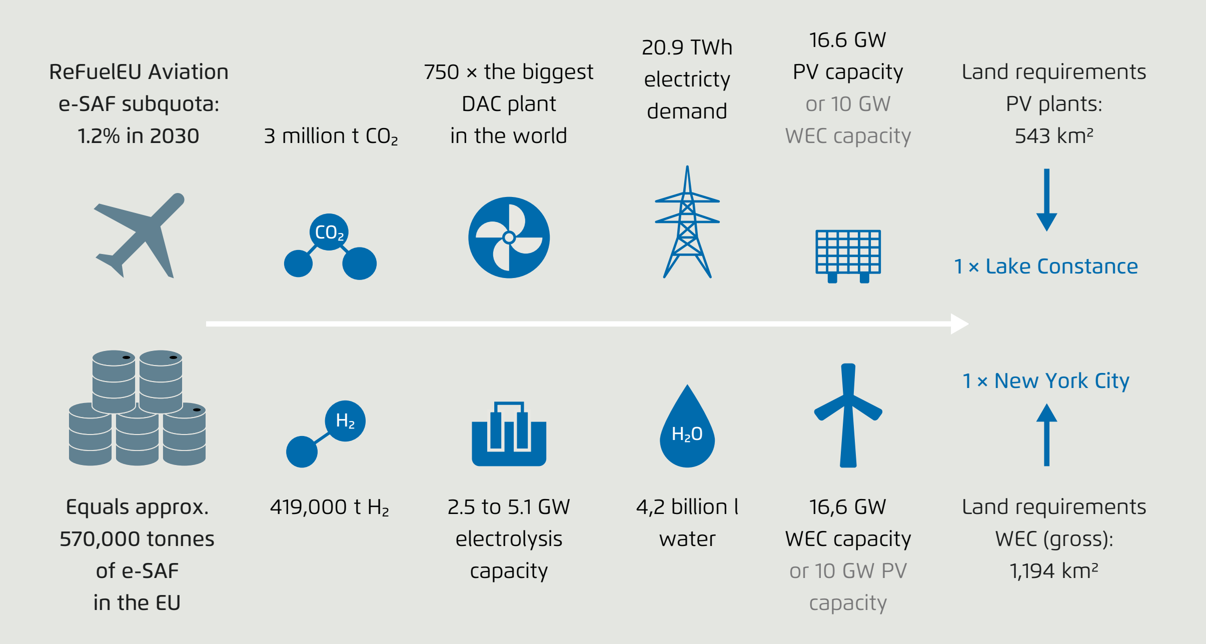
Alternatively, the required electricity could also be generated by onshore wind turbines. In this case, additional wind turbines with a capacity of around 10 gigawatts would have to be newly built. This corresponds to approximately 2% of the EU target for installed wind energy capacity in 2030. The land area required for these turbines would only amount to 12 square kilometres (if the turbines were constructed right alongside one another). However, in order to avoid wind wake effects, turbines must be spread out over a significant area. Wind turbines with a combined capacity of 10 GW would need to be distributed over some 1,200 square kilometres (460 square miles), which is roughly the area of New York City.

The additional PV or wind capacity that is required to produce a given volume of e-fuels would be correspondingly lower in "sweet spot" regions with high full load hours. Yet even if e-fuel production capacity were developed in favourable regions outside of Europe, with the goal of producing e-fuels for import to the EU, enormous renewable generation and fuel production capacities would be required.

In addition to an ample supply of renewable electricity, which, as discussed, places demand on land resources, sustainable CO_2 is required as a feedstock. To meet the aforementioned RFNBO quota in 2030 with e-SAF, about three million tonnes of CO_2 would be needed per year, which would need to be provided either from the air or from biogenic sources to realize a closed CO_2 cycle. By comparison, the largest DAC plant operating in the world can currently capture up to 4,000 tonnes per year from the air. Accordingly, some 750 such plants would be needed by 2030. Even if all plants were of the same size as the largest future facility currently under construction, more than 80 such plants would be needed.[92]

92 The currently largest plant ('Orca') is operated by Climeworks in Iceland. The next largest plant ('Mammoth') has a planned capacity of 36,000 tonnes of CO_2 per year and is currently under construction. Climeworks (2023a); Climeworks (2023b).

Estimating the energy, material and land requirements to fulfill the EU e-SAF quota obligation in case of full supply from Central Europe — Figure 10



Agora Verkehrswende (2024) | Note: Authors' projection, data in appendix; DAC = direct air capture, WEC = wind energy converter.

Fossil CO_2 from industrial point sources may be used until 2035 (and in certain cases until 2040) while still fulfilling EU RED sustainability requirements.[93] Thus, a short-term plant ramp-up could be achieved with low-cost CO_2. However, additional fossil CO_2 would continue to be emitted when the e-fuels are used. In order to ensure these plans are able to produce CO_2-neutral e-fuels in the future, readiness for conversion to direct air capture should be taken into account during the plant design phase.

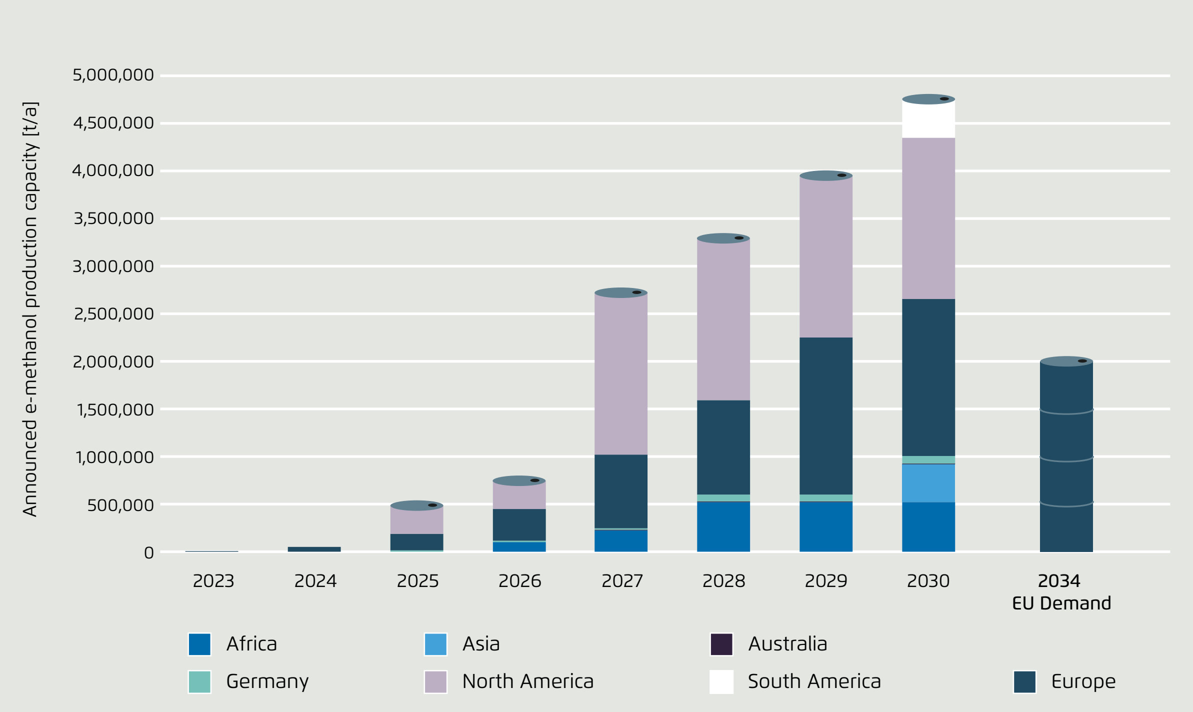
In addition to aviation fuels, the synthesis process produces e-diesel and e-naphtha (also known as crude gasoline), an important feedstock in the chemicals industry and a precursor to gasoline. Thus, in addition to the 570,000 tonnes of e-SAF needed to meet the ReFuelEU RFNBO quota, about 100,000 tonnes of e-naphtha (corresponding to about 0.5 percent of the German gasoline sales in 2019) and 275,000 tonnes of e-diesel (about 0.8 percent of German diesel sales in 2019) would be produced. These by-products, which are also CO_2-neutral, could be used to help defossilize the chemicals industry or other difficult-to-abate segments of the transport sector, such as shipping. Alternatively, these by-products could be used to reduce the climate impact of the existing car and truck fleet during its transition to electric vehicles.

