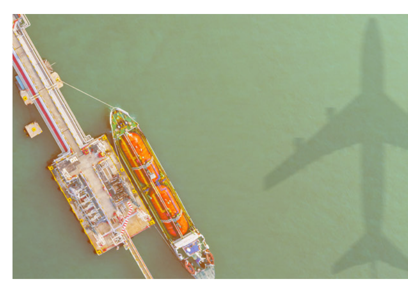
The Potential of E-fuels to Decarbonise Ships and Aircraft



Corporate Partnership Board Report

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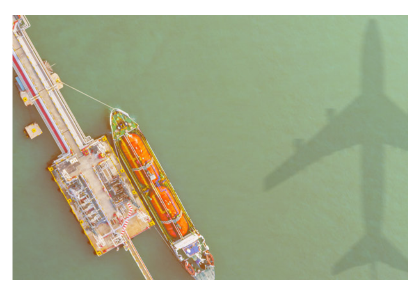

Corporate Partnership Board Report

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The International Transport Forum is an intergovernmental organisation with 64 member countries. It acts as a think tank for transport policy and organises the Annual Summit of transport ministers. ITF is the only global body that covers all transport modes. The ITF is politically autonomous and administratively integrated with the OECD.

The ITF works for transport policies that improve people's lives. Our mission is to foster a deeper understanding of the role of transport in economic growth, environmental sustainability and social inclusion and to raise the public profile of transport policy.

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The report is based on original research and builds upon discussions that took place during an expert workshop organised on 1 April 2022 with members of the ITF Corporate Partnership Board (CPB) and external guests. A workshop participant list is included at the end of this report.

At the ITF, credits go to Sharon Masterson and Maria Santos Alfageme for contributions to the organisation of the workshop and to Lauren Chester for her valuable work copyediting the draft.

The work for this report was carried out in the context of a project initiated and funded by the CPB. CPB projects are designed to enrich policy discussion with a business perspective. They are launched in areas where CPB member companies identify an emerging issue in transport policy or an innovation challenge to the transport system. Led by the ITF, work is carried out collaboratively in working groups consisting of CPB member companies, external experts and ITF staff.

The project was managed by Matteo Craglia and Till Bunsen. Sharon Masterson manages the CPB and its activities.

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Abbreviations and acronyms

CAPEX	Capital expenditure
CCU	Carbon capture and utilisation
CCS	Carbon capture and sequestration/storage
CORSIA	Carbon Offsetting and Reduction Scheme for International Aviation
DAC	Direct air capture
EU	European Union
ETS	Emissions trading system
FT	Fischer–Tropsch
GHG	Greenhouse gas
ICAO	International Civil Aviation Organisation
IMO	International Maritime Organisation
ITC	Investment tax credit
LCFS	Low-carbon fuel standards
PTC	Production tax credit
PtL	Power-to-liquid
R&D	Research and development
SAF	Sustainable aviation fuel

Executive summary

What we did

This report examines the potential of electrofuels (e-fuels) to decarbonise long-haul aviation and maritime shipping. E-fuels like hydrogen, ammonia, e-methanol or e-kerosene can be produced from renewable energy and feedstocks and are more economical to deploy in these two modes than direct electrification. The analysis evaluates the challenges and opportunities related to e-fuel production technologies and feedstock options to identify priorities for making e-fuels cheaper and maximising emissions cuts. The research also explores operational requirements for the two sectors to deploy e-fuels and how governments can assist in adopting low-carbon fuels.

What we found

Aviation and maritime shipping are among the most challenging modes of transport to decarbonise. To do so, they require low-carbon, energy-dense fuels. E-fuels are produced primarily using electricity as their source of energy and could significantly reduce emissions in these hard-to-decarbonise sectors.

Maritime transport and aviation face similar barriers to shifting away from fossil fuels. The fuel used in international journeys in both sectors is exempt from taxation. Their exposure to international competition prevents governments from implementing unilateral rules that increase costs to operators. The lack of fuel taxation means that fuel prices do not appropriately reflect the environmental damage caused by aircraft and ships burning fossil fuels. The lack of taxation is also one reason why novel, low-carbon fuels are not cost-competitive and unable enter the market without additional policy intervention.

There are two families of e-fuels. The first is carbon-based e-fuels such as e-kerosene and e-methane. They can be made compatible with existing vehicles and infrastructure with relatively minor modifications. The benefits in their downstream use contrast with challenges in their upstream production. To be considered low-carbon, carbon-based e-fuels must be produced with renewable hydrogen and carbon feedstocks sourced from the atmosphere. Carbon feedstocks will remain expensive until cheap low-carbon energy becomes widely available. Alternative carbon feedstocks can be sourced from industrial point sources but only offer a limited decarbonisation benefit. These factors mean that other forms of low-carbon liquid fuels, such as sustainable biofuels, will likely be a more cost-competitive, low-carbon solution during the transition. However, even sustainable biofuels have low market shares in the shipping and aviation industries. Sustainable aviation fuels, for instance, only account for 0.1% of kerosene use today. Sustainable biofuels also face competing demand from many other sectors.

The second family of e-fuels are non-carbon-based fuels, such as hydrogen and ammonia. These fuels are relatively easy to produce compared to carbon-based e-fuels. They are also generally cheaper to make. However, they are far more difficult to handle in use and incompatible with existing vessel and aircraft technologies. To become a viable option, non-carbon-based fuels require complex transport and refuelling infrastructure and will need technological advances with regard to fuel storage and propulsion systems. Since non-carbon-based fuels are not drop-in fuels that are compatible with existing technology and infrastructure, their adoption will likely be slow, as it depends on fuel availability and vehicle fleet turnover.

Hydrogen requires dedicated transport and highly specialised fuel tanks on-board. Ammonia avoids some of these disadvantages and could thus be more suitable as a shipping fuel. Further research is needed to understand non-CO_2 climate and environmental impacts associated with the production, distribution and use of ammonia as a maritime fuel. CO_2 emissions benefits of ammonia could be entirely offset by reactive nitrogen emissions from its combustion. Avoiding this requires highly effective after-treatment technologies and the minimisation of fugitive emissions. A rigorous monitoring system would likely be necessary. Ammonia could also cause environmental disasters in the event of a spill, making strict safety guidelines necessary.

Hydrogen aircraft must meet very stringent safety and performance requirements to become a viable option. Feasibility studies suggest they could serve short- to medium-haul flights. Aircraft manufacturers have announced plans to introduce aircraft using this technology in the 2030s. However, additional technology development is needed.

Today, the production of low-carbon e-fuels has not yet reached a commercially significant scale. The costs are high and the technology is at a relatively early stage. To replace significant amounts of fossil fuel use in shipping and aviation, production volumes will need to increase rapidly and this will happen only with targeted government support. Renewable electricity generation must increase to keep up with demand from fuel production assets. Electrolyser and carbon capture technologies must advance to lower costs and enable genuinely renewable sources of carbon feedstocks from direct air capture or biogenic sources of CO_2.

A significant level of e-fuels use will take at least a decade to achieve. Even that will depend on solid policy support to reduce the price gap with conventional fossil fuels. E-fuels will likely remain a scarce resource in the medium term, given the timescales involved in scaling up production capacity. In the meantime, governments and companies should not neglect initiatives to reduce avoidable trips, improve the energy efficiency of shipping vessels and aircraft, and shift transport demand to more energy-efficient modes, for instance from flights to high-speed rail.

What we recommend

Introduce carbon pricing for shipping and aviation

Little financial incentive currently exists for operators of aircraft and ships to use alternative fuels due to their high costs. Global or regional carbon pricing, potentially complemented by feebates or low-carbon fuel standards, can help to address this financial barrier. Carbon pricing proposals will also likely need to include mechanisms to balance their impacts on states. Revenues generated in this way can be used to advance the adoption of low-carbon fuels and energy efficiency in the aviation and maritime sectors.

Scale up the production of low-carbon e-fuel through targeted policies

Governments must ensure that investments support the initial demand growth for a range of fuels until there is greater clarity about their individual long-term feasibility and cost competitiveness. However, broad technology-neutral regulations across all alternative fuels will be insufficient to scale up e-fuels because they are currently less market-ready than other fuels. Targeted assistance and incentive programs to sustain e-fuel technologies' development must start today, even though e-fuels will likely capture significant market shares only in the longer term. Supply-side incentives should target e-fuel production and support research and development in vehicle technologies that enable their uptake. For drop-in e-fuels, blending mandates with specific targets or temporary multiplier effects in accounting mechanisms can help to drive their initial adoption. Non-drop-in e-fuels require bespoke vehicle technologies and refuelling infrastructure. Pilot projects to use these fuels on specific transport corridors can help to develop technologies while limiting early-stage infrastructure deployment.

Accelerate the deployment of electrolyser and renewable electricity generation capacity

Producing e-fuels cheaply and in large volumes hinges on expanding renewable power generation and hydrogen production capacity via electrolysis and advancing fuel production processes and technologies. Governments should prioritise deploying these technologies for decarbonising existing hydrogen demand and phasing out fossil fuels in power generation where the financial barriers to entry are lower than in creating e-fuels. Doing so can kick-start technology development, attract investment and reduce costs. These gains can also benefit decarbonisation efforts in shipping, aviation and industry.

Regulate the lifecycle emissions intensity of e-fuels, including non-CO_2 emissions

E-fuels can only be low-carbon if the energy and feedstocks used to produce them are from renewable sources. Strict regulations and standards are necessary to ensure transparency and give fuel consumers confidence that they meet sustainability criteria. These regulations should include stringent additionality criteria to ensure that the electricity used to produce e-fuels is from additional renewable energy capacity and not diverted from existing electricity demand. For carbon-based e-fuels, regulations need to account for the source of CO_2 feedstock and avoid double counting of emissions reduction credits. This is particularly the case for carbon sourced from existing heavy industries using fossil fuels such as cement plants. Regulations must cover all greenhouse gas emissions, including nitrous oxides, and all stages of the fuel supply chain.

Introduction

The Glasgow Climate Pact adopted at the 2021 UN Climate Change Conference (COP26) reaffirmed countries' ambitions to rapidly decarbonise their economies, limiting the impacts of climate change and aiming to keep 1.5°C of warming "within reach". Achieving the Climate Pact's goals will require sharp emissions reductions in all modes of the transport sector. However, the solutions used to reduce emissions will differ by vehicle mode. The maritime shipping and aviation sectors are commonly referred to as the "hard-to-abate" modes due to the high costs of emissions reduction measures and their comparatively low technological readiness. For road-based transport modes, technologies such as electrification are increasingly well-developed and offer a clear path towards emissions reductions (ITF, 2021a). Electrification could decarbonise short-distance aviation (<1 000 km) and short-sea shipping. This could account for up to 40% of containership traffic (Kersey et al., 2022). However, long-distance journeys in shipping and aviation cannot rely on direct electrification for significant emissions reductions. Both modes depend on low-carbon liquid and gaseous fuels to align with climate targets. This report investigates the barriers to and opportunities for their adoption.

The shipping and aviation sectors were each responsible for approximately 3% of global energy-related greenhouse gas (GHG) emissions in 2021 (IEA, 2022c). Both sectors depend on fossil fuels today in the form of marine fuel oil and aviation kerosene, with only negligible amounts of renewable fuels in use. The high energy density of these fossil fuels allows ships and aeroplanes to travel long distances without the need to refuel en route. Travelling long, intercontinental distances on electric aircraft or vessels is impossible because of the low energy density and high weight of existing battery technologies that offer a limited range. Low-carbon liquid and gaseous fuels with comparable energy densities to incumbent fossil fuel counterparts are the most promising options for decarbonising maritime shipping and aviation.

There are two main categories of such fuels:

1. **Biofuels:** fuels made from biomass feedstock using several production pathways (for further details, see the ITF's report on decarbonising maritime shipping [2020]). As plants grow, they convert the sun's energy into chemical energy and store it as biomass. Biofuels are the refined form of biomass that enable their chemical energy to be used in engines or turbines.
2. **E-fuels:** also known as electrofuels, power-to-X (PtX), power-to-liquid (PtL), or synthetic fuels. They are produced using an industrial process that converts electrical energy into chemical energy. E-fuels come in two categories: those with carbon building blocks (e.g. e-kerosene or e-methanol) and those without (e.g. hydrogen and ammonia).

In 2021, ships and aeroplanes consumed approximately 203 Mt and 250 Mt of fuel, respectively, equivalent to 8.7 EJ and 10.75 EJ (IEA, 2022c) (1 EJ = 10^{18} Joules). Replacing this extensive fossil fuel use with low-carbon alternatives will require several pathways, including biofuels and e-fuels. Biofuels are already widely used in the road transport sector and are a promising avenue to contribute towards decarbonising aviation and shipping. However, the volume of biomass feedstock that can be grown sustainably limits the scalability of biofuels in the midterm (ITF, 2020). E-fuels can complement biofuels and potentially face fewer long-term scalability constraints. However, they are at a lower level of technological maturity than biofuels. This means their scale-up in the transport sector is uncertain.

This report focuses on the production and use of e-fuels in the aviation and maritime sectors. It aims to explore their barriers to adoption and their opportunities for GHG emissions reductions in these two hard-to-abate sectors. The scope excludes biofuels and power-and-biomass-to-liquid (PBtL) pathways. These are other important transport decarbonisation options with distinct production technologies and scalability challenges.

What are e-fuels?

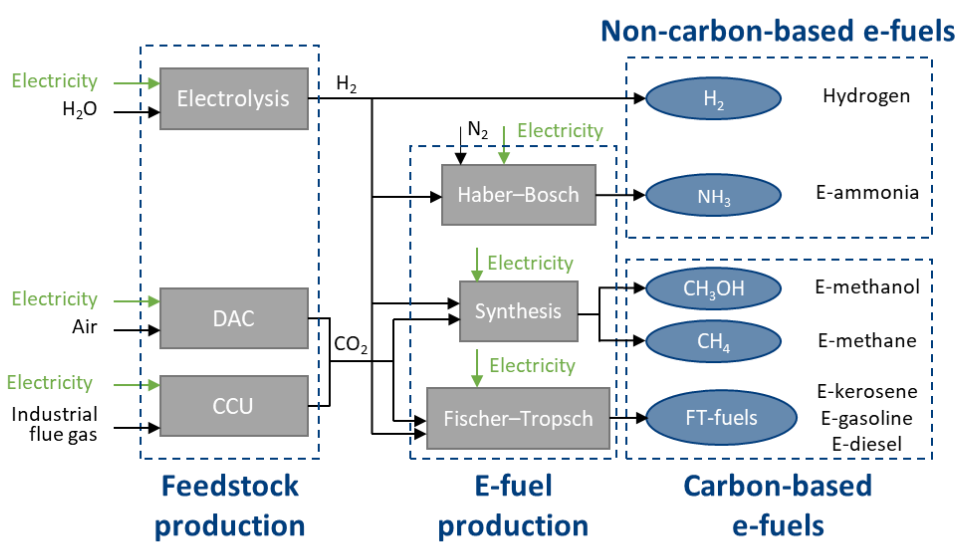
E-fuels are synthetic fuels produced using electricity as their primary source of energy. When made from renewable electricity, they can lower GHG emissions. There are several different types of e-fuels. The simplest e-fuel is hydrogen (H_2), which can be produced via water electrolysis using electricity. Hydrogen can be used as a fuel directly, for example, in an internal combustion engine or a fuel cell, or converted into several other e-fuels in subsequent processing steps.

One option is ammonia (NH_3), whose production combines hydrogen with nitrogen in a chemical process known as the Haber–Bosch process. Compared with pure hydrogen fuel, ammonia has the relative advantage of easier handling due to its liquid form and higher volumetric energy density (ITF, 2020).

Alternative e-fuels can be synthesized from hydrogen (H_2) and carbon atoms, for example, combining H_2 and carbon dioxide (CO_2) to make e-methanol. These carbon atoms can be sourced from the exhaust gases of industrial processes by carbon capture and utilisation (CCU) or by extracting CO_2 from atmospheric air in a process known as direct air capture (DAC). Various other synthetic hydrocarbons can be produced from H_2 and a carbonaceous source in industrial processes known as methane synthesis and the Fischer–Tropsch (FT) process. These can be gases (e.g. methane) or liquids (e.g. methanol, kerosene and diesel). They are similar, if not identical, to their fossil fuel equivalents, differing only in the methods used to produce them. While the FT process has been known for nearly 100 years with coal as the carbonaceous source (e.g. via coal gasification), very few production plants exist that use CO_2 as a carbon source.

E-fuels are commonly prefixed with the letter “e” (e.g. e-methanol, e-kerosene, e-diesel) to distinguish between fossil fuel hydrocarbons and carbon-based e-fuels.