7.2 E-methanol and e-ammonia for shipping

In contrast to aviation, where the possible fuel options are clearly defined by strict technical specifications, various fuel options are available for shipping. New models of ships that run on methanol are already

93 This is mandatory for the produced e-fuels to count towards the fulfillment of EU quota obligations, even if the fuels are produced outside of the EU.

Anticipated global e-methanol production capacity up to 2030 and FuelEU Maritime demand   Figure 11



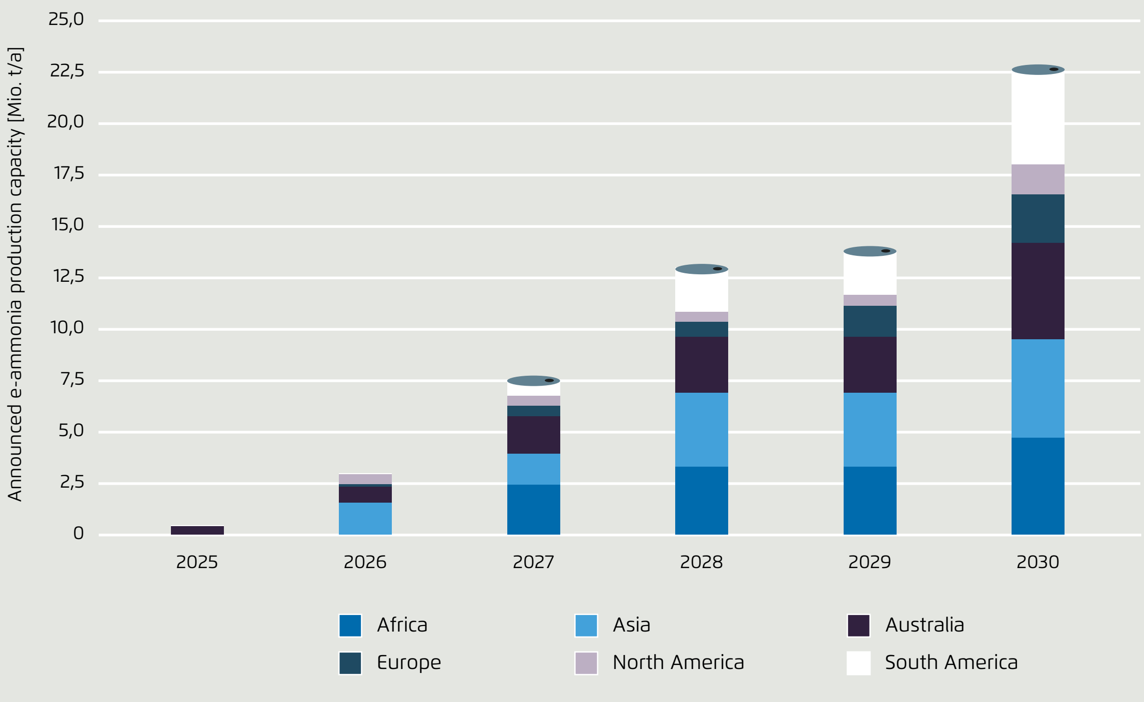
Agora Verkehrswende (2024) | Note: Authors' projection based on public announcements, data in appendix; EU demand corresponding to FuelEU Maritime quota of 2% in 2034.

commercially available, and e-ammonia is also frequently seen as a promising option for decarbonizing global shipping. Compared to e-SAF, considerably larger production capacities have already been announced for e-methanol. This is partly attributable to easier processmanagement and the wide range of applications for methanol. Under current market conditions, methanol can be used flexibly as a raw material in the chemicals industry; as a fuel additive or substitute (e. g. in shipping); or can be further processed into drop-in fuels such as e-gasoline (MtG, methanol-to-gasoline process) or e-SAF (MtJ, methanol-to-jet process). According to current announcements, several plants with varying production capacities (from 10,000 to 1 million tonnes per year) are slated to go into operation in the coming years. As figure 11 shows, these plants should collectively produce some 2.7 million tonnes of e-methanol by 2027. Just over half of this capacity will come from a single plant planned by HIF global in the USA, scheduled to produce 1.4 million tonnes by 2027.[94] While some projects already foresee partnerships for the use of e-methanol as a fuel in shipping, it is not clear what quantities will actually be available for the transport sector. Additionally, at least some of the methanol produced by these plants will be directly processed into gasoline on site, meaning that e-gasoline production volumes could see a notable increase from 2027 onwards.

Due to additional projects that have been announced for various locations globally, overall e-methanol production capacities could increase to roughly 4.7 million tonnes by 2030. By way of comparison, some 46 million tonnes of marine fuels were consumed in the EU in 2019.[95] Based on this level of demand and assuming an e-methanol blending share 2% from 2034 onward (as foreseen by the FuelEU Maritime Regulation), quota fulfillment would

94 Cision PR Newswire (2022b).
95 European Commission (2021).

Anticipated global e-ammonia production capacity up to 2030 — Figure 12



Agora Verkehrswende (2024) | Note: Authors' projection based on public announcements, data in appendix.

require 2 million tonnes of e-methanol.[96] This corresponds to nearly half of the e-methanol that will be produced in 2030 based on existing project announcements.

Compared to methanol, regular ships that run on ammonia do not yet exist, and ammonia bunkering infrastructure is also lacking. That being said, due to lower production costs and easier synthesis, siginificantly larger e-ammonia production capacities have been announced compared to e-SAF and e-methanol.

Accordingly, fairly lare scale production capacities adding up to roughly 3 million tonnes per year could be operational by 2026 (see figure 12). More than one third of this total is attributable to a project in Saudi Arabia coordinated by the NEOM Green Hydrogen Company, which is expected to produce 1.2 million tonnes e-ammonia by 2026.[97] According to official announcements, global e-ammonia production may increase more than two and a half times by 2027, reaching roughly 7.5 million tonnes per year. Due to extremely large projects with planned annual production capacities in the millions of tonnes, global e-ammonia production could even rise to more than 21 million tonnes by the end of this decade.

However, when speaking about e-fuels, none of these projects has an exclusive or even partial focus on the transport sector. Many of the announced projects are focused on producing e-ammonia as a replacement for fossil-based ammonia in fertilizer production. Others are dedicated to using e-ammonia as carbon neutral energy carrier to replace fossil fuels within the energy system, especially in countries such as South Korea and Japan. Due to the range of market applications for e-ammonia, at least some of the e-ammonia capacity that comes on line may also be used for other purposes (e. g. as a marine fuel); however, it is hard to foresee whether and to which extent this will occur.

96 Due to the higher energy content of diesel, approximately twice the amount of methanol is required to provide the same amount of energy: assumed calorific value of diesel = 43 megajoules per kilogram; assumed calorific value of methanol = 19.9 megajoules per kilogram.

97 Neom (2023).

8 | Sweet spot regions: Enormous renewables demand and land-use requirements

As is evident from the foregoing discussion, the volume of e-fuels required to defossilize air and sea transport is enormous. Indeed, covering just a small fraction of the demand in these subsectors (e. g. to meet the EU's initially low quota obligations) will necessitate tremendous increases in e-fuel production. However, domestic production at the necessary scale is unlikely to be possible in many countries, including in particular industrialized nations with significant air and sea hubs that are already reliant on energy imports. Accordingly, these nations will need to import e-fuels from "sweet spot" regions that have excellent meterological conditions for renewables as well as plentiful fresh water resources.

However, large-scale e-fuel development will present numerous challenges, even in sweet spot regions. In addition to placing stress on water resources, e-fuel production will require large-scale renewables expansion, which will bring enormous land-use requirements. Ensuring access to sufficient volumes of sustainable CO_2 is yet another hurdle to e-fuel development. Notably, these challenges are rarely addressed in discussions related to transport decarbonization, particularly when it comes to e-fuels in road transport. Given the hopes that are often attached to e-fuels as solution for enabling continued reliance on ICE vehicles, the following question naturally arises: What would it mean for sweet spot regions if e-fuel production was sufficiently expanded to fully decarbonize road transport in the G20?

The G20 nations consumed some 1.6 billion tonnes of petrol and diesel in 2019.[98] Global fuel consumption significantly dropped due to the Covid pandemic, but has since returned to pre-pandemic levels. Accordingly, the 2019 figures are roughly equivalent to current consumption. While fuel demand is expected to decline significantly due to various factors – including increasing shares of battery electric vehicles; the broader shift to more sustainable forms of transport ("modal shift"); and demand reduction measures – the following estimations are based on the assumption of stable fuel demand levels looking forward. In our scenario estimations, the annual electricity generation required for e-fuel production at a scale sufficient to replace petrol and diesel in road transport would be more than 32 petawatt hours.[99] This is more than total global electricity production today (which stood at 28.8 petawatt hours in 2022).[100] If this electricity were to be produced using PV systems installed in very favorable locations in the southern hemisphere, some 11.9 terrawatts of nominal power capacity would have to be newly developed. This is roughly ten times the PV capacity currently installed worldwide (which stood at roughly 1,177 gigawatts in 2022).[101] The land area required for these PV systems would be equivalent to some 326,800 square kilometres (126,000 square miles), which is more than the total area of Côte d'Ivoire.

The required overall capacity would be lower if onshore wind turbines were used, due to their higher full-load hours compared to PV. However, some 6,285 gigawatts of onshore capacity would nevertheless be required, which is six times currently global capacity (which stood at 842 gigawatts in 2022).[102] The area required for wind turbines is significantly larger than that for photovoltaic systems due to the required minimum distance between single turbines. Accordingly, some 748,240 square kilometers (289,000 square miles) would be required for the installation of this onshore wind capacity. This is roughly the combined area of the Atacama Desert in Chile (105,000 square kilometeres), the Great Victorian Desert in Australia (420,000 square kilometers), and the Eastern Desert between the Nile River and the Red Sea (including parts of Egypt, Eritrea, Sudan, Ethiopia; 220,000 square kilometers). However, the unused space between turbines can be dedicated to other purposes, which is why the net area requirement – i. e. the area required solely for turbines and access roads – is significantly lower, amounting to 7,480 square kilometers (2,888 square miles).

It is highly unlikely that the enormous production capacities required to defossilize G20 road transport would be concentrated in one region of the world.

98 Eurostat (2024), IEA (2023a). Data includes the entire fuel consumption of the European Union. The African Union was excluded since it joined the G20 in 2023 and our data are from 2019. International aviation and maritime bunker fuels are included.

99 The electricity demand calculated here includes hydrogen production, the DAC and e-fuel synthesis. The boundary conditions assumed for calculating the area and energy requirements can be viewed in the data appendix.

100 IEA (2023c).

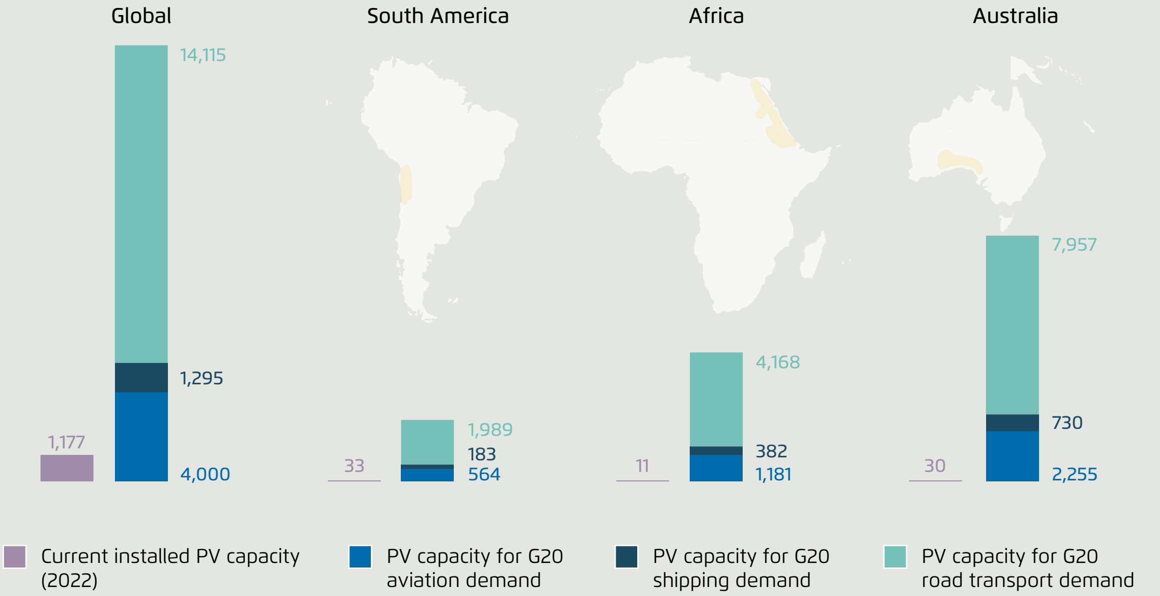
101 Statista (2024a).