Figure 1. Pathways for producing e-fuels



Notes: DAC = direct air capture; CCU = carbon capture and utilisation; FT = Fischer–Tropsch.

The feasibility of displacing existing fossil fuels in aviation and shipping varies for different e-fuels based on their chemical properties, handling requirements and production costs (see Table 1). Drop-in fuels are alternative fuels compatible with existing technology and infrastructure systems. For aviation fuels, the standardisation body American Society for Testing and Materials (ASTM) certifies the maximal blending rate of drop-in fuels for safe use in aircraft (ASTM International, 2022b).

Other fuels (i.e. non-drop-in fuels) can be used in existing technologies with some adaptations, either in the engine itself, in the fuel delivery system or both. For example, hydrogen could be used in a turbine with technical changes. However, the required fuel storage and delivery system differs and would require novel equipment like cryogenic fuel tanks.

There is no significant production of carbon-based e-fuels today. This is principally due to high production costs compared with conventional fossil alternatives and low technology readiness levels of several steps required in their production. Fuel costs usually account for 20-34% of operating expenses in the shipping industry (Mærsk Mc-Kinney Møller Center for Zero Carbon Shipping, 2022), with up to 53% for container/bulk vessels (European Commission, 2021) and around 20-30% in the aviation industry (ICAO, 2017). As e-fuels are still more expensive than their fossil counterparts, significant cost reductions and policy support are necessary for their adoption into the market.

Table 1. Feasibility of e-fuels compared to the most commonly used fossil fuels

E-fuel	Gravimetric energy density (LHV) [MJ/kg]	Density at atm and 20°C [kg/m^3]	Volumetric energy density [MJ/l]	Boiling point [°C]	Technical feasibility in shipping	Technical feasibility in aviation
Hydrogen (H_2)	120	0.08	0.0108 (at atm) 3.12 (at 350 bar) 8.5 (liquid)	-252	Potentially feasible	Potentially feasible
(E-)Ammonia (NH_3)	18.8	0.73	12.8 (liquid)	-33	Potentially feasible	Not considered feasible.
(E-)Methanol (CH_3OH)	19.9	0.79	15.6	65	Feasible	Not considered feasible.
(E-)Methane (CH_4)	50	0.67	0.0378 (at atm) 20.8 (liquid)	-163	Feasible	Not considered feasible.
E-kerosene (Jet A)	45.7	0.8	~40	>150	Not considered feasible.	Feasible
Diesel fuels (MGO, MFO, VLSFO, HFO)	~43	0.82	~41	>250	Feasible	Not considered feasible.

Note: LHV = lower heating value; MGO = marine gasoil; MFO = marine fuel oil; VLSFO = very low sulphur fuel oil; HFO = heavy fuel oil; atm = atmospheric pressure. Natural gas is mainly composed of methane.

Maritime e-fuels: Hydrogen, ammonia and e-methanol

E-diesel and e-methane are e-fuels that could be drop-in substitutes for existing maritime diesel fuels and liquefied natural gas. Their advantage is being able to use existing infrastructure and engine technologies. Other candidate e-fuels options for maritime shipping include hydrogen, ammonia and e-methanol. These fuels are not widely used today, and the suitability of their downstream use in the shipping sector is briefly discussed in this section.

Hydrogen

There is growing interest in the use of hydrogen in maritime shipping. At a high purity level, it can be used in fuel cells to produce electricity and provide mechanical traction through an electric motor. Likewise, internal combustion engines can burn hydrogen – both pure and in a dual-fuel mixture with conventional diesel fuels – and provide propulsive power. The use of hydrogen can deliver near-zero emissions in a well-to-wheel lifecycle analysis if produced only from renewable/nuclear electricity. However, there can be non-CO_2 GHG emissions like NO_x.

Hydrogen has some disadvantages. It has a relatively low volumetric energy density (see Table 1). Increasing its energy storage density requires liquefying and storing it cryogenically at -252°C, which incurs energy losses of approximately 30% and increases system costs (Sdanghi et al., 2019). Boil-off losses due to heat transfer to the liquid fuel tank also increase system costs during fuel transport and use. Finally, hydrogen requires careful handling as it is explosive and permeates through materials, making them brittle and prone to failure.

Ammonia

Like hydrogen, ammonia does not produce direct CO_2 emissions when burned in an engine, yet it offers several advantages over pure hydrogen. At standard atmospheric conditions, it is gaseous but can be stored as a liquid by cooling it to -33°C at ambient pressure or without cooling at 10 bar. Liquid ammonia also has a higher volumetric energy density than liquid hydrogen, is not explosive and can use storage tanks similar to those used today for liquefied petroleum gas (LPG). Ammonia is highly toxic to human health and hazardous to flora and fauna. Ammonia can be a hydrogen carrier for vessels if split in an upstream process on the ship to release hydrogen. However, this complex process reduces systemic energy efficiency, making it less practical than its direct use without splitting (Department Of Energy, 2006; Chatterjee et al., 2021).

E-methanol

Methanol is the simplest alcohol (CH_3OH) and a frequently used feedstock for the chemical industry. It is liquid at ambient temperature, making it compatible with modified existing ship engines and bunkering infrastructure. Conventional engines can burn methanol blended with conventional diesel fuel or 100% methanol. Using methanol fuel requires some relatively minor modifications. For example, to deal with its greater corrosive properties and lower lubrifying properties compared with diesel fuel (Verhelst et al., 2019). It can also be used in a fuel cell to produce electricity, propelling the ship through an electric motor (ITF, 2020). The advantage of a fuel cell over a combustion engine is that it can be more efficient. Also, it creates fewer pollutants related to high combustion temperatures, like nitrous oxides, and therefore requires fewer after-treatment technologies. The main disadvantage of fuel cells is their relatively high cost and lower power density than internal combustion engines.

E-methanol is chemically identical to methanol but produced from renewable feedstock, including CO_2 and hydrogen. Methanol is biodegradable, miscible (capable of being mixed) in water and less hazardous to the environment than diesel or heavy fuel oil. If accidentally spilt into the sea, it is 1 900 and 240 times less lethal to marine life than gasoline and diesel, respectively (Malcolm Pirnie, Inc., 1999). Methanol is already available through existing infrastructure in more than 100 ports globally (DNV, 2022).

The methanol market is growing strongly and has increased from 40 Mt in 2009 to 100 Mt in 2019. However, less than 0.2 Mt is produced renewably, mostly via biogenic pathways (IRENA and Methanol Institute, 2021). Current methanol production uses natural gas and coal as feedstock. Using it as a fuel would cause more environmental impacts than conventional shipping fuels due to its higher lifecycle GHG emissions (Balcombe et al., 2017). In principle, e-methanol production can use biomass, DAC or CCU technologies as CO_2 feedstock to produce a low-carbon fuel. The source of CO_2 feedstock then determines the carbon intensity of this fuel. These characteristics make it a potential candidate to help decarbonise maritime shipping.

The use of methanol as a fuel in shipping has already been trialled in a number of pilot projects and is technically feasible (ITF, 2020). Methanol was approved for inclusion in the International Maritime Organisation's (IMO) Interim Guidelines for Low Flash Point Fuels in November 2020, which lowers the barriers to its use as a maritime fuel (ABS, 2021). Mærsk has ordered 19 ocean-going methanol vessels with a dual-fuel system that can use methanol and conventional fuel as bunker fuel (Mærsk, 2022). Other relevant fleet operators such as Stena Bulk, Eastern Pacific Shipping, or Mitsui O.S.K. Lines use methanol-fuelled ships or announced strategic partnerships with maritime engine manufacturers or renewable methanol manufacturers (S&P, 2021). Recently, Freudenberg announced a methanol-powered fuel cell system for a marine application that received approval from the international marine classification society RINA for ocean-going vessels (Freudenberg, 2022). This modularized system combines a fuel cell of 500 kW modules with a steam reformer to transform methanol into hydrogen, which uses the waste heat from the fuel cell. The modules can be combined up to the elevated MW range to be suitable for large-scale marine applications.

Aviation e-fuels: E-kerosene and hydrogen

Aviation has more stringent technology and safety requirements than shipping. A high gravimetric energy density is particularly important for aviation fuels as aeroplanes are more weight sensitive than other transport modes. This limits considered e-fuel types to e-kerosene and hydrogen. E-kerosene meets the specifications of conventional aviation fuel and is compatible with existing aircraft technology. Using hydrogen in aviation depends on breakthroughs in aircraft technology and significant investments at airports to transport and store hydrogen fuel.

E-kerosene

Sustainable aviation fuels (SAF) can substitute fossil jet fuel. SAFs are derived from biomass or power-to-liquid (PtL) pathways, the latter producing e-kerosene. The ASTM has approved seven SAF pathways, including liquid FT fuels, for a maximum blend rate of up to 50% with conventional kerosene (ASTM International, 2022a). Conventional turbines, on-board fuel storage and storage are compatible with e-kerosene.

Producing sustainable e-kerosene relies on H_2 from water electrolysis and atmospheric CO_2, both being very energy-intensive processes. However, input electricity must be from renewable sources to provide significant potential for emissions savings. The availability of green electricity is a significant challenge for the large-scale production of e-kerosene.

An alternative is a solar pathway, which can produce e-kerosene directly via solar energy. While the feedstock remains the same (hydrogen from water, CO_2 from the atmosphere), the main energy input to the process is not electricity but heat from solar radiation (Schäppi et al., 2022).

Hydrogen

Hydrogen aircraft are an emerging novel technology that could replace conventional aircraft models and reduce fossil jet fuel use on selected mission profiles. However, their market entry relies on overcoming several technological challenges related to the properties of hydrogen, which differ from conventional aviation fuel and e-kerosene.

Hydrogen has a gravimetric energy density three times higher than conventional kerosene. However, the weight of storage tanks reduces this weight advantage significantly. Additionally, hydrogen has a very low volumetric energy density. Liquefying hydrogen by cooling it to -253°C at ambient pressure increases its volumetric energy density but imposes some constraints on the combustor and fuel system of aircraft. Liquid hydrogen requires cryogenic tanks that are larger and heavier than conventional systems and do not fit in aircraft wings. Fuel tanks may therefore need to be installed in the aircraft body, affecting the aircraft seating capacity. Hydrogen can be a safe aviation fuel but requires major adaptations to airport fuel delivery and storage systems. This challenges wide-scale adoption.

Early-market hydrogen turbines already exist for stationary applications like power generation, which can burn up to 100% pure hydrogen (GE Gas Power, 2022). Major jet engine manufacturers have already announced tests on hydrogen-combusting jet engines (CFM International, 2022; Rolls-Royce, 2022; Pratt & Whitney, 2022).

Ammonia is not considered feasible as a fuel for the aviation sector since it produces NO_x emissions when burned. This can react to form N_2O, a powerful greenhouse gas. Conventional aviation fuels produce NO_x emissions from high temperatures during combustion (thermal NO_x), which can be reduced effectively using Rich-Quench-Lean combustors. Burning ammonia would produce this type of NO_x emissions. However, it would also produce NO_x from nitrogen in the fuel (fuel NO_x), which would require large, cumbersome after-treatment technologies that are unlikely to be feasible in weight-sensitive applications such as aviation.

Techno-economic barriers to non-carbon-based e-fuels

This section explores the technical and economic barriers to non-carbon-based e-fuels related to their production and use. It first explores the challenges in hydrogen production before examining important considerations involved in the downstream use of hydrogen in the aviation and maritime sectors.

Hydrogen production

Hydrogen is widely used as a base product in industrial processes. An overwhelming share (>99%) is currently produced from fossil sources like natural gas via steam reforming (IEA, 2022b). Green hydrogen is produced by splitting water (H_2O) in an electrolytic process into hydrogen (H_2) and oxygen (O_2) using renewable electricity. Several technologies exist at different technology readiness levels (TRL), with global energy conversion efficiencies between 49-71% (Vincent and Bessarabov, 2018). The alkaline electrolyser is today's most common technology due to its comparably high TRL and low costs. Proton exchange membrane electrolysis offers slightly higher conversion efficiencies but is more expensive and has a shorter lifespan due to the catalysts required. Apart from electricity, both pathways require low-temperature heat input. Combining this pathway with processes that produce heat (e.g. the Fischer–Tropsch process) can be an option to increase efficiency. Current research focuses on new technologies like solid oxide electrolysers that offer efficiencies above 80% yet require additional high-temperature process heat. This makes it more difficult to couple the process with the waste heat from another process. Supercritical water electrolysing pathways are still in an early research stage. They could increase global efficiency because they produce hydrogen at high pressure, reducing liquefaction costs (Chen et al., 2020).

To deliver GHG savings, electrolysers in fuel production must use low-carbon electricity. Hydrogen is considered a crucial energy carrier for the energy transition. The International Energy Agency (IEA) estimates that hydrogen supply must grow six-fold to achieve net zero in the energy sector by 2050 (IEA 2021a; IEA, 2022b). In addition, hydrogen production will have to shift completely from today’s fossil fuel production routes to renewable pathways. Today, green hydrogen from electrolysis has a negligible market share compared to steam methane reforming. It represented only 0.03% of the total hydrogen supply in 2020 (IEA, 2022b). Reaching hydrogen production targets requires expanding electrolyser capacities and large investments in renewable electricity generation.

Depending on electrolyser technology, input electricity accounts for up to 90% of the levelised costs of hydrogen. Therefore, the large-scale production of low-cost hydrogen will depend on the availability of cheap renewable power. Current hydrogen costs range between USD 3-5/kg using electricity prices of USD 50-100/MWh. They may decrease to USD 2/kg by 2030 at USD 25/MWh. Hydrogen production costs from fossil sources range from USD 0.5-1.7/kg, depending on natural gas prices (IEA, 2022b).

Deploying hydrogen and ammonia in shipping

Hydrogen and ammonia are uncommon maritime fuels today. This section explores the technical and economic barriers to their adoption in greater detail.

Technical challenges

Electrochemical reactions to produce ammonia are an alternative to the Haber–Bosch process but remain in the early research stages (The Royal Society, 2020). The main advantage of ammonia over hydrogen is its lower refuelling and on-board storage requirements. However, even if technology is readily available for ships, challenges to introducing the refuelling infrastructure remain. Establishing "green corridors" can accelerate the uptake of e-fuels (see Box 1).

MAN ES, one of the leading manufacturers of two-stroke engines for ships, has announced a commercially available ammonia combustion engine for maritime applications by 2024 (MAN ES, 2022). Additionally, both MAN ES and Wärtsila announced retrofit packages for existing fossil fuel two-stroke engines for 2025 (Wartsila, 2022; MAN ES, 2022). The companies are developing safety solutions for fuel handling, including double-wall tank solutions, and contribute to the regulatory framework for ammonia shipping. The volumetric energy density of methanol and ammonia is about half that of conventional fossil fuels. Accordingly, the range of the ships is halved for the same tank size, neglecting any possible differences in engine efficiency.

Pilot projects to equip ships with fuel cells have been limited to relatively small vessels (ITF, 2020). Increasing the capacity of fuel cells to the MW scale has proven challenging. Due to technical challenges, MAN ES does not consider hydrogen a viable fuel option for ships with fuel cells or combustion engines. Wärtsila is developing small hydrogen internal combustion ship engines (typically four-stroke models for small vessels) and fuel cell technologies (ITF, 2020).

Box 1. Existing port infrastructure can assist in deploying maritime e-fuels

Strategies to bring novel fuels to the maritime sector can leverage existing hydrogen applications and infrastructure located at or near ports, such as refining or petrochemical production. These existing use cases typically rely on hydrogen from fossil origin. Yet, the existing assets and experience may support bringing green hydrogen and derived fuels into the maritime sector.

Supply infrastructure at selected large ports can initiate a fuel transition for the sector. Nearly half of the global maritime cargo goes through the world's twenty largest container terminals. Decarbonisation strategies for the sector may focus on rolling out low-carbon fuels at these ports first, where targeted fuel infrastructure investments could serve a high share of maritime transport. Ship engines are comparably flexible to operate on different fuels, for example, either e-methanol or conventional maritime fuel, which offers options for a staggered rollout of e-fuel supply and can ease the early stages of adoption.

Source: UNCATD (2021).

Safety and environmental concerns

While the use of alternative fuels is receiving increasing attention for shipping, little information is available on the potential environmental impacts that their large-scale application would bring. The impacts can be direct, such as in the event of a spill, and indirect, such as climate change (excessive GHG emissions) or the global nitrogen cycle (excessive reactive nitrogen emissions).

In case of contact with water, ammonia reacts to ammonium hydroxide. Both ammonia and ammonium hydroxide are highly toxic to human health and the environment. A spill would be hugely detrimental to any nearby aquatic life (ORNL, 2021).

Deploying ammonia in shipping reduces CO_2 emissions if produced from low-carbon feedstock. Therefore, fuel switching at a large scale could reduce the sector's global footprint. However, other non-CO_2 emissions produced during the combustion and the entire fuel supply cycle of ammonia can weaken its climate benefits. Ammonia combustion releases hazardous gases like nitrogen oxides (NO_x) that can be converted back into harmless inert nitrogen and water in on-board exhaust gas treatment systems. However, these will inevitably never be 100% effective. The remainder can form nitrous oxide (N_2O) in the atmosphere, which is a 298-times more potent GHG than CO_2 (Kobayashi et al., 2019). For example, the conversion rate of NO_x in research engines varies from 99-99.99% (Lhuillier et al., 2020; Imhoff et al., 2021). However, this may be significantly lower under real operating conditions. A leak rate of just 0.38% of ammonia throughout the fuel supply chain would offset the CO_2-based GHG benefits from switching to ammonia if converted to N_2O directly or indirectly (Wolfram et al., 2022). The lack of emissions tests under real-world operating conditions poses uncertainty on how factors such as degradation in exhaust gas after-treatment devices (such as catalytic converters) could impact the environmental performance of ammonia in maritime transport.

In addition to GHG-related global warming impacts, reactive nitrogen (N_r) emissions (nitrogen derivatives like NH_3, NH_4, NO, NO_2, NO_3, or N_2O) can damage the ecosystem. In environmental science, the measure of planetary boundary quantifies harmful substances and defines a "safe operating space" for humankind to avoid irreversible changes to the earth system (Rockström et al., 2009; Steffen et al., 2015). While climate change is well-researched and currently the focus of public attention, the risk of excessive reactive nitrogen (N_r) as a harmful substance is largely unknown to the public (Steffen et al., 2015).

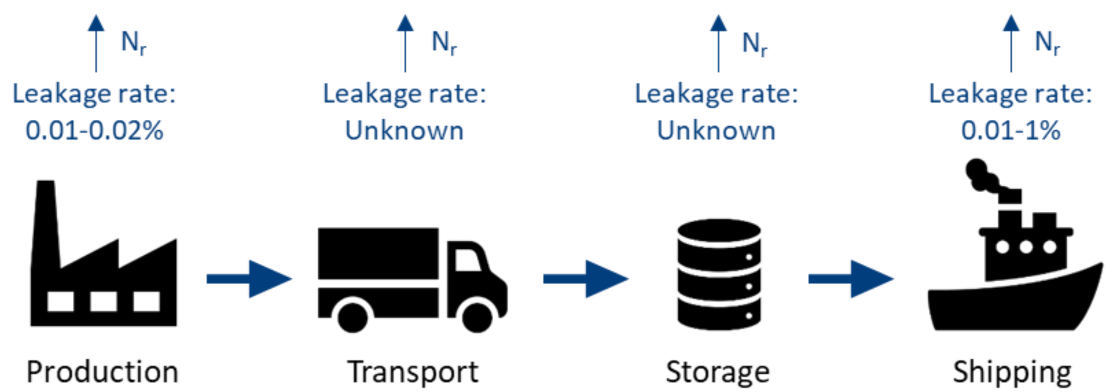
The nitrogen cycle describes the conversion of inert nitrogen (N_2) to harmful reactive nitrogen (N_r). One estimate of the planetary boundary for emissions of N_r is between 62-82 Mt per year (Steffen et al., 2015). In 2015, the global output exceeded 250 Mt of N_r per year, mostly from unabsorbed agricultural fertilizer. Switching the global maritime fuel demand (330 Mt fossil fuels in 2018) to ammonia may theoretically cause up to 586 Mt of N_r per year if poorly managed. It is uncertain how much of this N_r would actually remain in the atmosphere without strict emissions regulation. However, the end-use of ammonia as a fuel for maritime shipping could potentially overshoot the estimated planetary boundary up a factor of seven.

There may also be emissions of reactive nitrogen in the upstream fuel supply. Very little quantitative information is available on leakage rates throughout the ammonia supply chain (production, distribution, storage and refuelling). Still, it is most likely non-negligible due to the gaseous nature of ammonia under ambient conditions. Even low leakage rates can have a big impact if the global fossil fuel demand is replaced with ammonia. Leakage rates in ammonia production facilities are between 0.01-0.02%, but little is known about fuel distribution, storage and fuel handling (Wolfram et al., 2022). Figure 2 shows schematically the relevant steps of the supply chain of ammonia with its respective leakage rates, which poses additional uncertainties.

Existing techno-economic analyses identify ammonia as a promising decarbonisation option to replace fossil fuels in shipping. Several research priorities have emerged to minimise risks of unintended consequences:

- Quantify the real-world emissions from incomplete ammonia combustion in ship engines.
- Research the conversion rates of catalytic NO_x reduction over the lifetime of a catalytic converter under real operating conditions.
- Quantify the leakage rates of ammonia throughout the entire fuel value chain.

Figure 2. The ammonia value chain with estimated leakage rates



Source: Based on (Wolfram et al., 2022).

Economic challenges and barriers to scaling up

The use of hydrogen or ammonia in the shipping sector is still at a low stage of technology readiness. Further pilot tests and research are needed to better understand the feasibility of using these fuels in the real world.

E-fuels currently cost more than conventional fossil fuels, and significant policy support is required to bring them to scale. The current renewable ammonia costs are USD 720-1400 per tonne and are expected to drop to USD 310-610 per tonne by 2050 due to decreasing energy and hydrogen costs (IRENA and AEA, 2022). For comparison, the current cost for the most commonly used fuels in maritime shipping (intermediate fuel oil [IFO] and heavy fuel oil [HFO]) is around USD 450 per tonne (Ship and Bunker, 2022). Approximately 90% of the costs of renewable ammonia are related to the costs of hydrogen.

Both liquefied hydrogen and ammonia have lower energy densities compared with conventional shipping fuels (4.6 times lower for H_2 and 3.1 times lower for NH_3). All else being equal, this will lead to reduced range capabilities of ships or lower payload capacities if fuel tanks need to be increased.

Unlike carbon-based e-fuels, neither hydrogen nor ammonia are drop-in fuels in maritime applications. This means that the speed of their adoption in the maritime sector is partly constrained by the turnover of the shipping fleet and the speed that ammonia/hydrogen-capable powertrains enter new builds or retrofits.

Hydrogen in aviation

Aeroplanes depend on liquid fuels with high energy density, which minimise their weight and allow them to fly long distances. E-kerosene is a direct substitute for kerosene thanks to its almost identical fuel characteristics. Hydrogen may enter the sector if the disruptive technology of hydrogen aircraft becomes available.

Aircraft requirements and challenges

Propulsion systems of conventional aircraft convert the chemical energy of kerosene in a combustion turbine. For hydrogen aircraft, there are two energy conversion pathways. Hydrogen combustion turbines have a similar design to conventional turbines that burn fossil kerosene. Alternatively, on-board fuel cells convert hydrogen to electricity to propel the aircraft.

Combustion engines deliver a higher power-to-weight ratio than fuel cell systems, which makes them a more promising technology option for hydrogen aircraft. Fuel cell technology would need significant breakthroughs to become a viable option to fuel larger aircraft. For example, ambitious technology scenarios expect fuel cells to reach a power density of 1.5-2 kW/kg in 5-10 years, which would be a two-to-threefold increase from existing technology (Clean Sky 2 JU and FCH 2 JU, 2020). The future technology of fuel cells would still fall short compared to the power density of existing turbines in the range of 10 kW/kg (Johnson & Brown, 2005); for example, the GE90-115B turbine, which is typical to power a wide-body aircraft Boeing 777. Contrary to fuel cells' low power density, comparable power densities can be expected for hydrogen turbines due to a similar operating principle, even if no production turbines are running on pure hydrogen yet.

On-board fuel storage systems for hydrogen aircraft need a more advanced design than conventional ones. The resulting weight increase is a significant technical challenge. The so-called gravimetric index (GI) describes tank mass as the ratio of the mass of on-board fuel to the weight of the entire fuel delivery system with a full tank. The current state-of-the-art hydrogen fuel tanks have a GI of 0.2 (Clean Sky 2 JU and FCH 2 JU, 2020). However, a hydrogen aircraft that can operate typical medium-haul flights (3500 km, 165 passengers) would require a system with a GI of 0.35-0.38 (ICCT, 2022).

The lower energy density of hydrogen and the heavier fuel systems of hydrogen aircraft reduce their range compared to conventional aircraft technology. This makes hydrogen aircraft most suitable for short-haul flights, a segment where they could replace a considerable share of flights. A feasibility study by the International Council on Clean Transportation (ICCT) on a narrow-body hydrogen aircraft with 165 seats, equivalent to an Airbus A320 that typically operates on short-to medium-haul flights, found that flight ranges of 3 200 km could be feasible in 2035. While the range of 3 200 km is significantly shorter than the range stated by Airbus for a conventional A320neo (6 500 km), it would suffice to cover 90% of the missions currently flown by this aircraft type (ICCT, 2022). The ICCT analysis considers performance penalties from the higher energy requirements per revenue-passenger kilometre (RPK). The hydrogen fuel system with an assumed GI of 0.35 limits the maximum take-off weight (MTOW). Accommodating the larger fuel tank in the vessel body requires an elongated aircraft design that may also impact aerodynamic characteristics (ICCT, 2022).

Airport requirements and challenges

Surveys show that travellers perceive hydrogen at airports as riskier than conventional kerosene (ACI, 2021). However, industry experience in handling hydrogen reaches back decades, and risks are generally well known. The different physical fuel properties require some safety adaptations, such as reducing flammability risks. A feasibility study by Airports Council International (ACI) found that technical barriers to the widespread use of hydrogen at airports can be overcome. However, perceived safety risks by passengers require strong engagement between different stakeholders to increase acceptance (ACI, 2021).

Airports could produce hydrogen on-site or import it using trucks or pipelines. Producing hydrogen on-site (via water electrolysis and liquefaction) may reduce transport and storage costs yet incurs additional surface needs for production and liquefaction equipment, depending on the production scale. Barriers at an early adoption stage, when airports would switch 5-10% of their fuel capacity to hydrogen, are expected to be relatively minor. For example, studies estimate surface requirements for early-stage production and liquefaction (10 tonnes per day) at no more than 350 m^2 per tonne onsite production capacity (ACI, 2021). However, large-scale hydrogen production at airports faces significant challenges. For example, switching 25% of flights at large airports to hydrogen would require 500 tonnes daily production capacity and incur land requirements of over 175 000 m^2 for production assets. This area compares to 1% of Frankfurt Airport's surface area (the largest European airport by area) or three times the footprint of London Heathrow's Terminal 2 (ACI, 2021).

Importing gaseous hydrogen by pipeline would only partially reduce challenges related to surface needs at airports because on-site liquefaction facilities have a high share of the mentioned area requirements. Medium-sized airports supplying about 4 000 tonnes of aviation fuel per day may rely on hydrogen shipments (ACI, 2021). Storing hydrogen requires four to seven times more space than kerosene for the same amount of energy, depending on the physical state of hydrogen. Liquid hydrogen storage usually uses spherical tanks whose surface-to-volume ratio reduces heat exchange and boil-off losses. Yet, it comes with a larger area footprint than other tank geometries. The resulting larger storage area or more frequent deliveries for supplying hydrogen (compared to kerosene) may increase costs.

Challenges related to local fuel distribution at airports add to production and storage implications. Adapting existing kerosene hydrants would incur high costs for cryogenic refurbishment. Building hydrogen refuelling platforms away from passenger gates may increase safety. However, it would also prolong the turnaround time for aircraft.

Barriers to scaling up hydrogen at airports would emerge mostly after an initial small-scale roll-out. High costs may add to technology barriers, and the lack of comprehensive cost assessments incurs uncertainty. Ongoing research focuses on quantifying the costs of isolated subsystems, such as for transmission and cryopumps for liquid hydrogen at airports (Hoelzen et al., 2022). However, global costs related to implementing liquid hydrogen infrastructure at airports have not been quantified in detail.

Economic implications for airports and airlines

The market entry of hydrogen aircraft disrupts the existing aviation ecosystem and is subject to significant uncertainty. In addition to overcoming technological barriers, a successful technology rollout will depend on the cost competitiveness of hydrogen aircraft with other (low-emission) aircraft technologies. The cost of aeroplane purchase, hydrogen fuel and fuel infrastructure will determine the total cost of ownership (TCO) of operating hydrogen aircraft and the cost savings they may offer compared to other technologies. Fuel costs tend to have the most decisive impact on the total cost of ownership (Clean Sky 2 JU and FCH 2 JU, 2020). Box 2 discusses some implications for the aviation sector that would come with a market entry of hydrogen aircraft.

Existing analyses estimate the total cost of ownership of hydrogen aircraft to be up to 25% higher than conventional technologies due to higher capital (CAPEX) and operational expenditure (OPEX). The CAPEX of hydrogen aircraft exceeds that of conventional aircraft by about 30%, mostly due to the higher technology costs for the hydrogen fuel system. More complex technology components drive maintenance costs that increase by up to 50% (Clean Sky 2 JU and FCH 2 JU, 2020).

The longer refuelling time of hydrogen aircraft prolongs their turnaround time and reduces flight cycles by about 7% compared to conventional aeroplanes. The resulting decrease in aircraft use and potentially higher airport service fees come at a cost. Airport landing fees typically increase along with the aircraft's maximum take-off mass (MTOW). Hydrogen aircraft may pay more due to increased mass from the heavy hydrogen tank unless airports offer discounts for hydrogen aircraft (Clean Sky 2 JU and FCH 2 JU, 2020).

The higher CAPEX of hydrogen aircraft may slow down the rate of fleet renewal compared to today's fleet. The average lifetime of aircraft is 15-20 years. There were unusually many aircraft replacements in 2014-2020 (IATA, 2019). A dip in fleet renewal may follow in the remaining 2020s. The next major fleet replacement may be due after the scheduled market entry of hydrogen aircraft in the 2030s. Future replacement programs can provide an opportunity to bring hydrogen aircraft into the aviation sector, depending on how their TCO compares to conventional technologies and the availability of policy incentives.

Box 2. The aviation ecosystem is preparing for the first hydrogen aircraft

Integrating hydrogen aircraft into the existing aviation system will come with challenges because its infrastructure and operations are optimised for conventional aeroplanes. The industry conducts feasibility studies to prepare for the market entry of this novel propulsion technology. Airbus has announced launching hydrogen aircraft by 2035 and entered collaborations with several airports and airlines.

For airports, a challenge in preparing for the market entry of hydrogen aircraft will be to develop hydrogen infrastructure. Airbus, together with hydrogen specialist Linde, works with airports to study their potential to become hydrogen hubs, typically starting with ground vehicles. The collaboration airports are in Europe (VINCI Airports, 2021), Singapore (Airbus, 2022c), Korea (Airbus, 2022a) and Japan (Airbus, 2022b).

Hydrogen aircraft will rely on refuelling infrastructure at the departure and destination airports. Equipped airports would also need a diversion airport that can supply hydrogen to diverted flights, for example, by fuel trucks (ACI, 2021). The technology rollout could start from regional airport pairs before extending to longer distances and networks. Factors determining the routes hydrogen aircraft will operate first will include the range and seat capacity of the first models. For example, single aisle narrow body jets could connect large airports with high transport demand, while small regional aircraft would be more suitable for flights to small periphery airports. For small airports, the number of flights suitable for hydrogen aircraft must be large enough to justify investments in dedicated refuelling infrastructure.

For airlines, deploying hydrogen aircraft will need adjustments to existing operations. Airlines collaborating with Airbus to prepare for the arrival of hydrogen aircraft include Wizz Air and Delta Air Lines. Delta announced that the collaboration would focus on aspects such as integrating aircraft concepts into Delta's fleet and operations (i.e., flight range limits, refuelling time and airport compatibility) as well as infrastructure needs and costs (Delta, 2022).

Single-aisle narrow-body hydrogen aircraft are expected to cover ranges of over 3 200 km. This covers most flight routes these aircraft service today but is less than the range of existing types, which can exceed 6 000 km (ICCT, 2022). The smaller range of hydrogen aircraft and their reliance on airports with hydrogen infrastructure means that adopting airlines and leasing companies will lose some flexibility offered by current aircraft models. However, the decarbonisation prospects of this technology may compensate for these disadvantages.

Carbon-based e-fuels

Carbon-based e-fuels have the advantage of being similar, if not identical, to fuels that are already used within the transport sector. In many cases, carbon-based e-fuels are drop-in fuels that can be used with relatively minor modifications to conventional engines and use existing fuel distribution and refuelling infrastructure. The main technical and economic challenges associated with e-fuels are, therefore, in fuel production rather than in downstream use. The following chapter will focus on the technologies used to produce carbon-based e-fuels for the aviation and maritime sectors, including carbon capture technologies, the Fischer–Tropsch (FT) process and methanol synthesis.