102 Statista (2024b).

Required PV capacity to meet G20 e-fuel demand

Figure 13

In GW, compared to current PV capacity, globally and split up among continents with typical sweet spot regions (indicated here by selected deserts), share in required capacity proportionate to share in global land area



Agora Verkehrswende (2024) | Note: Authors' projection, data in appendix. Source: Installed PV capacity from IRENA (2023).

Nevertheless, within the southern hemisphere, there are numerous desert regions that offer highly attractive conditions for renewables production, not least because they are sparsely populated. Across Africa, Australia and South America, various deserts, including the Eastern Desert, Great Victoria Desert and Atacama Desert, have the potential to produce vast quantities of renewable electricity. Theoretically, overall G20 fuel demand could be met with renewables capacity in these three regions. Figure 13 shows the resulting PV capacity that would need to be additionally installed in these regions in relation to their land area as well as, each region's currently installed capacity. As the figure makes evident, the roughly 5.3 terrawatts needed cover e-fuel production for G20 aviation and shipping alone exceeds current capacities by many multiples. While globally installed PV capacity has significantly increased over the last decade in a trend that is most likely continue, the additional PV capacity that would be needed to replace diesel and gasoline in the transport sector would appear to be wholly out of reach.

These estimates show that e-fuels are not a realistic option for completely replacing petrol and diesel consumption in the G20, even given a focus on importation from sweet spot regions. Decarbonizing aviation and shipping alone will demand enormous quantities of renewable power. Reliance on e-fuels in additional segments of the transport sector (e.g. passenger vehicles) would place substantial additional demands on land and water resources and renewables generation in sweet spot regions.

As highly favourable locations for renewables production are relatively rare from a global perspective, they should be harnessed in a judicious and sustainable manner. As additional sectors of the economy electrify as part of the broader energy transition, demand for renewable electricity will further increase. At the same time, in many regions with favourable production conditions for e-fuels, renewable energy remains underdeveloped, and in some cases, local populations do not have access to any form of electricity.

While this section has focused exclusively on estimating electricity demand, associated hydrogen production would also require large quantities of fresh water. Particularly in sunny regions, this will require significant seawater desalinated, which would further increase power demand needs and the stress placed on natural resources. A related issue is the need to consider the rights and interests of local communities in sparsely populated areas.

An additional and no less significant challenge pertains to the supply of sustainable carbon dioxide. The actual costs of direct air capture (DAC) may be higher than anticipated in the past.[103] And while biogenic CO_2 is another suitable source for carbon neutral e-fuels, it is normally supplied in a decentralized manner – when available at all – which would in term necessitate considerable logistical expenditures. In this way, sweet spot regions for renewable electricity are far from a panacea for mastering the challenges attendant to large-scale e-fuels production. One thing is clear: addressing these challenges will require an overarching strategy that considers all major dimensions of e-fuels production, including renewable electricity supply, sustainable carbon sources and financing options.

103 Sievert et al. (2024).

9 | Conclusion: Energy efficiency must remain a top priority

E-fuels are sure to play an essential role in the coming years as a replacement for fossil fuels in aviation, maritime shipping and parts of the chemicals industry, thereby reducing the climate impact of these sectors. At the same time, these fuels will remain inefficient, expensive and only available in very limited quantities for decades to come. Accordingly, it will be imperative to produce and consume e-fuels in a targeted manner. Ultimately, any reliance on e-fuels in road transport will mean less e-fuel availability in sectors that are much more difficult to abate.

An ambitious production ramp-up is necessary to reduce costs and enable large-scale deployment. A clear focus should be placed on air and sea transport from the outset, as e-fuels are the only long-term climate protection option for abating residual energy demand in these subsectors. In this way, production facilities should align their product range to serve aviation and maritime shipping. By-products inherent to the production process can then be used to defossilize other transport modes during their transition to electromobility and those parts of the chemicals industry that continue to rely on carbon-based raw materials. In view of the small amount of currently planned production capacities and the fact that in most markets regulatory frameworks are still being deliberated, the global production volumes anticipated up to 2030 are very low, even given an ambitious ramp-up. Accordingly, the e-fuel quantities that can be produced in the coming years should not be used in road transport. From an environmental and economic policy perspective, it will only be sensible for the existing road vehicle fleet to begin relying on e-fuels insofar as sufficient quantities of e-fuels are already being produced to fully serve the needs of hard-to-abate sectors. And even under very optimistic assumptions, this will not occur before 2035.