Carbon capture technologies

Carbon capture technologies enable the removal of carbon dioxide (CO_2) from the atmosphere or from processes that emit CO_2 in high concentrations, such as industrial flue gases or biogenic processes like fermentation. Carbon capture technologies can be categorised according to the end-use of CO_2. Carbon capture and storage (CCS) stores CO_2 in geological formations, where it mineralises to solid carbonate minerals. Carbon capture and utilisation (CCU) uses the captured CO_2, for example, as a potential feedstock to produce e-fuels.

Direct air capture (DAC) is the technology to remove CO_2 from the atmosphere. There are currently 18 DAC facilities in operation globally, where 16 plants utilise the captured CO_2 in further processing (IEA, 2022a). There are two main DAC technologies, which can be distinguished according to their modes of operation, solid and liquid direct air capture (S-DAC and L-DAC, respectively).

- S-DAC: uses a solid material that acts as an absorber of atmospheric CO_2. The CO_2 is then released by heating the material with medium-elevated process heat at around 100°C. Current research focuses on the electrical or pressure-based recovery of the absorbing material to increase the process efficiency (McQueen et al., 2021).
- L-DAC: uses an alkaline liquid to capture CO_2 and requires much higher temperatures to release the CO_2 (300-900°C).

Around 80% of the total energy needed to capture atmospheric CO_2 must be supplied by process heat. The high-temperature process heat required for L-DAC is still supplied by the combustion of natural gas, which also releases CO_2. This CO_2 can be directly captured within the process to avoid being emitted into the atmosphere. However, this lowers the efficiency of CO_2 capture (the ratio of emitted to captured CO_2). Therefore, S-DAC technology, which does not require high-temperature heat, is more efficient. Unfortunately, the costs for S-DAC are currently 1.5 times higher than for L-DAC (IEA, 2022a), neglecting technologies in the research stage. The advantage of S-DAC over L-DAC is that the low-temperature heat can be more easily recovered from the waste heat of other processes, like the FT process. This can reduce costs and enhance system integration if the processes are combined. Low-temperature heat can also be supplied using heat pumps, which can be powered using renewable electricity.

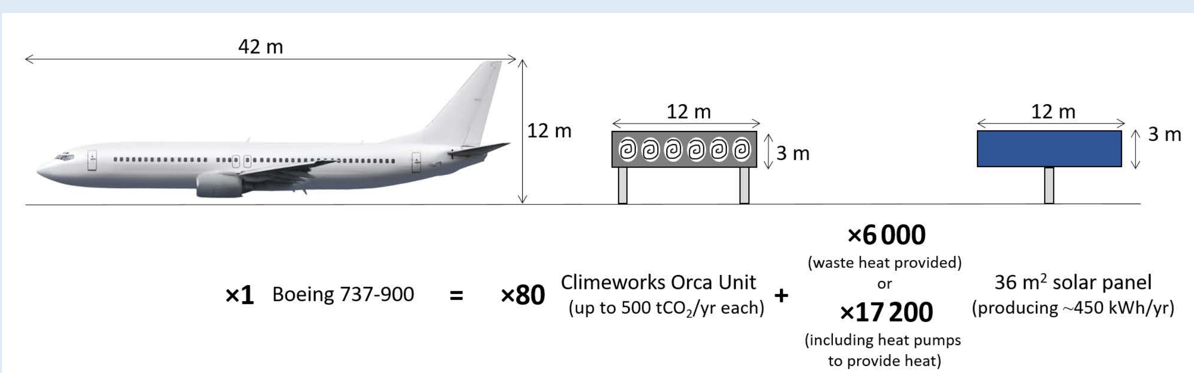
Box 3. The physical scale of direct air capture

Business-as-usual aviation CO_2 emissions in 2050 are expected to be approximately 1 500 Mt, which is around three times the total aviation-related CO_2 emissions from 2015 (ITF, 2021b). To extract this quantity of CO_2 from atmospheric air (which is at concentrations of 400 parts per million), about 2.2×10^{15} m^3 of air would have to be processed per year[1]. Processing this amount of air would require 63 000 of the world's largest jet engines (the Rolls-Royce Trent 9000) to run 24/7 per year, equivalent to one running for every aircraft in operation and capturing 100% of the CO_2 from the air that passes through them.

Expressed in terms of new direct air capture (DAC) technologies available today, the Climeworks Orca units can reportedly capture 500 tonnes of CO_2 per year (Climeworks, 2022). To capture total aviation emissions in 2019 (1 035 $MtCO_2$) would require 2 million units, equivalent to 80 units running 24/7 for each aircraft in operation in the global fleet. Each unit measures roughly H × W × D = 3 × 12 × 3 metres and would require roughly 2 700 m^2 of solar panels to power each Orca unit assuming waste heat is readily available. Approximately 7 800 m^2 of solar panels would be needed if the low-temperature heat is provided using heat pumps. For a sense of scale, Figure 3 compares the size of the Climeworks Orca units and solar panels required to power them to the dimensions of a Boeing 737-900. These infrastructure requirements do not account for any energy used to subsequently produce e-fuels using the captured CO_2.

Including non-CO_2 effects from aviation, the embodied carbon footprint of the DAC system (which is estimated by Climeworks at approximately 10% of the DAC capture rate), and any additional energy required to convert the CO_2 into an e-fuel would increase the number of DAC units and solar panels by at least a factor of 2-3. Conversely, future efficiency improvements to aircraft and reduced energy requirements for DAC units could reduce the number of required DAC units and solar panels by a similar amount.

Figure 3. Size comparison between an aircraft, state-of-the-art direct air capture units and solar panels



Notes: Aircraft dimensions of a Boeing 737-900. The electricity of 2 700 m^2 of solar panels is required to drive one DAC unit. DAC = direct air capture.

Photo credit: ssuaphotos/Shutterstock

The efficiency and costs of carbon capture technologies scale with the concentration of CO_2 that is being captured. The concentration of CO_2 in the atmosphere is low at 0.04%. This requires a high throughput of ambient air to capture significant amounts of CO_2 (see Box 3). The low CO_2 concentration in the air also makes DAC one of the most expensive carbon capture options. Flue gases from industrial processes have CO_2 concentrations more than two orders of magnitude above, at approximately 10% for fossil power plants, >20% for steel plants (IEA, 2022a) and around 85% from biogenic sources like ethanol fermentation (Laude et al., 2011).

The Fischer–Tropsch process and methanol synthesis

Methanol synthesis and the Fischer–Tropsch (FT) process are two families of catalytic reactions to produce liquid hydrocarbon (HC) fuels from syngas (a mixture of carbon monoxide and hydrogen). Syngas can be produced from several carbonaceous sources, like coal gasification, natural gas or biomass gasification. Fuels produced in this manner from fossil feedstocks are not considered e-fuels since electricity is a minor source of the energy inputs to the process. However, both the FT process and methanol synthesis can also be used to produce carbon-based e-fuels using CO_2 feedstocks supplied from DAC or CCU combined with H_2 from electrolysis.

Fischer–Tropsch process

The FT process has been used at scale for more than half a century, and several industrial plants worldwide are already in operation to produce synthetic hydrocarbons. Conventional FT-synthesis production plants using fossil feedstocks are already available at scale with outputs of up to 10 000 tons per day (Dieterich et al., 2020). In South Africa, the energy company SASOL produces synthetic hydrocarbons using coal as feedstock (coal-to-liquids). There are also large-scale gas-to-liquids plants that convert natural gas into liquid fuels in Malaysia, Nigeria, Qatar and South Africa (Nichols, 2017).

There are two main pathways for e-fuel production using the FT process. In the first pathway, CO_2 is directly processed with H_2 in the presence of a catalyst. In this process route, the product yield is poor for liquid fuels because of many unwanted gaseous side products like methane (Dieterich et al., 2020). In the second indirect pathway, CO_2 is first converted to syngas via hydrogenation before being fed into the FT process. This has the advantage of the subsequent FT process remaining very similar to conventional fossil fuel pathways (Zhang et al., 2014). This second pathway requires high-purity syngas with low residual concentrations of CO_2 to avoid catalyst degradation and deterioration of conversion efficiency (Dieterich et al., 2020). Due to higher technology readiness, all current or planned production plants are based on the indirect pathway.

Nordic Electrofuel, a company based in Norway, is planning a pilot plant to produce 10 million litres of synthetic fuel in 2025 via the Fischer–Tropsch process at Herøya Industrial Park in Norway with CCU from geothermal (Nordic Electrofuel AS, 2022). According to the plant operator, the technology readiness level (TRL) is 8, and the main output fuels are synthetic kerosene and diesel. TRL 8 represents a technology that has been tested and qualified under operational conditions, like large-scale manufacturing. Upon successful implementation, a second production plant is planned for 2030.

The output products from the FT process include a variety of synthetic hydrocarbons, varying from short-chained, gaseous hydrocarbons (e.g. methane) to liquid hydrocarbons (e.g. synthetic diesel or kerosene) and up to long-chained hydrocarbons like waxes. A significant amount of research is dedicated to optimising the distribution of different products by refining the catalyst's reactor design and process parameters. This becomes more challenging when the production process is dynamic due to variable renewable electricity generation. Recent research has suggested that the dynamic operation of the FT process might even enhance the process and increase the yield of liquid HC (Wentrup et al., 2022).

However, this is still in an early research phase and needs more investigation to be applied on prototypes or industrial scale.

Methanol synthesis

Methanol is produced in a similar catalytic process to Fischer–Tropsch but differs as there is no polymerisation of carbon monoxide (Klerk, 2020). Similar to the FT process, the technical challenges of upscaling e-methanol production lie in the adaptation of chemical catalysts and operational considerations like the efficient removal of reaction heat to avoid undesired by-products from high temperatures (Dieterich et al., 2020). While the catalyst chemistry for conventional methanol production (mostly fossil fuel-based) is well known, current research focuses on developing new catalysts for novel production routes from CO_2. The process for e-methanol is already at a demonstration scale with few commercial plants. Currently, the largest plant in operation (George Olah Renewable Methanol plant by Carbon Recycling International) produces 4 000 tons of e-methanol from geothermal flue gases per year. Very recently, Ørsted announced the final investment decision to build the production plant FlagshipONE in Sweden to produce 50 000 tons of e-methanol per year (135 tons per day for 24/7 operation) starting in 2025 (Ørsted, 2022a). The facility is expected to have 70 MW of electrolyser capacity and to source CO_2 from captured flue gases from a combined biomass heat and power plant. Carbon Recycling International started building a production plant in China to produce up to 110 000 tons of low-carbon methanol per year, where the CO_2 is captured above a steel plant (Carbon Recycling International, 2022b).

Process integration

The FT process and methanol synthesis are exothermic reactions, producing excess heat as a side product. Waste heat recovery or process coupling with other processes that require heat, such as DAC or high-temperature hydrogen electrolysis, could help increase the process's overall efficiency.

All current production plants use CCU from industrial point sources, like geothermal flue gas (Carbon Recycling International, 2022a), combined power–heat plants using biomass (Ørsted, 2022a) or from coke and steel plants (Carbon Recycling International, 2022b), which are industrial processes with a predictable output. If renewable electricity is instead used to produce the feedstocks via DAC and H_2 electrolysis, the processes are subject to fluctuations from variable renewable electricity production. Developing synthesis processes more able to follow intermittent renewable supply can reduce the need for large buffer capacities for both hydrogen and carbon dioxide. While H_2 electrolysis allows changing from partial to full load within relatively short timeframes, tens of hours are necessary to adjust the e-methanol synthesis to normal conditions at variable CO_2 supply (Pontzen et al., 2011). Current research focuses on improving the synthesis for dynamic operation. A direct connection to the electricity grid and the use of conventionally produced electricity can help to bridge times of low availability of renewable energy. This is a trade-off between higher process efficiencies and higher production costs, as grid electricity is more expensive through grid fees. Additionally, the CO_2 emissions intensity of the e-methanol may be worse depending on the carbon intensity of the grid electricity.

Economic barriers to carbon-based e-fuels

The costs of carbon-based e-fuels largely depend on the costs of the hydrogen and CO_2 feedstocks. Hydrogen accounts for between 66-83% of costs in e-fuel production, followed by the cost contributions of CO_2 (IRENA and Methanol Institute, 2021; Schemme et al., 2020). Renewable hydrogen costs and CO_2 from DAC depend highly on the underlying costs of renewable energy needed to produce them. This means that the economic viability of such projects is highly dependent on the availability of cheap renewable energy. The rapidly decreasing cost of renewable electricity production (IRENA, 2020) is particularly important as an avenue to open up new opportunities for electrolysis and synthetic fuels.

The costs for CO_2 sourced from DAC are currently higher than for CCU. For this reason, most production plants planned or in operation use CCU to obtain CO_2 as a feedstock. The current costs of DAC are estimated to vary between USD 340-540/tCO_2 and are expected to fall below USD 100/tCO_2 in 2050. If the waste heat from other processes (such as Fischer–Tropsch or methanol synthesis) is used as process heat, it may be possible for costs to decrease to approximately USD 50/tCO_2 for S-DAC applications in 2050 (IEA, 2022a).

Box 4. Industry partnerships to scale up e-fuels

Existing applications of e-fuels do not reach commercial scales, and fuel producers currently do not supply volumes beyond pilot projects. However, recent announcements from industry partnerships herald increasing deployment in the coming years and often bring together prominent players from the energy and transport sectors. Emissions reduction ambitions from involved stakeholders and public support programs appear to drive these projects to produce e-fuels despite currently high technology costs. There are several projects where transport companies have partnered with renewable energy companies to invest in fuel production:

- The Hyskies project in Sweden with energy company Vattenfall, Scandinavian Airlines and fuel producer Lanzatech will produce power-to-liquid (PtL) SAF from 2025-26. The planned production volume reaches 50 000 tonnes per year, or 30% of kerosene used on domestic flights in Sweden. Based nearby Arlanda airport, the production will use renewable electricity and point-source carbon capture from a nearby power plant.
- The Green Fuels for Denmark project is a partnership between the energy and transport industries with Ørsted, DSV, Maersk, DFDS, Copenhagen Airports and Scandinavian Airlines. It will produce a slate of PtL products for the road, aviation and maritime sectors. The project plans to start production in 2025 with over 50 000 tons of PtL fuel from wind power. The European Commission recognised Green Fuels for Demark as an important project of common European interest (IPCEI), allowing the Danish government to support the project with public funding (DKK 850 million).
- Atmosfair started operation at a PtL aviation fuel plant in 2021. The plant is located in Werlte, Germany, and the transport companies Lufthansa and Kuehne+Nagel will purchase the annual production of 25 000 litres of aviation fuel.
- Luxembourg Airport has entered a consortium to produce PtL aviation fuel to meet the PtL blending target of the ReFuelEU Aviation policy proposal. The consortium partners include e-fuel producer Sunfire, DAC specialist Climeworks, and wind power company Norsk Vind. Production is planned for 2024 in Norway.

E-fuel pathways typically produce a slate of different fuels, and investments in new assets can bring emissions reduction benefits to several sectors simultaneously, for example, by producing both e-kerosene for aviation and e-methanol for maritime applications.

Source: Deutsche Welle (2022); Lufthansa (2022); Luxembourg Airport (2022); Luxembourg Government (2022); Ørsted (2022b); Vattenfall (2021).

Other opportunities to reduce the costs of e-fuels include scaling up the size of production plants to decrease costs via economies of scale. For example, methanol costs are expected to reduce by approximately 40% when scaling production outputs from 2 000 to 10 000 tons per day (Dieterich et al., 2020). Many industry consortia and public-private partnerships are currently underway to help spread the investment risk associated with the early-stage scale-up of novel e-fuels (see Box 4).

In the short term, e-methanol produced from hydrogen and DAC is expected to cost between USD 1 200-2 400/t. Using CO_2 from CCU, the wholesale price of e-methanol is USD 800-1600/t (IRENA and Methanol Institute, 2021). With anticipated reductions in the cost of renewably generated energy, the costs are expected to decrease to USD 250-630/t in 2050. In contrast, the costs for fossil fuel-based methanol are currently in the range of USD 100-250/t and methanol produced via a biogenic pathway are expected in the range of USD 320-770/t (IRENA and Methanol Institute, 2021). Without policy support or carbon pricing, e-fuels will likely remain more expensive than their fossil counterparts.