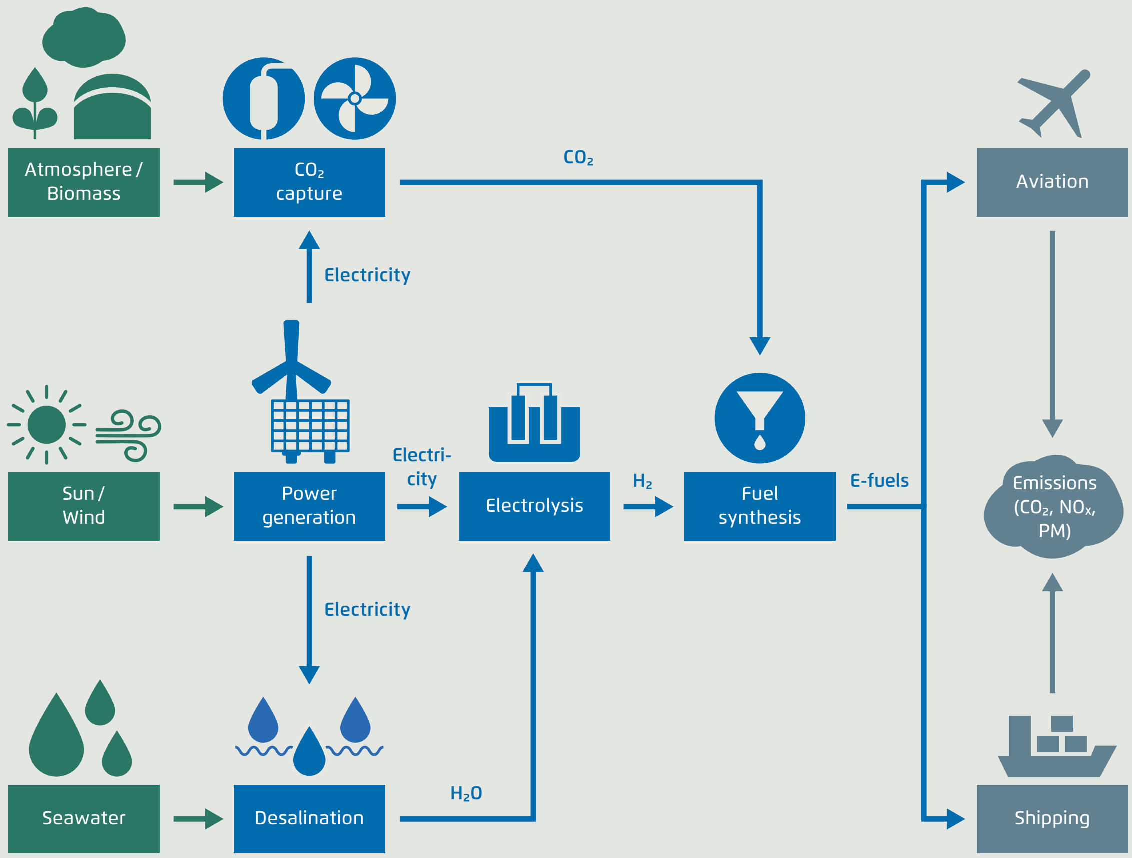
The development of production plants that are dedicated to e-fuels for road transport – as is currently being done in Chile – is incompatible with an economically sensible strategy for climate neutrality in which scarce resources are used in a benefit-maximizing manner. As indicated by current developments in the automotive industry, electric vehicles and associated charging infrastructure are poised to experience rapid growth in coming years. If e-fuels are integrated into road transport to reduce the climate impact of the existing vehicle fleet as it transitions to electric vehicles, one should harness the by-products of e-fuel production for aviation and shipping, rather than construct dedicated e-diesel or e-gasoline plants. Indeed, given ever-greater electric vehicle penetration rates, reliable long-term demand for e-fuels can only be expected in martitime shipping, aviation, and in the chemicals industry. Investments in e-fuel production plants for road transport would be unlikely to pay off and could quickly become stranded assets.

When developing e-fuel production sites around the globe, the interests of all concerned countries and regions will need to be taken into account in an equitable manner. In particular, sufficient quantities of renewable energy must be reserved for domestic consumption in countries that are to serve as e-fuel exporters. Furthermore, efforts should be made to support domestic value creation in countries that are to receive foreign direct investment in e-fuel production infrastructure. Therefore, linkages to existing economic structures must be strengthened or newly established. If a global e-fuel economy were to exploit and perpetuate existing unequal power relations – as exists, for example, in the oil trade – this could lead to undesirable developments, including geopolitical tensions on the macro level or the marginalization of vulnerable groups on the micro level. In addition to importing e-fuels, major energy consumers such as the G20 countries should therefore strive to keep their energy requirements in the transport sectors as low as possible, in part by continuing to encourage the adoption of electric vehicles and a broader "modal shift", for even the higher capacity utilization of wind power and photovoltaic systems in sweet spot regions cannot make up for the poor energy conversion efficiency of combustion engines.

Policy measures that seek to encourage the development and targeted use of e-fuels are being introduced in an increasing number of countries (e.g. blending quotas in air and sea transport, subsidy mechanisms, and sustainability criteria). These measures should be further strengthened and expanded. However, one main takeaway from our analysis is that comprehensive regulatory frameworks for the sustainable production and use of e-fuels are for the most part still at an early stage of development, and in some cases there is a sole focus on hydrogen. Overall, the likelihood of market fragmenation and carbon leakage will decline given a greater number of countries introducing comprehensive policy measures. At the same time, countries are subject to widely divergent political and economic conditions which must be taken into account when devising measures to support and regulate the market

Targeted e-fuel production for aviation and shipping

Figure 14



Agora Verkehrswende (2024)

ramp-up of e-fuels. All relevant actors – including national governments, companies and international organizations – should thus focus on encouraging the rapid expansion of e-SAF and marine e-fuel production while also striving to reducing production costs. In this connection, targeted R&D measures should be undertaken to further optimize e-fuel production processes and make sustainable sources of CO_2 available, particularly through direct air capture.

Realizing a climate neutral transport sector in line with the targets of the Paris Agreement is an enormous challenge, especially in hard to abate sectors such as shipping and aviation. While e-fuels will play an important role in defossilizing these subsectors, it will also be important to promote reduced energy demand, such that e-fuels are only needed to cover residual energy needs. In addition to technology-based efficiency improvements, important demand-reduction measures include encouraging a modal shift and reliance on direct electrification or hydrogen whenever possible. Nevertheless, given the enormous demand for e-fuels that will result as part of the shift to climate neutrality, a sole focus on developing production capacities in sweet spot regions will not be sufficient. Indeed, a new overarching strategy for the supply of carbon-neutral e-fuels is necessary, one that addresses all major facets of their production, including renewable energy supply, sustainable carbon inputs, and associated financing needs, yet without losing sight of the imperative to support inclusive economic development and a just transition.

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Annex

List of announced projects for e-fuels production via the Fischer-Tropsch route (not exhaustive) — Table 4a

Project	Involved parties[a]	Announced capacity (t/a)[b]	Status[c]	Sources
–	Channel Infrastructure, Fortescue Future Industries	48,000 (n.s.)	Planned	Fortescue (2023a)
–	Ineratec	3,500 (2024)	Under construction	Ineratec (2022)
	Ineratec, Zenith Terminals	35,000 (2027)	Planned	Ineratec (2023)
–	Infinium, Mo Industrial Park	Not specified	Planned	Infinium (2024a)
–	P2X-Europe, The Navigator Company	40,000 (2026)	Planned	The Navigator Company (2022)
Alpha Plant	Climeworks, Lux-Airport, Norsk E-Fuel, Paul Worth SMS Group, Sunfire, Valinor	40,000 (2026)	Planned	Norsk E-Fuel (2024)
Bilbao Decar-bonization Hub	Enagas, Repsol, EVE	2,100 (2024)	Planned	argusmedia.com (2022)
Brazoria electrofuels	Denbury, Infinium	Not specified	Planned	Infinium (2022)
Breogán Project	Greenalia, P2X Europe	20,000 (2027)	Planned	P2X Europe (2024)
Carbonshift PtL	Willis Sustainable Fuels	14,000 (2026)	Planned	WLFC (2023)
Concrete Chemicals	Cemex, Enertrag, Sasol	7,600[d] (2027) 30,500[d] (2030)	Planned	Concrete Chemicals (2023)
e-Alto	Clariant Catalysts, Technip Energies, Velocys	Not specified	Planned	Velocys (2022)
E-Fuel 1	Nordic Electrofuel, P2X-Europe	8,000 (2026)	Planned	P2X Europe (2023)
Fairfuel	Atmosfair	350 (2022)	In operation	Atmosfair (2023)
Green Fuels Hamburg	Airbus, Uniper, Siemens Energy	10,000[d] (2026)	Planned	Green Fuels Hamburg (2023)
HyShiFT	Enertrag, Hydregen, Linde, Sasol	Not specified	Planned	HyShift (2023)
IðunnH2	IðunnH2	45,000[d] (2028)	Planned	IðunnH2 (2024)
KerEAUzen	Air France-KLM, Engie	70,000 (2028)	Planned	Engie (2023a)
Moses Lake E-Jet Plant	Twelve	121[d] (2024)	Under construction	FastCompany (2023)
NetZeroLEJ	Airbus, DHL, HH2E, Sasol	200,000 (n.s.)	Planned	HH2E (2023)
NextGate	H&R Group, Mabanaft, P2X Europe	350 (2022)	In operation	P2X Europe (2022)
Pathfinder	Amazon, Howard Energy Partners, Infinium, NextEra Energy	Not specified	In operation	Infinium (2024b)
Plant Zero.1	Global E&C, Zero	Not specified	Under construction	Zero (2023)
Reuze	Engie, Infinium	100,000 (2026)	Planned	Reuze (2023)

List of announced projects for e-fuels production via the Fischer-Tropsch route (not exhaustive)

Table 4b

Project	Involved parties[a]	Announced capacity (t/a)[b]	Status[c]	Sources
SynKero	City of Amsterdam, KLM, Port of Amsterdam, Royal Schiphol Group, SkyNRG, SynKero	50,000[d] (n.s.)	Planned	Synkero (2023)
Vordingborg eFuels plant	Arcadia eFuels, Sasol, Topsoe	80,000 (2026)	Planned	Arcadia eFuels (2022)
Zenid One	Climeworks, SkyNRG, Uniper, Zenid	Not specified	Planned	Zenid (2023)

a In alphabetical order; listed companies were named in public communications in connection with the projects, this does not imply any financial involvement in the project.
b Total planned capacity in each case as announced; year refers to announced commissioning or expansion.
c According to public announcements as of March 2024; "Planned" includes all project phases from feasibility studies to concrete engineering.
d Data refers to e-kerosene only.

Agora Verkehrswende (2024)

List of announced projects for e-fuels production via the methanol route (not exhaustive) — Table 5a

Project	Involved parties[a]	Announced capacity (t/a)[b]	Status[c]	Sources
–	AP Moller Holding, C2X, Maersk	300,000 (2028)	Planned	Hydrogen Insight (2023a)
–	AP Moller Holding, C2X, Maersk	1,000,000 (n.s.)	Planned	C2X (2023)
–	eFuel Steyerberg GmbH	52,500[d] (2026)	Planned	Spiegel (2023)
–	ReNew E-fuels Private Limited	500,000 (n.s.)	Planned	Hydrogen Insight (2023b)
–	ReNew E-fuels Private Limited	300,000 (n.s.)	Planned	Hydrogen Insight (2023b)
–	State Power Investment Corp	10,000[e] (2025) 400,000 (2030) 400,000[e] (2030)	Planned	Hydrogen Insight (2023c)
Aabenraa / Kassø	European Energy, Mitsu	42,000 (2024)	Under construction	European Energy (2023)
Antofagasta Mining Energy Renewable (AMER)	Air Liquide	60,000 (2025)	Planned	Enlit (2022)
eM-Rhône	Elyse Energy, GIE Osiris	150,000 (2028)	Planned	Elyse Energy (2023)
Finfjord e-methanol plant	Carbon Recycling International, Finnfjord, Statkraftl	100,000 (n.s.)	Planned	Carbon Recycling International (2023a)
FlagshipONE	Liquid Wind AB, Orsted	50,000 (2025)	Under construction	Ørsted (2023a)
FlagshipTWO	Liquid Wind AB, Sundsvall Energi	100,000 (2026)	Planned	Liquid Wind (2023)
FlagshipTHREE	Liquid Wind AB, Umeå Energi	100,000 (2027)	Planned	Liquid Wind (2023)
George Olah	Carbon Recycling International	4,000 (2012)	In operation	Carbon Recycling International (2023b)
Green Fuels for Denmark Phase 2a/2b	Everfuel, Haldor Topsøe, Nel, Orsted	50,000 (2025) 100,000 (2027)	Planned	Ørsted (2022)
Green Meiga	Clientes, Iberdrola	100,000 (2027)	Planned	European Commission (2023b)
Green UMI	Foresa, Iberdrola	2,900 (2025)	Planned	Iberdrola (2022)
Haru Oni	Empresas Gasco, ENAP, enel, ExxonMobil, HIF, Porsche, Siemens Energy	350 (2022) 100[d] (2022)	In operation	HIF (2022)
HIF Cabo Negro eFuels facility	HIF	173,000 (n.s.) 70,000[d] (n.s.)	Planned	HIF (2023a) HIF (2024a)
HIF Matagorda eFuels facility	Bechtel Energy, Siemens Energy, Topsoe	1,400,000 (2027) 562,500[d] (2027) 475,700[e] (2030)	Planned	Cision PR Newswire (2022b) Biofuels Central (2023b
HIF Paysandu	HIF	700,000 (n.s.) 250,000[d] (n.s.)	Planned	HIF (2023b)
HIF Tasmania eFuel facility	HIF, Technip Energies	210,000 (2028) 56,250[d] (2028)	Planned	HIF (2024b)
Humansdorp	Earth and Wire, Enertrag, 24 Solutions	120,000 (2027)	Planned	Earth & Wire (2021)

List of announced projects for e-fuels production via the methanol route (not exhaustive) — Table 5b