The emissions intensity of e-fuels

E-fuels are only useful for combatting climate change if they can be produced in a low-carbon, sustainable way compared with the conventional fossil fuels they replace. The production of e-fuels is energy-intensive due to the low energy efficiencies of carbon capture and hydrogen production with electrolysis. Therefore, the potential of e-fuels for GHG mitigation depends on the carbon intensity of the energy used to produce the e-fuel and the origin of the CO_2 used to make carbon-based e-fuels.

Carbon can be sourced from either DAC or from industrial point sources, such as cement production plants or coal power plants using CCU. DAC is particularly energy-intensive, requiring between 6.6-10 GJ/tonne of CO_2 (IEA, 2022a) due to the low concentrations of CO_2 in the air. Conversely, capturing CO_2 from industrial point sources with CCU is less energy intensive than DAC due to the higher concentrations of CO_2 in industrial exhaust gases than in atmospheric air. However, the net emissions intensity of using CO_2 from CCU depends upon the origin of the CO_2 and how the benefit of its capture is allocated between the industrial point source and the e-fuel produced with it.

The other major source of energy demand in the production of e-fuels is hydrogen production. Fossil fuels are used to produce the majority of current global hydrogen demand, either by steam methane reformation (76%) or by coal reformation (23%) (IEA, 2019b). Low-carbon hydrogen production pathways include electrolysis using renewable/nuclear electricity, biomass gasification, methane pyrolysis and hydrogen produced with CCS (see the ITF's report on decarbonising maritime shipping [2020] for more information).

The circularity of carbon-based fuels

Using conventional fossil fuels involves removing carbon from the earth's crust, refining it into usable fuel, such as kerosene, and releasing it into the atmosphere as CO_2 after combustion in an engine. Within this supply chain (shown in "case 1" in Figure 4), CO_2 emissions are released during the extraction process of fossil fuels, from the fuel production/refining process and finally from the end-use of the fuel. All of these processes result in a net addition of CO_2 into the atmosphere, causing global warming.

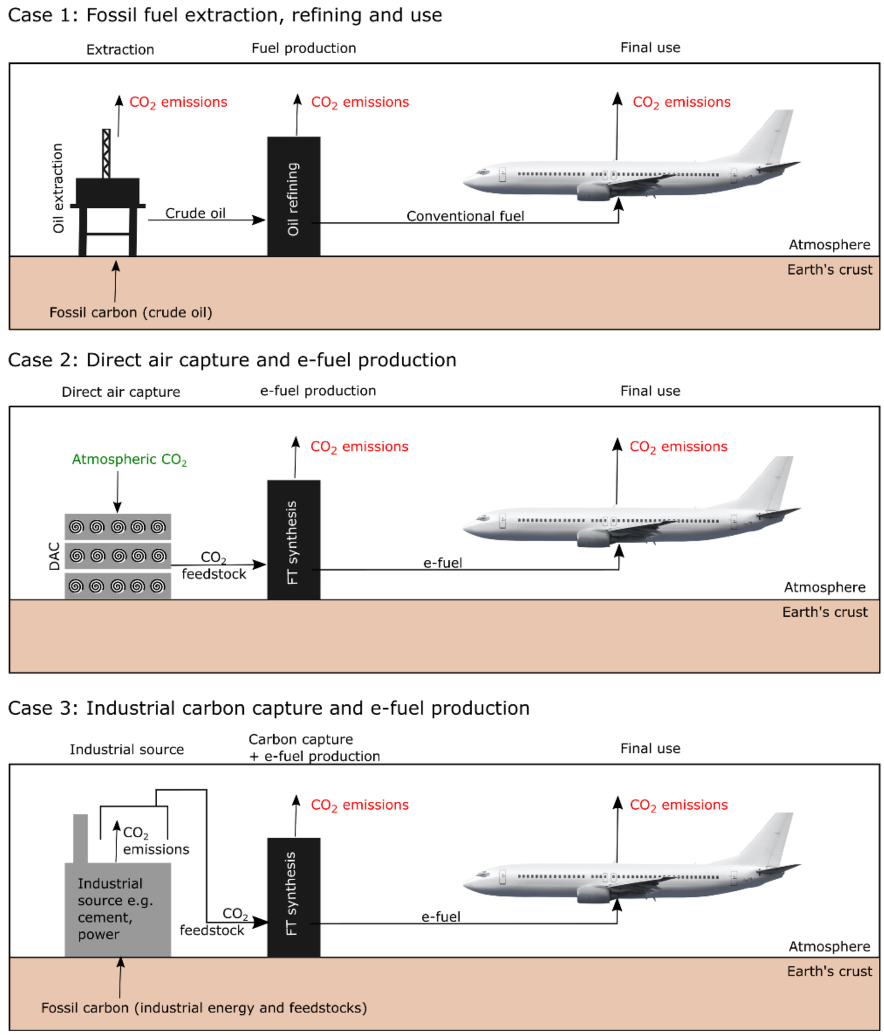
The carbon intensity of carbon-based e-fuels depends on the net emissions released into the atmosphere during their production and use. DAC absorbs CO_2 from the atmosphere, which is then used to make fuel (see "case 2" in Figure 4). The subsequent combustion of the fuel returns the CO_2 to the atmosphere. In theory, the CO_2 absorbed by the DAC process can offset the emissions from the production and use of the fuel. This closed-loop (circular) carbon cycle is essential if e-fuels are to lead to meaningful reductions in GHG emissions savings. For this to happen, the energy used to power the DAC process and the energy used to produce hydrogen must be renewable (net zero carbon). If carbon-intensive energy is used to power DAC, hydrogen production and fuel synthesis, then the net emissions to the atmosphere will still be positive and cause climate change.

Alternative sources of carbon reactants include those sourced using carbon capture of CO_2 emissions from industrial point sources or power generation (see “case 3” in Figure 4). E-fuels produced using these feedstocks would still be a net contributor to global GHG emissions since fossil carbon is extracted from the earth’s crust and ultimately released into the atmosphere. However, they may have a lower impact than the continued unabated use of fossil fuels in the industrial and transport sectors, provided the emissions associated with the carbon capture process and fuel production are low.

When CO_2 emissions are captured from an industrial point source and stored permanently underground, the industries’ activities can be considered zero-carbon because the stored emissions offset those produced during fossil fuel combustion. If instead, the captured CO_2 is used to produce an e-fuel, the credit from capturing it remains the same. It can be used to offset the production emissions from the industrial point source or to claim that a carbon-based e-fuel produced with this CO_2 is zero carbon. How this credit is allocated between the industrial point source and the e-fuel is essential in determining the carbon intensity of each process. Importantly, the industrial point source and the e-fuel cannot both claim to be zero carbon. For carbon-based e-fuels to lead to any climate change benefit, it is essential to avoid double-counting carbon emissions reduction credits generated by CCU.

The carbon footprint from sourcing CO_2 from municipality waste incineration depends on the waste composition and is only fully renewable if no petro-based products such as plastics are burnt. The fermentation or gasification of second-generation biomass could provide CO_2 feedstocks for near-zero e-fuels.

Figure 4. The circularity of fossil fuels



Notes: DAC = direct air capture of CO_2, FT = Fischer–Tropsch.

Photo credit: ssuaphotos/Shutterstock

Producing fuels from captured industrial carbon is often considered a possible transition step between today's use of fossil fuels and a decarbonised future. Fitting existing industrial infrastructure with carbon capture facilities could potentially help to reduce the emissions they would otherwise produce over their lifetimes and avoid stranded assets. However, it would entail the construction of expensive additional carbon capture infrastructure and would remain a net contributor to climate change, meaning it would still have to be shut down as quickly as possible to reach the most ambitious climate goals. Premature closure of the industrial point source may be preferable.

Another important aspect in determining the carbon intensity of e-fuels is ensuring that any renewable electricity generation used is "additional" and is not simply claimed from another sector of the economy. Having strict "additionality criteria" is vital to ensure that dedicated renewable electricity generation capacity is installed to produce e-fuels rather than simply claiming relatively cheap guarantees of origin certificates. The European Commission had included proposals for additionality criteria during the consultation stages of its latest amendments to the Renewable Energy Directive II (European Commission, 2022). These aimed to ensure hydrogen producers would have to source electricity from a dedicated supply. However, the European Parliament did not vote in favour of including these additionality criteria in the final text, reportedly to reduce the barriers to early-stage hydrogen production (Parkes, 2022). Hydrogen producers will therefore be able to claim their fuel is low carbon using power purchase agreement certificates.

Recent analyses for the United States by Ricks et al. (2022) and Europe by Zeyen et al. (2022) highlight that the absence of additionality criteria could lead to hydrogen production with carbon intensities worse than today's fossil fuel pathways. One proposed solution is to require electrolysers using grid electricity to match their electricity consumption with additional renewable generation on an hourly basis.

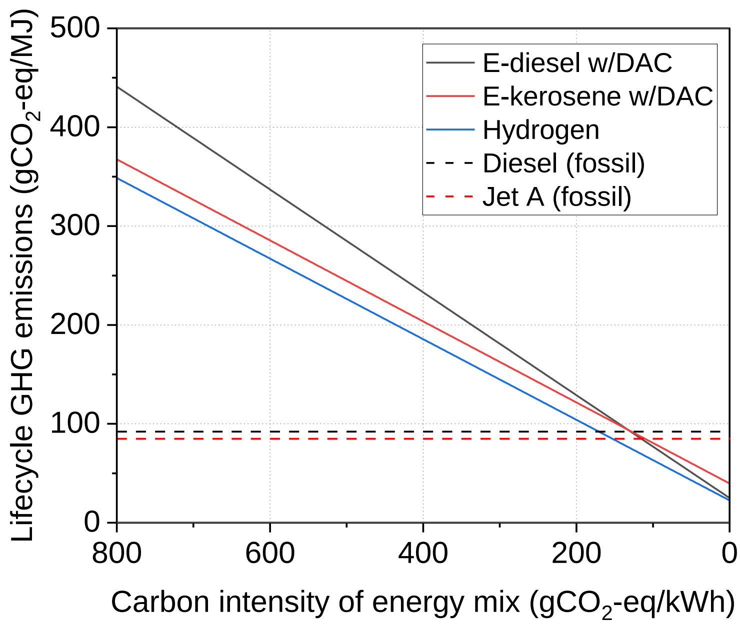
Lifecycle emissions of e-fuels

E-fuels only reduce emissions if their lifecycle emissions footprint is lower than conventional fuels. The high energy requirements for production translate to a high lifecycle carbon footprint unless all production steps rely on low-carbon electricity. The carbon footprint of electricity, conversion efficiency factors of production steps and the resulting CO_2 emissions from fuel combustion determine the emissions savings from using e-fuels compared to the production and CO_2 emissions from fossil fuel combustion. Figure 5 shows how the embedded emissions of input electricity impact the carbon footprint of three e-fuels (e-diesel, e-kerosene and hydrogen) compared with conventional fossil fuels (Jet A and diesel) based on analysis by Ueckerdt et al. (2021). For a direct comparison between various fuels, this analysis only considers the lifecycle emissions from the fuel, including fuel combustion, but not the conversion efficiency in an engine or turbine. The carbon-based fuels in Figure 5 use DAC as a feedstock.

Conventional fossil fuels have relatively little electricity input during production, meaning their lifecycle emissions are broadly constant over a varying carbon intensity of the energy mix and governed mainly by CO_2 emissions from fuel combustion – although future carbon intensity reductions are possible (IEA, 2021c). In contrast, the lifecycle emissions of e-fuels increases sharply in line with an increasing carbon footprint of power.

Hydrogen is the e-fuel with the lowest lifecycle GHG emissions and achieves emissions savings as long as the input electricity has a carbon intensity of less than 160 gCO_2-eq/kWh. The lifecycle GHG emissions of e-kerosene are higher because it involves more production processes than pure hydrogen. For this fuel, the input electricity must have a carbon intensity of 110 gCO_2-eq/kWh or less to safeguard climate benefits. For comparison, the average carbon intensity of electricity in 2021 was 270 gCO_2-eq/kWh in Europe and 425 gCO2-eq/kWh worldwide (Our World in Data, 2022). A substantial expansion of renewable electricity assets is necessary to ensure GHG emissions savings from using e-fuels in aviation or shipping.

Figure 5. Lifecycle GHG emissions of different aviation and maritime fuels under varying carbon intensity of the input electricity



Source: Adapted from Ueckerdt et al. (2021) with data from European Commission (2016).

Note: DAC = direct air capture; figure results do not account for non-CO_2 GHG effects of aviation such as NO_x, high-altitude soot particles, SO_2, contrail formation and accumulation of water vapour (Climate Action, 2020; Fuglestvedt et al., 2010). gCO_2-eq = grams of CO_2 equivalent.

The scale of renewable electricity required

Despite the record-high additions of new renewable energy capacity in major economies, mostly wind and solar, the energy mixes in most countries are far from being 100% renewable (IEA, 2020). Even continuing at this pace, more years are required to decarbonise the electricity sector. Displacing all primary fossil energy from transportation with e-fuels requires a significant amount of renewable energy, not least due to the poor conversion rate from electrical energy to e-fuels. Box 5 estimates the energy requirements for producing green hydrogen to displace the globally used fuel for shipping with e-methanol.

Additionally, all e-fuels rely on renewable hydrogen; the electrolyser capacity to produce hydrogen from renewable energy is one of the main impediments to the widespread adoption of e-fuels. Renewable hydrogen production is still rare, representing just 0.03% of the total hydrogen supply in 2020 (IEA, 2022b). The demand is gaining momentum as many energy-intensive sectors consider hydrogen a key to net zero (industry or chemical feedstock, long-distance transport and even energy storage). The global capacity for green hydrogen needs to grow 6 000 to 8 000 fold, relative to the 2021 baseline, to meet climate targets in line with the Paris Agreement (IEA 2021a; Odenweller et al., 2022).

Two key insights emerge from these considerations: First, significant electrolyser capacity and renewable energy growth is necessary to incorporate demand until 2050. Despite bold announcements of installed electrolyser capacities, many are not backed with final investment decisions, so uncertainties remain.

Long-term uncertainties in the role of hydrogen in the future can become more prominent if they are significant at the beginning of the growth rate. Therefore, large-scale hydrogen penetration will strongly benefit from demand increases in the early growth phase (Odenweller et al., 2022).

Second, renewable hydrogen will remain scarce in the near future. Thus, there will be competition between the sectors for green hydrogen. Accordingly, all sectors that can be decarbonised by measures other than hydrogen, such as via direct electrification in individual transport or road-based long-distance freight transportation, are of lower priority to use green hydrogen and e-fuels. The remaining hard-to-abate sectors should be allocated according to a merit-order system, which prioritises the sectors with the highest decarbonisation potential (Ueckerdt et al., 2021).

Box 5. Energy requirements for decarbonising shipping with e-methanol

The global maritime fuel demand reached approximately 203 Mt in 2021 (IEA, 2022c). Replacing this fossil fuel use with e-methanol (which has lower specific energy) would require a supply of 408 Mt if ship engines operate at similar efficiencies. Producing this amount of methanol requires approximately 126 Mt of renewable hydrogen, considering a 2% conversion loss (IEA, 2021b). To highlight the scale of infrastructure required to meet this demand, consider Australia's Western Green Energy Hub, one of the world's largest production plants for renewably produced hydrogen. Its planned capacity of 50 GW (with 3.5 Mt hydrogen production per year) represents approximately 7.5 times Germany's wind and solar capacity additions in 2021 (Umweltbundesamt, 2022). Producing enough hydrogen to displace the global shipping fuel demand in 2021 with synthetic methanol would require installing an additional 1.1 TW renewable electricity assets. This would be equivalent to approximately 22 plants with the capacity of the Western Green Energy Hub or the installation of 167 times the total added capacity from 2021 of renewable energy in Germany. If the emitted CO_2 is recaptured via DAC to ensure the circularity of carbon dioxide, additional renewable electricity generation would be required to operate the DAC facilities.

Policy frameworks to support e-fuels

E-fuels can cut emissions in the aviation and shipping sectors, but they are not competitive with conventional technologies today. Costs may decline with increasing production volumes and advancing technology. However, they are unlikely ever to be cheaper than current fossil fuel levels, which do not reflect environmental costs. Broad adoption by the two sectors in the absence of policy interventions is unlikely. International shipping and aviation face less environmental regulation today than other transport modes, which further hinders the self-sustaining market growth of e-fuels. However, effective policies can bring e-fuels to scale, and governments have several tools available to promote production and uptake by the two sectors.

This section presents policy designs that have proven effective for bringing low-carbon fuels into road transport. They have also undergone their first applications in selected markets in the aviation and shipping sectors. The section then provides an overview of existing frameworks to reduce climate impacts from fuel use in the two sectors. They include international programs from the International Maritime Organisation (IMO) and the International Civil Aviation Organisation (ICAO) and national policies in selected markets.