Project	Involved parties[a]	Announced capacity (t/a)[b]	Status[c]	Sources
HyGATE Demonstrator	Mabanaft, Vast	7,500 (2027)	Planned	Mabanaft (2024)
IRIS	Motor Oil Hellas	Not specified	Planned	European Commission (2023b)
Jangada	energy4future, Hy2gen	64,000 (2028)	Planned	Hy2gen (2023a)
KeroSyn100	Raffinerie Heide, CAC	Not specified	Planned	KEROSyN100 (2023)
Madoqua Synfuels	Madoqua Ventures	Not specified	Planned	Madoqua Ventures (2023)
Masdar Hassan Allam Utilities E-Methanol	Hassan Allam Utilities, Masdar	100,000 (2026)	Planned	Reuters (2022)
Nascar	Cetaer, Técnicas Reunidas	37,000 (2026)	Planned	Offshore Energy (2023a)
Nautilus	EWE Netz, Hy2gen, revis bioenergy,	60,000 (2027)	Planned	Hy2gen (2023b)
Pacífico Mexinol	International Finance Corporation, Transition Industries	400,000 (2030)	Planned	Mexico Business News (2023)
Power-to-Methanol Lappeenranta project	Aker Carbon Capture, St1, SWECO	25,000 (2026)	Planned	Sweco (2023)
Power-to-X project in the Gulf Coast	Maersk, Ørsted	300,000 (2025)	Planned	Ørsted (2023b)
RHYME Bavaria	Wacker	15,000 (2025)	Suspended	Wacker (2024)
SolWinHy	Green Enesys, Viridi RE, SolWinHy Cádiz	29,000 (n.s.)	Planned	Businesswire (2023)
Tambor Green Hydrogen Hub	Enertrag, SEG Ingeniería	Not specified	Planned	Fuel Cell Works (2022)
Triskelion	Forestal del Atlántico	40,000 (n.s.)	Planned	European Commission (2023b)
Vanadis Fuels Project	Aliceco Energy, TEH2, Total Eren	400,000 (2029)	Planned	Renewables Now (2023)

a In alphabetical order; listed companies were named in public communications in connection with the projects, this does not imply any financial involvement in the project.
b Total planned capacity in each case as announced; year refers to announced commissioning or expansion.
c According to public announcements as of March 2024; "Planned" includes all project phases from feasibility studies to concrete engineering.
d Share of e-gasoline.
e Share of e-kerosene.

Agora Verkehrswende (2024)

List of announced projects for e-ammonia production (not exhaustive) — Table 6a

Project	Involved parties[a]	Announced capacity (t/a)[b]	Status[c]	Sources
–	TransHydrogen Alliance	1,000,000 (2030)	Planned	TransHydrogen Alliance (2024)
–	AES Brasil Energia	800,000 (n.s.)	Planned	Renewables Now (2022)
–	Allied Green Ammonia, Técnicas Reunidas	912,500 (2028)	Planned	Técnicas Reunidas (2023)
–	ACWA Power Electricity Generating Authority of Thailand, PTT	1,200,000 (n.s.)	Planned	ACWA Power (2022)
–	OCP	1,000,000 (2027) 3,000,000 (2032)	Planned	OCP (2024)
AMAN	CWP Global	Not specified	Planned	CWP Global (2024a)
AMUN	CWP Global	5,800,000 (n.s.)	Planned	CWP Global (2024b)
AREH (Asian Renewable Energy Hub)	BP, CWP Global, Macquarie Capital and Macquarie's Green Investment Group, InterContinental Energy	9,000,000 (n.s.)	Planned	BP (2022)
Bear Head Energy	Bear Head Energy	2,000,000 (n.s.)	Planned	Government of Nova Scotia (2023)
Cape Hardy Project	Amp Energy, Iron Road	5,000,000 (n.s.)	Planned	Amp Energy (2023)
Coega	Hive Energy, ITOCHU	900,000 (2028)	Planned	Offshore Energy (2023b)
Courant	Hy2gen	237,000 (2028)	Planned	Hy2gen (2024)
Eyre Peninsula Gateway	H2U	800,000 (n.s.)	Planned	H2U (2024)
Gente Grande	HIVE Energy, Transitional Energy Group	1,300,000 (n.s.)	Planned	Hive Energy (2023a)
GERI (Geraldton Export-Scale Renewable Investment)	BP	1,000,000 (n.s.)	Planned	BP (2024)
Gibson Island Green Hydrogen and Ammonia Project	Fortescue Energy, Incitec Pivot Limited	400,000 (2026)	Planned	Fortescue (2023b)
Green Energy Oman	EnerTech, InterContinental Energy, OQ, Shell	10,000,000 (n.s.)	Planned	GEO (2024)
Green Pegasus	Glenfarne Energy Transition, Samsung Engineering	459,000 (n.s.)	Planned	Glenfarne Energy Transition (2023)
H2biscus	Lotte Chemical, Posco, Samsung Engineering, Sarawak Economic Development Corporation Energy (SEDC Energy)	850,000 (2028)	Planned	Offshore Energy (2023c)
H2-Hub Gladstone	H2U, Vopak	1,7000,000 (n.s.)	Planned	Vopac (2023)

List of announced projects for e-ammonia production (not exhaustive) — Table 6b

Project	Involved parties[a]	Announced capacity (t/a)[b]	Status[c]	Sources
H2Perth	Woodside Energy	3,250,000 (n.s.)	Planned	Western Australian Environmental Protection Agency (2023)
H2Tas	IHI Corporation, Marubeni Corporation, Woodside Energy	800,000 (n.s.)	Planned	Environmental Protection Agency Tasmania (2022)
H2V Cabeza del Mar	Ghenergy, FreePower	Not specified	Planned	Ghenergy (2024)
Han-Ho H2 Hub	Ark Energy, Hanwha Impact, Korea Zinc, SK Gas	1,000,000 (n.s.)	Planned	Ark Energy (2023)
Hemnes Project	Fortescue Energy	225,00 (2028)	Planned	Fortescue (2024a)
HIVE H2 Albamed	HIVE Energy	200,000 (2027)	Planned	Hive Energy (2023b)
HNH Green Ammonia	HNH Energy	1,400,000 (2028)	Planned	Oppenhoff (2024)
Holmanest Project	Fortescue Energy, Técnicas Reunidas	225,00 (2027)	Planned	Fortescue (2024b)
Horizonte de Verano	Veran Energy	420,000 (2027) 1,650,000 (2032)	Planned	Energy Global (2024)
HØST PtX Esbjerg	Copenhagen Infrastructure Partners (CIP)	600,000 (2029)	Planned	CIP (2024)
Hydrogen City Green Hydrogen Production Hub	ABB, Green Hydrogen International (GHI)	1,000,000 (2030)	Planned	ABB (2024)
Hydrogen / Ammonia Project	Sun Brilliance Group	400,000 (2025) 800,000 (n.s.)	Planned	Sun Brilliance Group (2024)
HyEnergy	Province Ressources	3,350,000 (n.s.)	Planned	CSIRO (2024)
HyEX	Enaex, Engie	18,000 (2025) 700,000 (2030)	Planned	Enaex (2024)
HyNQ – North Queensland Clean Energy Project	CS energy, Energy Estate, idemitsu	Not specified	Planned	HyNQ (2024)
Hyphen	Enertrag, Hyphen Hydrogen Energy, Nicholas Holdings	1,000,000 (2027) 2,000,000 (2030)	Planned	Hyphen (2024)
HYPORT Duqm	Deme, Hydrom, OQ	330,000 (2026) 1,000,000 (n.s.)	Planned	ZAWYA (2021)
Hyrasia One	SVEVIND Energy Group	11,000,000 (n.s.)	Planned	Hyrasia (2024)
Iverson	Copenhagen Infrastructure Partners (CIP), Iverson eFuels, Hy2gen, Trafigura	200,000 (2029)	Planned	Iverson (2024)
Kakinada Project	Greenko ZeroC, Uniper	1,000,000 (2027)	Planned	Uniper (2023)
Karnataka	ACME Group	1,200,000 (2028)	Planned	ACME (2024a)
KARYSTA	Hy2gen, PlugPower	760,000 (n.s.)	Planned	Hy2gen (2023c)