Existing policies demonstrate an increasing recognition by governments that e-fuels are essential for reaching international climate objectives in hard-to-abate sectors. They will complement biofuels, which are more advanced and cost-competitive today but may face sustainability limits when scaling in a decarbonising economy. Targeted support for e-fuels within broader low-carbon fuel strategies, for example, through multipliers in incentive programs or sub-targets within fuel mandates, could enable the industry to make them a mainstream technology.

Regulatory frameworks can steer the market growth of e-fuels

Policy makers can promote e-fuel market growth in shipping and aviation with supportive frameworks. There are three basic policy designs: carbon pricing, fuel blending mandate and low-carbon fuel standards.

Carbon pricing

Regulators may implement a carbon price as an emissions trading system (ETS) or a carbon tax. An ETS, or cap-and-trade mechanism, sets an annual decreasing emissions target and issues emissions allowances to regulated entities. Entities receive or buy credits through auctions and trade allowances with one another to comply with the target. Companies emitting below their allowance can sell surplus allowances to companies overshooting their budget. An ETS thus creates a market for carbon credits with a market price approximating industry-wide marginal abatement costs.

Carbon taxes and other taxes levied on fuel and energy use are common outside the aviation and maritime sectors. Carbon taxes are set on the CO_2 emissions produced from fuel combustion and can also address other negative externalities (e.g. air pollution) and concerns (e.g. energy security). Contrary to ETSs, the carbon price under a carbon tax does not result from market forces but is administratively set.

Both carbon pricing options increase the price of conventional fuel and create a more level playing field for e-fuels. However, they may fail to bring prices to matching levels due to the high costs of e-fuels. Also, regulated actors would prioritise cheaper emissions-saving opportunities over deploying e-fuels. This is why carbon prices may be of limited use for promoting e-fuel production unless coupled with more targeted policy designs, such as blending mandates or low carbon fuel standards. ETSs cap absolute emissions levels, and credit prices may be volatile. An oversupply of credits may lead to collapsing prices for certificates that do not incentivise emissions savings. One advantage of ETSs is the cost-efficient allocation of abatement measures, where actors with the lowest marginal abatement costs reduce emissions first. Carbon taxes do not offer this flexibility nor control absolute emissions levels. However, they offer price certainty for the cost of emitting carbon. Carbon prices will only provide targeted incentives to adopt e-fuels once cheaper options to reduce emissions are exhausted. This limits their effectiveness in promoting investments.

Fuel blending mandate and low-carbon fuel standards

A fuel blending mandate aims to reduce the carbon intensity of fuel by promoting investment in lower-carbon fuel production. It prescribes the blending of specific quotas of alternative fuel with conventional fuel, either as a blending share or in absolute quantity, over given periods. The responsibility for blending can lie with different regulated entities: fuel suppliers, aircraft or ship operators.

Low-carbon fuel standards (LCFS) support the deployment of alternative fuels. They decrease the carbon intensity of fuel by setting a decreasing lifecycle-based carbon intensity target for fuel sold in the jurisdiction and allow regulated entities to trade credits to achieve the target. Fuels with a carbon intensity below the standard generate credits, while those above generate deficits. Trading credits establishes a prevailing market price. Regulated entities are fuel suppliers or companies producing, importing, distributing or selling fuel.

Both the fuel blending mandate and LCFS provide more targeted incentives to deploy e-fuels than carbon pricing. While they are effective at bringing a determined quantity of alternative fuels into the market, they do not offer price certainty. Overly ambitious policy targets may outstrip supply and lead to high fuel prices, while low requirements fall short of stimulating large investments in production. LCFS combine elements from fuel blending mandates and emissions trading systems. Their tradeable credits offer flexibility to regulated parties and promote a cost-efficient allocation of decarbonisation efforts. For the policy to be effective, penalties for non-compliance under blending mandates and LCFS must be higher than compliance costs. These policies may feature targeted support mechanisms for specific fuel types, such as e-kerosene within SAF programs, for example, through sub-blending mandates or credit multipliers.

Defining credible requirements on the lifecycle emissions footprint of alternative aviation fuels and on measuring and monitoring schemes is paramount to safeguarding a policy’s effectiveness for reducing emissions. Policies may define a minimum emissions reduction threshold for fuel eligibility or a list of eligible fuel production pathways and inputs.

Fuel tankering and carbon leakage may reduce the effectiveness of policies in increasing the deployment of e-fuels. Carbon leakage occurs if emissions-intense economic activities shift from regulated areas to those with less stringent rules. This limits the effectiveness of policies to realise net reductions. Fuel tankering is an airline practice of onboarding extra fuel to avoid refuelling at airports with higher fuel costs. This leads to excess fuel burn and CO_2 emissions. Both phenomena may reduce the effectiveness of policies, yet policy design can prevent them.

Financial instruments can direct capital to the emerging e-fuel sector

To support the market entry of e-fuels, financial instruments to mobilise R&D investments and first production assets are essential. Governments have a suite of tools available to complement or precede regulatory frameworks that mandate the deployment of e-fuels. Table 2 provides examples of policy designs, ranging from mechanisms that assist the industry in accessing finance from lenders to direct subsidies for economic activities that promote the deployment of e-fuels. Today, direct and indirect subsidies are common in the energy, shipping and aviation sectors. Although, their design often does not target activities or products that reduce emissions. Providing incentives contingent on complying with sustainability criteria can maximise products' sustainability benefits. Programs may focus on industry activities that would not be realised without government support, for example, where high uncertainty related to a new technology holds back private investments.

Table 2. Financial instruments to assist investments in decarbonisation technologies

Instrument	Description
Debt service reserves	Governments keep cash deposits to make interest and principal payments in case a private borrower fails to make scheduled payments.
Government-held subordinated debt	The public agency agrees to take on a lower priority position for debt repayment than senior debt holders, allowing senior debt holders to be repaid fully before other debt holders. This eases the borrower's access to private capital.
Credit insurance products for bond financing	Government insurance agrees to make bond payments in case the issuer defaults.
Public loans and loan guarantees	Include export credits for technology, where governments can lend directly to the private sector or act as a guarantor for the private sector to obtain a market loan with a lower interest rate.
Grants	Can fully or partially cover interest payments on private loans or specific project expenses.
Co-investment	Helps share commercial risk between the public sector and private partners.
Market commitments	Governments guarantee the purchase of a number of aircraft or an amount of fuel that meets specified emissions characteristics. In the case of fuels, these include offtake agreements – i.e. arrangements between a producer and a buyer to purchase or sell the (low-carbon) energy that will be produced.
Contracts for Difference	Commit the government to pay part or all of the cost difference between conventional fuels, vessels or aircraft and lower-emission versions.
Tax incentives	Advantageous tax treatment of R&D expenditures and incomes attributable to R&D or patents.

Note: This list is not exhaustive.

Source: ITF (2021a; 2021b).

Agreed criteria on what industry activities count as sustainable are essential to allocate policy support that optimises sustainable outcomes. They also assist industries in qualifying for green bonds, which are debt instruments used to finance green projects that deliver environmental benefits (OECD et al., 2016). The EU taxonomy for sustainable activities (EU taxonomy) is the most advanced set of green investment criteria and includes provisions on low-carbon fuels, including e-fuels. With the Inflation Reduction Act, the United States has recently launched a comprehensive subsidy programme to accelerate the adoption of affordable, green hydrogen (Box 6).

Box 6. Unlocking hydrogen production cost reductions: The Inflation Reduction Act

Decarbonisation strategies for hard-to-abate sectors rely on strong production increases and cost reductions of green hydrogen. This includes e-fuel deployment in aviation and shipping.

Renewable electricity costs strongly impact the price of green hydrogen production. The cost of electricity from renewables is already lower than that of thermal generation in many regions. Further reductions, along with electrolyser technology improvements, are key technology policy objectives.

Several governments have launched strategies to scale up green hydrogen. The United States 2022 Inflation Reduction Act (IRA) is a flagship policy among these. The comprehensive policy package embraces several sectors of the economy. It offers tax credits to incentivise renewable electricity and hydrogen production from green (renewables with electrolysis), pink (nuclear power with electrolysis) and blue (natural gas with CCS) pathways. The IRA proposes investment tax credits (ITC) and production tax credits (PTC). ITC accrues as a one-time incentive, and PTC accrues over ten years.

ITC and PTC result in variable incentives for hydrogen production – between USD 0.6-3/kg. It is highest for production pathways that maximise emissions reductions and enterprises that fulfil domestic manufacturing and employment conditions criteria. The program is expected to benefit green hydrogen the most because its supply chain will benefit from stacked incentives for both renewable electricity and hydrogen production.

The United States framework offers the most support for green hydrogen among existing policies. It may reduce green hydrogen costs to USD 0.39/kg by 2030, significantly lower than price projections for conventional pathways. Incentives are highest for projects that launch no later than 2023, which signals increasing capacity for green hydrogen production starting from the short term.

Cheap green hydrogen will benefit decarbonisation efforts in several hard-to-abate segments in the industry and transport sectors, including shipping and aviation. The United States Grand SAF Challenge is a government plan to scale up SAF to reach 3 billion gallons of SAF use by 2030 (11-12% of projected aviation fuel demand) and 40 billion gallons (100% of projected aviation fuel demand) by 2050. The policy does not define a sub-target for e-kerosene, yet the strong support for green hydrogen under the IRA could promote e-kerosene within the SAF mix.

Source: Atlantic Council (2022); Seiple (2022).

Policies to promote e-fuels in aviation

The successful market entry of e-kerosene and hydrogen aircraft depends on supportive policy frameworks. This is because they are currently at an early technology stage and not cost-competitive with conventional fuel and aircraft technologies. Many governments have launched programs to promote SAF from bioenergy and PtL. These programs benefit the market scale-up of e-kerosene and hydrogen (a component of e-kerosene). However, the existing SAF supply predominantly consists of first-generation biofuels, and the e-kerosene market share will remain very small until 2025.

Existing aviation policy frameworks focus more on SAF than on novel propulsion technologies. SAF, including e-kerosene, is more market-ready than hydrogen aircraft because of its compatibility with existing aircraft technology. Hydrogen aircraft face more challenges due to their earlier technology stage and incompatibility with existing refuelling systems. Nevertheless, public R&D programs supporting this emerging technology could reduce emissions on selected flight missions.

Policy frameworks to promote alternative fuels and efficient technologies in aviation tend to be less strict than other transport modes. For example, many markets mandate the use of biofuels in the road sector, while frameworks focusing on SAF have only emerged recently in selected markets.

Airlines operate in global markets, and individual governments that implement environmental regulations or taxes face higher risks of distorting competition than equivalent policies, for example, in road freight transport. Existing fuel tax exemptions for most international flights and many domestic markets create a low global fuel cost benchmark and challenge environmental regulations that would increase airline costs.

The common practice of exempting international aviation from fuel taxation originates from the 1944 Convention on International Civil Aviation (Chicago Convention), which led to the creation of ICAO. ICAO recommends not taxing fuel use for international aviation. Its resolutions are only binding if ratified into national law (ITF, 2021b), yet air service agreements between countries commonly adopt its fuel tax exemption principles. Domestic aviation does not fall under the Chicago Convention, and several governments apply fuel taxes for domestic flights.

ICAO is responsible for international aviation regulations, including environmental issues and sector objectives. In 2010, ICAO member states adopted the goals of achieving average fuel efficiency improvements of 2% per year between 2020 to 2050 and carbon-neutral sector growth from 2020 to 2040 (ICAO, 2010). The 41st ICAO Assembly in September-October 2022 adopted a long-term global aspirational goal for international aviation to reach net-zero CO_2 emissions by 2050. This recognises SAFs as an essential measure for reducing emissions in the sector (ICAO, 2022).

The ICAO instruments to reach carbon-neutral growth from 2020 onwards are: operational improvements, aircraft technology, deploying bioenergy SAF and a voluntary market-based measure called the Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA). After the Covid-19 outbreak in 2020, ICAO changed the baseline year for this carbon-neutral growth from a 2019/2020 average to 2019 levels. This baseline reflects pre-pandemic aviation activity levels. The gradual recovery of air travel means that airlines' emissions may remain below the CORSIA baseline for several years without additional decarbonisation efforts (ITF, 2021b).

Airlines in markets that participate in CORSIA can offset emissions growth over the threshold by buying tradeable carbon credits or offsets or by deploying CORSIA-eligible fuels with low carbon intensity. The definition of CORSIA-eligible fuels is currently under development. CORSIA was designed for implementation in phases, with a pilot period (2021-23) and a first phase (2024-26) that applies to states that have volunteered to participate. A second phase (2027-35) will apply to states that account for the vast majority of total international aviation activity (ICAO, 2019).

With its tradeable emissions offsets, ICAO's CORSIA is currently the only global market-based measure that addresses CO_2 emissions from international civil aviation. However, the low market prices for emissions certificates provide limited incentives for airlines to increase the deployment of SAF, especially e-kerosene, which comes at a higher abatement cost. Aircraft technology improvements are one of the various measures to achieve carbon-neutral growth from 2020 to 2040. This could include hydrogen aircraft in a wider sense.

The European Union (EU) is the first large aviation market with an elaborate SAF strategy explicitly promoting e-fuels. The ReFuelEU Aviation policy proposal, released by the European Commission in 2021 and amended by the European Parliament in 2022, envisages a gradually increasing SAF blending target for the regional block. These include sub-targets for e-fuels that would apply to domestic and international flights departing from EU airports. The SAF blending mandate would go into effect in 2025 with 2% of all supplied fuel, increasing to 6% by 2030 and reaching 85% by 2050. Synthetic fuels are allocated shares within the general SAF blending target, starting from an initial 0.04% within the SAF mandate in 2025, increasing to 2% by 2030 (equivalent to 0.1% in all aviation fuel supply) and reaching 50% (equivalent to 42.5% in all aviation fuel supply) by 2050 (Table 3). Following adoption by the European Parliament, the proposal is currently under negotiation with the EU member states.

Table 3. Proposed sustainable aviation fuel blending targets under ReFuelEU Aviation

Target date (1 January)	Minimum share of sustainable aviation fuel in total fuel use (%)	Minimum share of e-fuels in sustainable aviation fuel use (%)	Minimum share of e-fuels in total fuel use (%)
2025	2	0.04	< 0.00
2030	6	2	0.1
2035	20	5	1
2040	37	13	4.8
2045	54	27	14.6
2050	85	50	42.5

Note: The listed target values reflect amendments by the European Parliament to an initial European Commission proposal. The amendments were adopted in 2022 and increased the ambition of the blending targets initially proposed by the European Commission.

Source: European Parliament (2022).

The blending mandate would apply to fuel suppliers at all EU airports. A ten-year transition period will offer flexibility to meet blending requirements as an average across airports, for example, through book-and-claim or mass balance approaches for SAF distribution and accounting. The transition period will enable the rollout first at airports where supplying SAF is the cheapest. Provisions require flight operators to take up at least 90% of fuel needs at the origin airport to prevent airlines from fuel tankering, i.e. carrying excess kerosene on inbound flights from non-EU airports with lower fuel costs. The framework would penalise non-compliant parties, and collected fines would contribute funding to a Renewable and

Low-Carbon Fuels Value Chain Industrial Alliance, a program to support SAF research and production. The blending mandate for synthetic aviation fuels (e-fuels) considers renewable hydrogen, renewable electricity and renewable fuels of non-biological origin[2]. ReFuelEU Aviation supports the objectives of the European Green Deal, the EU strategy to become a climate-neutral continent by 2050. It integrates with a broad regulatory framework concerning the energy and transport sectors.

Thanks to its binding blending mandate, the European framework is the most progressive policy to promote SAFs. E-kerosene will play a smaller role than bioenergy-based SAFs until 2050, given its lower blending target and higher costs. Nevertheless, ReFuelEU Aviation creates the market demand for e-kerosene and provides certainty to invest in increasing production, thus opening a path for market growth and cost reductions. Further to the regional framework of ReFuelEU Aviation, several European national strategies promote e-kerosene.

EU member Germany launched a PtL roadmap in 2021. It intends to produce 200 000 tonnes of e-kerosene by 2030, representing a 2% share of aviation fuel use at German airports in 2019 (BMDV, 2021). The roadmap will support the German industry to reach targets under ReFuelEU Aviation and integrates with the National Hydrogen Strategy (BMWi, 2020). Germany plans to launch several government programs to support R&D and e-kerosene production to scale up from pilot plants to commercial production.

Germany's funding program for renewable fuels reaches EUR 1.54 billion for 2021-24, of which EUR 640 million is available for R&D and EUR 900 million for production and market ramp-up. Only projects using advanced bioenergy feedstock are eligible for funding, as listed under Part B of Annex IX in the EU's Renewable Energy Directive. A dedicated platform and funding guidelines to support PtL are currently under development. The guideline design is under revision by the European Commission for state aid approval. The funding guideline aims to reduce production costs for e-kerosene. It narrows the price gap with other SAFs and focuses on plants that produce more than 10 000 tonnes of fuel per year, aiming for price reductions within ten years. There is no requirement for eligible plants to produce e-kerosene exclusively, yet their output must have a minimum share of e-kerosene. Support for these pioneering plants will focus on domestic projects. Yet, there are expectations for an e-kerosene production increase in other regions with high renewable energy potential once the technology becomes commercial (BMVI, 2021).

The United Kingdom's policy proposal to promote SAF combines a regulatory framework that would mandate the use of SAF with several incentive programs to encourage production using innovative pathways – both advanced bioenergy and PtL. After a public consultation on the policy design, the government confirmed in 2022 plans for a SAF mandate to go into effect in 2025 and reach a 10% SAF share in 2030. The policy design is a low-carbon fuel standard under which fuel suppliers must meet defined average emissions intensity rather than a SAF volume. Entities that over or underperform can trade credits. E-kerosene has a smaller emissions footprint than bioenergy SAF, making it more eligible for incentives. To offer additional incentives for e-kerosene, the government confirmed intentions for a sub-target for e-kerosene with an unconfirmed volume (as of September 2022). The consultation documents also recommend aligning targets with the EU's ReFuelEU Aviation framework. Once adopted, the policy will be a stand-alone policy promoting SAF uptake with more targeted support than offered by the existing Renewable Transport Fuel Obligation, which currently includes aviation fuel (Department for Transport, 2022).

Policies to promote e-fuels in maritime transport

In 2018, the International Maritime Organisation (IMO) adopted an initial strategy for reducing GHG emissions from ships to align with temperature targets of the UN Paris Agreement in 2015 (well below 2°C above pre-industrial levels and pursuing efforts to limit the temperature increase to 1.5°C of warming) (IMO, 2018). However, existing IMO regulations are insufficient to reach these goals, and there have been no specific proposals to promote e-fuel adoption. One shortcoming of the IMO Energy Efficiency Design Index (EEDI) (GLOMEEP, 2020) is its focus on direct CO_2 emissions that do not account for fuel production emissions. This failure to account for all lifecycle emissions risks creating incentives to adopt inappropriate fuels.

In 2021, the European Commission published a proposal for a regulation to promote the use of renewable and low-carbon fuels in the maritime sector, commonly referred to as the FuelEU Maritime proposal (European Commission, 2021). The proposal contains specific targets for the GHG intensity of fuels used in the European maritime sector, increasing stringency over time. The targets are expressed in terms of well-to-wake GHG emissions accounting for upstream fuel production emissions. They aim to lower the GHG intensity of fuels by 2% by 2025, 13% by 2035 and 75% by 2050 from a reference value. The proposal aims for renewable and low-carbon fuels to represent between 6-9% of fuel use in 2030 and between 86-88% by 2050.

However, the proposal has received criticism for including LNG within the list of permitted fuels until 2040. Since the target design is "technology-neutral", only the cheapest alternative fuel is likely to be adopted. This strongly promotes LNG. Ship operators would have little incentive to adopt other lower-carbon but more expensive fuels under current proposals. One suggested remedy to this problem is to include "multiplier" effects within the policy. This would give additional emissions reduction credit to novel renewable e-fuels to stimulate their adoption and cost reductions via economies of scale (Transport & Environment, 2021).

The FuelEU Maritime proposal is part of a basket of measures included in the EU's Green Deal policy package. In 2020, the European Parliament approved the inclusion of CO_2 emissions from the maritime sector in the EU Emissions Trading System (ETS). This uses revenues to support investment in innovative technologies and infrastructure to decarbonise the maritime transport sector (European Parliament, 2020). Further developments will follow negotiations with member states on the final shape of the legislation.

The Clydebank declaration, a recent policy initiative launched at COP26 in Glasgow in 2021, aims to promote "green shipping corridors". The 24 signatory governments from around the world seek to establish at least six maritime trade routes using zero-emissions fuels in ships by 2025, to scale up to a larger number by 2030. The initiative aims to accelerate partnerships between ports, ship operators and other stakeholders from the freight value chain to jointly develop projects for zero-emissions ships (Department for Transport, 2021).

Notes

1 Aircraft activity is set to triple from today's levels (1 035 Mt in 2019) by 2050. Assuming aircraft manage to improve in efficiency by 50%, that means annual emissions in 2050 will be 1.5 times today's levels, so 1.5 Gt CO_2 that would have to be removed from the atmosphere every year (ignoring non-CO_2 effects). CO_2 makes up 0.04 mol % of the air (400 ppm), which corresponds to 0.018 kg CO_2/kmol of air. So to capture 1.5 GtCO_2, one would have to process 8.3×10^{13} kmol of air, assuming a 100% capture rate of the CO_2. Air has a molar mass of 29 kg/kmol. So you would have to process 2.41×10^{15} kg air per year. Since the density of air is about 1.23 kg/m^3 at atmospheric conditions, this corresponds to about 2×10^{15} m^3 of air per year. Putting that in simpler language: you would have to process 62.6 million cubic metres of air per second, assuming 24/7 operation. A Rolls-Royce Trent 9000 jet engine, one of the world's largest jet engines, which is used to power the Airbus A380 airliner, has an air mass flow rate of 1 245 kg/s (approx. 1 000 m^3/s at sea level). In order to displace 62.6 million cubic metres per second, you would need 63 000 engines running 24/7 per year.

The global fleet of aircraft in 2019 was approximately 25 000 vehicles (excluding small turboprops which emit a negligible share of emissions) (Oliver Wyman, 2021). Assuming aircraft numbers triple in line with demand 25 000 × 3 = 75 000 vehicles by 2050. This means to offset the emissions from each aircraft (neglecting non-CO_2 effects) would require one of the largest jet engines running 24/7 and capturing 100% of the CO_2 that passes through it. Orca units today reportedly require 0.7 kWh of electricity and 11.9 MJ of low-temperature heat per kg of CO_2 captured (Deutz and Bardow, 2021). The low-temperature heat could potentially be supplied using a heat pump requiring 1.3 kWh of electricity per kg of CO_2. Climeworks aim to reduce energy needs to 0.5 kWh of electricity and 5.4 MJ of heat per kg of CO_2 in future. We retain today's energy requirements for illustration purposes. Each Orca unit would therefore require 350 MWh of electricity to capture 500 t of CO_2 per year assuming freely available waste heat or 1 GWh of electricity if the waste heat were produced with a heat pump (with coefficient of performance 2.51). Assuming solar panels deliver approximately 0.35 kWh/m^2/day (van de Ven et al. 2021) in high solar potential areas means that each Orca unit would require ~2 700 m^2 of solar panels (~7 800 m^2 with heat pumps).

2 As defined in Article 2 36 of Directive (EU) 2018/2001.

References

ABS (2021), *Sustainability Whitepaper: Methanol as Marine Fuel*, https://absinfo.eagle.org/acton/media/16130/sustainability-whitepaper-methanol-as-marine-fuel.

ACI (2021), *Integration of Hydrogen Aircraft into the Air Transport System*, www.ati.org.uk/wp-content/uploads/2021/08/aci-ati-hydrogen-report-1.pdf.

Airbus (2022a), "Airbus, Air Liquide, Korean Air and Incheon International Airport Corporation partner to pioneer the use of hydrogen in the decarbonization of the aviation sector in Korea", press release, www.airbus.com/en/newsroom/press-releases/2022-02-airbus-air-liquide-korean-air-and-incheon-international-airport (accessed 16 September 2022).

Airbus (2022b), "Airbus and Kansai Airports partner to study the use of hydrogen in the decarbonisation of the aviation sector in Japan", press release, www.airbus.com/en/newsroom/press-releases/2022-06-airbus-and-kansai-airports-partner-to-study-the-use-of-hydrogen-in (accessed 16 September 2022).

Airbus (2022c), "Airbus signs agreement to study hydrogen hub in Singapore", press release, www.airbus.com/en/newsroom/press-releases/2022-02-airbus-signs-agreement-to-study-hydrogen-hub-in-singapore (accessed 16 September 2022).

ASTM International (2022a), *Practice for Evaluation of New Aviation Turbine Fuels and Fuel Additives: D4054-22*, West Conshohocken.

ASTM International (2022b), *Standard Specification for Aviation Turbine Fuel Containing Synthesized Hydrocarbons: D7566-22*, West Conshohocken.

Atlantic Council (2022), "The Inflation Reduction Act will accelerate clean hydrogen adoption", *Atlantic Council,* 20 September, www.atlanticcouncil.org/blogs/energysource/the-inflation-reduction-act-will-accelerate-clean-hydrogen-adoption (accessed 6 October 2022).

Balcombe, P. et al. (2017), "The Natural Gas Supply Chain: The Importance of Methane and Carbon Dioxide Emissions", *ACS Sustainable Chemistry & Engineering*, Vol. 5/1, pp. 3-20, https://doi.org/10.1021/acssuschemeng.6b00144.

BMDV (2021), *PtL Roadmap 2021*, https://bmdv.bund.de/SharedDocs/DE/Anlage/G/ptl-roadmap-englisch.pdf?__blob=publicationFile (accessed 10 June 2022).

BMVI (2021), "Germany/BMVI Policies to support Power-to-Liquid", presentation at the "OECD/ITF DT Implement Aviation Common Interest Group Second Meeting", 7 December 2021.

BMWi (2020), *Nationales Reformprogramm 2020 – Die Nationale Wasserstoffstrategie (National Reform Programme – The National Hydrogen Strategy)*, www.bmwk.de/Redaktion/DE/Publikationen/Energie/die-nationale-wasserstoffstrategie.pdf?__blob=publicationFile&v=20 (accessed 10 June 2022).

Carbon Recycling International (2022a), "George Olah Renewable Methanol production plant", www.carbonrecycling.is/project-goplant (accessed 20 September 2022).

Carbon Recycling International (2022b), "The Shunli CO_2-to-methanol plant: commercial scale production in China", www.carbonrecycling.is/projects (accessed 20 September 2022).

CFM International (2022), "CFM and Airbus to Pioneer Hydrogen Combustion Technology – CFM International", press release, www.cfmaeroengines.com/press-articles/cfm-and-airbus-to-pioneer-hydrogen-combustion-technology (accessed 5 October 2022).

Chatterjee, S., Parsapur, R.K. and Huang, K.-W. (2021), "Limitations of Ammonia as a Hydrogen Energy Carrier for the Transportation Sector", *ACS Energy Letters*, Vol. 6/12, pp. 4390-4394, https://doi.org/10.1021/acsenergylett.1c02189.

Chen, J., Liang, J., Xu, Z. & E, J. (2020), "Assessment of supercritical water gasification process for combustible gas production from thermodynamic, environmental and techno-economic perspectives: A review", *Energy Conversion and Management*, Vol. 226, p. 113497, https://doi.org/10.1016/j.enconman.2020.113497.

Clean Sky 2 JU and FCH 2 JU 2020, *Hydrogen-powered aviation: A fact-based study of hydrogen technology, economics, and climate impact by 2050*, Luxembourg, https://doi.org/10.2843/471510.

Climate Action (2020), *Updated analysis of the non-CO_2 effects of aviation*, https://climate.ec.europa.eu/news-your-voice/news/updated-analysis-non-co2-effects-aviation-2020-11-24_en (accessed 29 August 2022).

Climeworks (2022), "Direct air capture technology and carbon removal", https://climeworks.com/direct-air-capture (accessed 06 October 2022).

Delta (2022), "A decarbonized future for flight: Delta and Airbus collaborate to pull forward the future of hydrogen fuel", *Delta News Hub,* 17 March, https://news.delta.com/decarbonized-future-flight-delta-and-airbus-collaborate-pull-forward-future-hydrogen-fuel (accessed 16 September 2022).

Department for Transport (2021), *COP 26: Clydebank Declaration for green shipping corridors*, policy paper, UK Government, http://www.gov.uk/government/publications/cop-26-clydebank-declaration-for-green-shipping-corridors (accessed 06 October 2022).

Department for Transport (2022), *Sustainable aviation fuels mandate: Summary of consultation responses and government response*, UK Government, https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/1100050/sustainable-aviation-fuels-mandate-summary-of-consultation-responses-and-government-response.pdf (accessed 30 September 2022).

Deutsche Welle (2022), "Aviation: Germany opens world's first plant for clean jet fuel", http://www.dw.com/en/sustainable-aviation-fuel-power-to-liquid/a-59398405 (accessed 06 October 2022).

Deutz S. and Bardow A. (2021), "Life-cycle assessment of an industrial direct air capture process based on temperature–vacuum swing adsorption", *Nature Energy*, Vol. 6, pp. 203-213, https://doi.org/10.1038/s41560-020-00771-9.

Dieterich, V. et al. (2020), "Power-to-liquid via synthesis of methanol, DME or Fischer–Tropsch-fuels: a review", *Energy & Environmental Science*, Vol. 13, pp. 3207-3252, https://doi.org/10.1039/D0EE01187H.

DNV (2022), "Methanol as a potential alternative fuel for shipping", http://www.dw.com/en/sustainable-aviation-fuel-power-to-liquid/a-59398405 (accessed 01 September 2022).

Department Of Energy (2006), *Potential Roles of Ammonia in a Hydrogen Economy: A Study of Issues Related to the Use Ammonia for On-Board Vehicular Hydrogen Storage*, United States Government, www.energy.gov/sites/prod/files/2015/01/f19/fcto_nh3_h2_storage_white_paper_2006.pdf.

European Commission (2016), *Alternative fuels for marine and inland waterways*, Joint Research Centre, https://doi.org/10.2790/227559.

European Commission (2021), Regulation of the European Parliament and of the Council on the use of renewable and low-carbon fuels in maritime transport and amending Directive 2009/16/EC, 2021st edition, Brussels, https://op.europa.eu/en/publication-detail/-/publication/9cb8364b-e637-11eb-a1a5-01aa75ed71a1 (accessed 10 May 2022).

European Commission (2022), "Commission launches consultations on the regulatory framework for renewable hydrogen", https://ec.europa.eu/info/news/commission-launches-consultation-regulatory-framework-renewable-hydrogen-2022-may-20_en.

European Parliament (2020), "Shipping industry must contribute to climate neutrality, say MEPs", www.europarl.europa.eu/news/en/press-room/20200703IPR82633/shipping-industry-must-contribute-to-climate-neutrality-say-meps (accessed 7 October 2022).

European Parliament (2022), "Sustainable aviation fuels (ReFuelEU Aviation Initiative): Ordinary legislative procedure: first reading", www.europarl.europa.eu/doceo/document/TA-9-2022-0297_EN.html (accessed 30 September 2022).

Freudenberg (2022), "Ship Lengths Ahead", press release, www.freudenberg.com/press-media/press-releases/detail/ship-lengths-ahead# (accessed 22 September 2022).

Fuglestvedt, J.S. et al. (2010), "Transport impacts on atmosphere and climate: Metrics", *Atmospheric Environment*, Vol. 44/37, pp. 4648-4677, https://doi.org/10.1016/j.atmosenv.2009.04.044.

GE Gas Power (2022), "Hydrogen-Fueled Gas Turbines", www.ge.com/gas-power/future-of-energy/hydrogen-fueled-gas-turbines (accessed 5 October 2022).

Hoelzen, J. et al. (2022), "H_2-powered aviation at airports – Design and economics of LH_2 refueling systems", *Energy Conversion and Management: X*, Vol. 14, 100206, https://doi.org/10.1016/j.ecmx.2022.100206.

IATA (2019), *Aircraft Technology Roadmap to 2050*, Geneva, https://www.iata.org/contentassets/8d19e716636a47c184e7221c77563c93/aircraft-technology-net-zero-roadmap.pdf.

ICAO (2010), *ICAO Resolution on Climate Change: Resolution A37-19*, www.icao.int/environmental-protection/37thAssembly/A37_Res19_en.pdf (accessed 26 September 2022).

ICAO (2017), *Airline Operating Costs and Productivity, Economic Development*, ICAO presentation, 20 February 2017, www.icao.int/mid/documents/2017/aviation%20data%20and%20analysis%20seminar/ppt3%20-%20airlines%20operating%20costs%20and%20productivity.pdf (accessed 20 September 2022).

ICAO (2019), *2019 Environmental Report: Destination Green: The Next Chapter*, http://www.icao.int/environmental-protection/Documents/ICAO-ENV-Report2019-F1-WEB%20%281%29.pdf (accessed 30 September 2022).

ICAO (2022), "Long term global aspirational goal (LTAG) for international aviation", www.icao.int/environmental-protection/Pages/LTAG.aspx (accessed 01 November 2022).