List of announced projects for e-ammonia production (not exhaustive)

Table 6c

Project	Involved parties[a]	Announced capacity (t/a)[b]	Status[c]	Sources
Korgen	Fuella	200,000 (n.s.)	Planned	Fuella (2024a)
Marengo	Hy2gen	180,000 (2028)	Planned	Hy2gen (2024b)
Midwest Green Ammonia	Korean Midland Power Co (KOMIPO), Progressive Green Solutions, Samsung C&T	1,000,000 (2027)	Planned	Government of Western Australia (2023)
Murchsion PtX	Copenhagen Infrastructure Partners (CIP), Murchison Hydrogen Renewables	2,000,000 (2030)	Planned	Murchison Green Hydrogen (2024)
Neom	ACWA Power, Air Products, NEOM Green Hydrogen Company	1,200,000 (2026)	Planned	Neom (2023)
Odisha	ACME Group	1,100,000 (n.s.)	Planned	ACME (2024b)
Oman Green Ammonia Project	Engie, FutureTech Energy Ventures Company, Korea East-West Power Co. (EWP), Korea Southern Power Co. (KOSPO), Posco, Samsung Engineering	1,200,000 (2030)	Planned	Engie (2023b)
Paracelsus	Atacama Hydrogen Hub	Not specified	Planned	Atacama Hydrogen Hub (2024)
Port of Victoria	ACME Greentech Ventures Americas, ACME Group	1,200,000 (n.s.)	Planned	Port of Victoria (2023)
Project Skipavika	EnBW, Fuella, Skipavik Næringspark	100,000 (2026)	Under construction	Fuella (2024b)
Red Sea Hydrogen Project	Amea Power	400,000 (2027) 800,000 (2030)	Planned	AMEA Power (2022)
Solatio Global	RCP Technologies, Solatio Energies	3,700,00 (n.s.)	Planned	SolatioGlobal (2024)
Southern Green Hydrogen	Meridian, Murihiku Regeneration, Woodside Energy	500,000 (n.s.)	Planned	Woodside Energy (2022)
Tamil Nadu	ACME Group	1,100,000 (n.s.)	Planned	ACME (2024c)
Tarafert-2	Tarafert	500,000 (2026)	Planned	Tarafert (2024)
The Oman Project	ACME Group	1,200,000 (n.s.)	Planned	ACME (2024d)
Vientos Magallánicos Green hydrogen/green ammonia project	RWE	475,000 (2030)	Planned	Renewables Now (2024)
Volta Project	MAE Energy	300,000 (2027) 600,000 (2030)	Planned	MAE (2024)

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Agora Verkehrswende (2024)

Assumptions for calculating the land and energy requirements for the production of e-kerosene via the Fischer-Tropsch route, e-methanol and e-gasoline via the methanol-to-gasoline route (reference year 2030 if corresponding data is available)

Table 7

Process step	Parameter	Unit	Value	Source
Fischer-Tropsch Synthesis	H2 demand	kg_H2/kg_e-kerosene	0.74	DLR; TUHH; JBV (2021)
	CO_2 demand	kg_CO_2/kg_e-kerosene	5.20	DLR; TUHH; JBV (2021)
	Electricity demand	kWh_el/kg_FT products	0.035	DECHEMA (2021)
	Naphtha co-production	kg_naphtha/kg_kerosene	0.17	DLR; TUHH; JBV (2021)
	Diesel co-production	kg_diesel/kg_kerosene	0.49	DLR; TUHH; JBV (2021)
Methanol synthesis	H2 demand	kg_H2/kg_e-methanol	0.20	Lonis et al. (2021)
	CO_2 demand	kg_CO_2/kg_e-methanol	1.42	Lonis et al. (2021)
	Electricity demand	kWh_el/kg_e-methanol	0.252	Lonis et al. (2021)
Methanol-to-Gasoline process	H2 demand	kg_H2/kg_e-gasoline	2.87	Schemme, et al. (2020)
	CO_2 demand	kg_CO_2/kg_e-gasoline	0.40	Schemme, et al. (2020)
	Electricity demand	kWh_el/kg_e-gasoline	0.214	Jones; Zhu, (2009)
Electrolysis	Electricity demand	kWh_el/kg_H2	48.3	IEA (2022)
	Water demand	kg_water/kg_H2	10.11	Kuckshinrichs et al. (2017)
DAC	Electricity demand	kWh_el/t_CO_2	225	Fasihi et. al (2019)
	Land demand	m^2/(t_CO_2 a)	0.1	Viebahn et al. (2019)
PV systems (single axis, ø Europe)	Full load hours	h/a	1260	Renewables Ninja (2022a)
	Area specific yield	MW/km^2	108	Bolinger; Bolinger (2022)
PV systems (single axis, sweet spot)	Full load hours	h/a	2,287	Renewables Ninja (2022a)
	Area specific yield	MW/km^2	43.2	Bolinger; Bolinger (2022)
Onshore WEC (ø Europe)	Full load hours	h/a	2,086	Renewables Ninja (2022b)
	Area specific yield[a]	MW/km^2	840	Bogdanov; Breyer (2016)
Onshore WEC (sweet spot)	Full load hours	h/a	5,137	Renewables Ninja (2022b)
	Area specific yield[a]	MW/km^2	840	Bogdanov; Breyer (2016)
	Area specific yield[b]	MW/km^2	8.4	Bogdanov; Breyer (2016)
Offshore WEA (German North Sea)	Full load hours	h/a	3,606	Renewables Ninja (2022b)

a Net area requirement for wind turbine, foundation and access road considered.
b Gross area requirement for wind turbine, also takes into account the distance between the turbines to avoid shading effects.

Agora Verkehrswende (2024)

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Agora Verkehrswende is a Berlin-based think tank that seeks to promote climate-friendly mobility. Non-partisan and non-profit, it works together with key stakeholders in the fields of politics, business, academia and civil society to decarbonise the transport system. To this end, the think-tank team develops evidence-based policy strategies and recommendations.

The Advancing Transport Climate Strategies (TraCS), funded by the German Federal Ministry for the Environment, Nature Conservation, Nuclear Safety and Consumer Protection's International Climate Initiative supports developing countries in assessing transport GHG emissions, in analysing emission reduction potentials and in optimising the sector's contribution to the mitigation target in countries' NDC.

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