ICCT (2022), *Performance Analysis of Evolutionary Hydrogen-Powered Aircrafts*, https://theicct.org/publication/aviation-global-evo-hydrogen-aircraft-jan22, (accessed 25 June 2022).

IEA (2020), *Carbon intensity of electricity generation in selected regions in the Sustainable Development Scenario, 2000–2040: Data & Statistics*, IEA, Paris, www.iea.org/data-and-statistics/charts/carbon-intensity-of-electricity-generation-in-selected-regions-in-the-sustainable-development-scenario-2000-2040 (accessed 07 October 2022).

IEA (2021a), *Net Zero by 2050: A Roadmap for the Global Energy Sector*, IEA, Paris, https://doi.org/10.1787/c8328405-en.

IEA (2021b), "Hydrogen Projects Database", IEA, Paris, www.iea.org/data-and-statistics/data-product/hydrogen-projects-database (accessed 31 August 2022).

IEA (2021c), "Vehicle Fuel Economy in Major Markets 2005–2019", *IEA Working Papers*, Paris, https://iea.blob.core.windows.net/assets/79a0ee25-9122-4048-84fe-c6b8823f77f8/GlobalFuelEconomyInitiative2021.pdf.

IEA (2022a), *Direct Air Capture: A key technology for net zero*, IEA, Paris, https://doi.org/10.1787/bbd20707-en.

IEA (2022b), *Global Hydrogen Review 2021*, IEA, Paris, www.iea.org/reports/global-hydrogen-review-2021 (accessed 30 August 2022).

IEA (2022c), "Tracking Clean Energy Progress: Assessing critical energy technologies for global clean energy transitions", IEA, Paris, http://www.iea.org/topics/tracking-clean-energy-progress (accessed 20 October 2022).

IEA (2022d), *Tracking Clean Energy Progress*, IEA, Paris, https://www.iea.org/reports/biofuels.

Imhoff, T.B., Gkantonas, S. and Mastorakos, E. (2021), "Analysing the Performance of Ammonia Powertrains in the Marine Environment", *Energies*, Vol. 14/21, 7447, https://doi.org/10.3390/en14217447.

IMO (2018), *Initial IMO Strategy on Reduction of GHG Emissions from Ships*, 72nd ed., https://www.imo.org/en/OurWork/Environment/Pages/IMO-Strategy-on-reduction-of-GHG-emissions-from-ships.aspx (accessed 09 September 2022).

IMO (2020), *Reduction of GHG Emissions from Ship: Fourth IMO GHG Study 2020 – Final report*, https://safety4sea.com/wp-content/uploads/2020/08/MEPC-75-7-15-Fourth-IMO-GHG-Study-2020-Final-report-Secretariat.pdf.

IRENA and AEA (2022), *Innovation Outlook: Renewable Ammonia*, Abu Dhabi, www.irena.org/publications/2022/May/Innovation-Outlook-Renewable-Ammonia.

IRENA and Methanol Institute (2021), *Innovation Outlook: Renewable Methanol*, Abu Dhabi, www.irena.org/publications/2021/Jan/Innovation-Outlook-Renewable-Methanol.

ITF (2019), *ITF Transport Outlook 2019*, OECD Publishing, Paris, https://doi.org/10.1787/25202367.

ITF (2020), "Navigating Towards Cleaner Maritime Shipping: Lessons from the Nordic Region", *International Transport Forum Policy Papers*, No. 80, OECD Publishing, Paris, https://doi.org/10.1787/ab3d3fbc-en.

ITF (2021a), "Cleaner Vehicles: Achieving a Resilient Technology Transition", *International Transport Forum Policy Papers*, No. 90, OECD Publishing, Paris, https://doi.org/10.1787/08cb5e7e-en.

ITF (2021b), “Decarbonising Air Transport: Acting Now for the Future”, *International Transport Forum Policy Papers*, No. 94, OECD Publishing, Paris, https://doi.org/10.1787/e22ae2ae-en.

ITF (2022), “Carbon Pricing in Shipping”, *International Transport Forum Policy Papers*, No. 110, OECD Publishing, Paris, https://doi.org/10.1787/250921ec-en.

Johnson, D. and Brown, G.V. (2005), “Power requirements determined for high-power-density electric motors for electric aircraft propulsion”, *Research and Technology 2004*, https://ntrs.nasa.gov/api/citations/20050217395/downloads/20050217395.pdf.

Kersey et al. (2022), “Rapid battery cost declines accelerate the prospects of all-electric interregional container shipping”, *Nature Energy*, Vol. 7, pp. 664-674, https://doi.org/10.1038/s41560-022-01065-y.

Klerk, A. de (2020), “Transport Fuel: Biomass-, Coal-, Gas- and Waste-to-Liquids Processes”, in Letcher, T. (ed.), *Future Energy: Improved, Sustainable and Clean Options for our Planet*, Elsevier.

Kobayashi, H. et al. (2019), “Science and technology of ammonia combustion”, *Proceedings of the Combustion Institute*, Vol. 37/1, pp. 109-133, https://doi.org/10.1016/j.proci.2018.09.029.

Laude, A. et al. (2011), “CO2 capture and storage from a bioethanol plant: Carbon and energy footprint and economic assessment” *International Journal of Greenhouse Gas Control*, Vol. 5/5, pp. 1220-1231, https://doi.org/10.1016/j.ijggc.2011.06.004.

Lhuillier, C. et al. (2020), “Experimental study on ammonia/hydrogen/air combustion in spark ignition engine conditions”, *Fuel*, Vol. 269, 117448, https://doi.org/10.1016/j.fuel.2020.117448.

Lufthansa (2022), “Sustainable Aviation Fuel”, http://www.lufthansagroup.com/en/responsibility/climate-environment/sustainable-aviation-fuel.html (accessed 06 October 2022).

Luxembourg Airport (2022), “Lux-Airport investing in the production of sustainable aviation fuel based on renewable energy by acquiring a shareholding in Norsk e-Fuel”, press release, http://www.lux-airport.lu/lux-airport-investing-in-the-production-of-sustainable-aviation-fuel-based-on-renewable-energy-by-acquiring-a-shareholding-in-norsk-e-fuel (accessed 06 October 2022).

Luxembourg Government (2022), “Lux-Airport investing in the production of sustainable aviation fuel based on renewable energy by acquiring a shareholding in Norsk e-Fuel”, press release, https://gouvernement.lu/en/actualites/toutes_actualites/communiques/2022/03-mars/29-bausch-luxairport.html (accessed 06 October 2022).

Mærsk (2022), “A.P. Moller - Maersk continues green transformation with six additional large container vessels”, press release, www.maersk.com/news/articles/2022/10/05/maersk-continues-green-transformation (accessed 07 October 2022).

Mærsk Mc-Kinney Møller Center for Zero Carbon Shipping (2022), “Deploying novel fuels in the shipping sector”, presentation at “ITF Corporate Partnership Board Project Workshop”, 1 April 2022.

Malcolm Pirnie, Inc. (1999), *Evaluation of the fate and transport of methanol in the environment*, www.methanol.org/wp-content/uploads/2016/06/White-Paper-The-Fate-Transport-of-Methanol-in-the-Environment-1999.pdf.

MAN ES (2022), “The case for two-stroke ammonia engines”, www.man-es.com/discover/two-stroke-ammonia-engine (accessed 12 September 2022).

McQueen, N. et al. (2021), "A review of direct air capture (DAC): scaling up commercial technologies and innovating for the future", *Progress in Energy*, Vol. 3/3, 32001, https://doi.org/10.1088/2516-1083/abf1ce.

Nordic Electrofuel AS (2022), "Unique Simulator for Electro Fuel Plant", press release, https://nordicelectrofuel.no/wp-content/uploads/2022/08/Press-Note-NEF-EFuel1-APPROVED.pdf (accessed 22 September 2022).

Odenweller, A. et al. (2022), "Probabilistic feasibility space of scaling up green hydrogen supply", *Nature Energy*, Vol. 7, pp. 854-865, https://doi.org/10.1038/s41560-022-01097-4.

OECD (2016), *Green Bonds: Country Experiences, Barriers and Options: In support of the G20 Green Finance Study Group*, OECD Publishing, Paris, www.oecd.org/environment/cc/Green_Bonds_Country_Experiences_Barriers_and_Options.pdf (accessed 10 June 2022).

Oliver Wyman (2021), "Global fleet and MRO market forecast 2021-2031", Insights blog, www.oliverwyman.com/our-expertise/insights/2021/jan/global-fleet-and-mro-market-forecast-2021-2031.html (accessed 16 December 2022).

ORNL (2021), *Spill behavior, detection and mitigation for emerging nontraditional marine fuels*, www.maritime.dot.gov/sites/marad.dot.gov/files/2021-05/ORNLAlt_Fuels_Spill_Study_Report_19Mar2021.pdf.

Ørsted (2022a), "Ørsted partners with Liquid Wind and expands presence in green fuels with investment in large-scale e-methanol project in Sweden", press release, https://orsted.com/en/media/newsroom/news/2022/01/orsted-partners-with-liquid-wind-and-expands-presence-in-green-fuels-with (accessed 19 September 2022).

Ørsted (2022b), "Partnership behind 'Green Fuels for Denmark' accelerates project and investigates production of green jet fuel by 2025", press release, https://orsted.com/en/media/newsroom/news/2022/02/20220204476711 (accessed 6 October 2022).

Our World in Data (2022), "Carbon Intensity of Electricity", dataset, https://ourworldindata.org/grapher/carbon-intensity-electricity?tab=table.

Parkes, R. (2022), "Scrapped | EU's controversial 'additionality' rules for green hydrogen are history after European Parliament vote", *Recharge*, 14 September, www.rechargenews.com/energy-transition/scrapped-eus-controversial-additionality-rules-for-green-hydrogen-are-history-after-european-parliament-vote/2-1-1299195.

Pontzen, F. et al. (2011), "CO_2-based methanol and DME – Efficient technologies for industrial scale production", *Catalysis Today*, Vol. 171/1, pp. 242-250, https://doi.org/10.1016/j.cattod.2011.04.049.

Pratt & Whitney (2022) "Pratt & Whitney Awarded Department of Energy Project to Develop Hydrogen Propulsion Technology", press release, https://newsroom.prattwhitney.com/2022-02-21-Pratt-Whitney-Awarded-Department-of-Energy-Project-to-Develop-Hydrogen-Propulsion-Technology (accessed 5 October 2022).

Ricks, W., Xu, Q., Jenkins, J. (2022) "Minimizing emissions from grid-based hydrogen production in the United States", *Environmental Research Letters*, Vol. 19/1, https://doi.org/10.1088/1748-9326/acacb5.

Rockström, J. et al. (2009), "A safe operating space for humanity", *Nature*, Vol. 461, pp. 472-475, https://doi.org/10.1038/461472a.

Rolls-Royce (2022), "Rolls-Royce announces leading-edge hydrogen programme and developments in hybrid-electric research", press release, www.rolls-royce.com/media/press-releases/2022/18-07-2022-rr-announces-leading-edge-hydrogen-programme-and-developments-in-hybrid.aspx (accessed 05 October 2022).

S&P (2021), "Methanol bunkers in the limelight after Maersk's latest ship orders", *S&P Global Commodity Insights,* 2021, www.spglobal.com/commodityinsights/en/market-insights/latest-news/energy-transition/091621-feature-methanol-bunkers-in-the-limelight-after-maersks-latest-ship-orders (accessed 22 September 2022).

Schäppi, R. et al. (2022), "Drop-in fuels from sunlight and air", *Nature*, Vol. 601, pp. 63-68. https://doi.org/10.1038/s41586-021-04174-y.

Schemme, S. et al. (2020), "H_2-based synthetic fuels: A techno-economic comparison of alcohol, ether and hydrocarbon production", *International Journal of Hydrogen Energy*, Vol. 45/8, pp. 5395-5414, https://doi.org/10.1016/j.ijhydene.2019.05.028.

Sdanghi, G. et al. (2019), "Review of the current technologies and performances of hydrogen compression for stationary and automotive applications", *Renewable and Sustainable Energy Reviews*, Vol. 102, pp. 150-170, https://doi.org/10.1016/j.rser.2018.11.028.

Seiple, C. (2022), "US Inflation Reduction Act set to make climate history", Wood Mackenzie, www.woodmac.com/news/opinion/us-inflation-reduction-act-set-to-make-climate-history (accessed 06 October 2022).

Steffen, W. et al. (2015), "Sustainability. Planetary boundaries: guiding human development on a changing planet", *Science*, Vol. 347/6223, 1259855, https://doi.org/10.1126/science.1259855.

Transport & Environment (2021), *FuelEU Maritime*, www.transportenvironment.org/wp-content/uploads/2021/08/FuelEU-Maritime.pdf (accessed 6 October 2022).

The Royal Society (2020), "Ammonia: zero-carbon fertiliser, fuel and energy store", https://royalsociety.org/topics-policy/projects/low-carbon-energy-programme/green-ammonia (accessed 01 September 2022).

Ueckerdt, F. et al. (2021), "Potential and risks of hydrogen-based e-fuels in climate change mitigation", *Nature Climate Change*, Vol. 11, pp. 384-393, https://doi.org/10.1038/s41558-021-01032-7.

Umweltbundesamt (2022), *Erneuerbare Energien in Zahlen (Renewable energies in figures)*, www.umweltbundesamt.de/themen/klima-energie/erneuerbare-energien/erneuerbare-energien-in-zahlen#strom (accessed 6 October 2022).

UNCATD (2021), *Review of Maritime Transport 2021*, New York, https://unctad.org/webflyer/review-maritime-transport-2021.

Vattenfall (2021), "SAS, Vattenfall, Shell and LanzaTech to explore synthetic sustainable aviation fuel production", press release, https://group.vattenfall.com/press-and-media/pressreleases/2021/sas-vattenfall-shell-and-lanzatech-to-explore-synthetic-sustainable-aviation-fuel-production (accessed 06 October 2022).

Verhelst, S. et al. (2019), "Methanol as a fuel for internal combustion engines", *Progress in Energy and Combustion Science*, Vol. 70, pp. 43-88, https://doi.org/10.1016/j.pecs.2018.10.001.

Vincent, I. and Bessarabov, D. (2018), “Low cost hydrogen production by anion exchange membrane electrolysis: A review”, *Renewable and Sustainable Energy Reviews*, Vol. 81, pp. 1690-1704, https://doi.org/10.1016/j.rser.2017.05.258.

VINCI Airports (2021), “Airbus, Air Liquide and VINCI Airports announce a partnership to promote the use of hydrogen and accelerate the decarbonization of the aviation sector”, press release, www.vinci-airports.com/en/news/airbus-air-liquide-and-vinci-airports-announce-partnership-promote-use-hydrogen-and-accelerate (accessed 16 September 2022).

Wartsila (2022), “Wärtsilä coordinates EU funded project to accelerate ammonia engine development”, press release, www.wartsila.com/media/news/05-04-2022-wartsila-coordinates-eu-funded-project-to-accelerate-ammonia-engine-development-3079950 (accessed 06 October 2022).

Wentrup, J., Pesch, G.R. and Thöming, J. (2022), “Dynamic operation of Fischer–Tropsch reactors for power-to-liquid concepts: A review”, *Renewable and Sustainable Energy Reviews*, Vol. 162, 112454, https://doi.org/10.1016/j.rser.2022.112454.

Wolfram, P. et al. (2022), “Using ammonia as a shipping fuel could disturb the nitrogen cycle”, *Nature Energy*, Vol. 7, pp. 1112–1114, https://doi.org/10.1038/s41560-022-01124-4.

Zeyen, E., Riepin, I., Brown, T. (2022) “Hourly versus annually matched renewable supply for electrolytic hydrogen”, *Zenodo*, https://zenodo.org/record/7457441#.Y6MFKo5KiUk.

Zhang, C. et al. (2014), “Efficient utilization of greenhouse gases in a gas-to-liquids process combined with CO2/steam-mixed reforming and Fe-based Fischer–Tropsch synthesis” *Environmental Science & Technology*, Vol. 48/14, pp. 8251-8257, https://doi.org/10.1021/es501021u.

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The Potential of E-fuels to Decarbonise Ships and Aircraft

This report examines the potential of novel fuels to decarbonise aviation and maritime shipping. Fuels like hydrogen, ammonia and synthetic hydrocarbons can be produced from renewable sources. They could also be easier to deploy than other emerging low- and zero-carbon technologies. Yet many uncertainties exist around scaling up their use. These include cost, infrastructure needs, operational requirements and health impacts. The project reviews the latest understanding of the production and use of novel fuels in the shipping and aviation sectors and highlights the policy requirements needed to accelerate their adoption.

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