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Low-carbon fuels: The last mile to net-zero

The role of synthetic fuels in decarbonizing the skies and the seas

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Table of contents

Glossary

Abbreviation	Meaning
CAPEX	Capital expenditure
$C_{12}H_{26}$	Kerosene
CH3OH	Methanol
CCUS	Carbon capture, utilization and storage
CO_2	Carbon dioxide molecule
DAC	Direct air capture
EU	European Union
EJ	Exajoules, equal to 10^{18} joules
FAO	Food and Agriculture Organization of the United Nations
FOGS	Fats, oils, and greases
GHG	Greenhouse gas
$GtCO_2$	Billion tons of CO_2
GW	Gigawatt, equal to 109 watts
HEFA	Hydro-processed Esters and Fatty Acids
HFO	Heavy-fuel oil
H2	Hydrogen molecule
HyPE	Hydrogen Pathway Explorer
ICCT	International Council on Clean Transportation
IEA	International Energy Agency
IMO	International Maritime Organization
IPCC	Intergovernmental Pannel on Climate Change
IRENA	International Renewable Energy Agency
ITF	International Transport Forum
kt	Kilotons
kW	Kilowatts

Abbreviation	Meaning
L-DAC	Liquid direct air capture
MJ	Megajoules
MSW	Municipal solid waste
$MtCO_2$	Million tons of CO_2
MtH_{2eq}	Million tons of hydrogen equivalent
MWh	Megawatt-hour
NH_3	Ammonia
NZE	Net-Zero Emissions
OECD	Organization for Economic Co-operation and Development
OPEX	Operational expenditure
RTKeq	Revenue Ton-Kilometers Equivalent
S-DAC	Solid direct air capture
SAF	Sustainable aviation fuels
t.km	Ton-kilometer
TRL	Technology readiness level
TWh	Terawatt-hour, equal to 10^{12} watt-hours
US	United States
WTO	World Trade Organization

Executive Summary

Reaching net-zero greenhouse gas emissions (GHG) by 2050 requires a fundamental transformation of society, from its current fossil fuel-centric model to an efficient, highly renewable and electrified energy system.

Clean hydrogen can complement electrification in some of the hard-to-abate sectors, such as steelmaking and chemicals. However, decarbonization of aviation and maritime shipping requires **low-carbon fuels**—including biofuels and synthetic fuels—with higher energy density than hydrogen and electricity.

Biofuels can be used handily as drop-in fuels in the existing combustion engines and fuel infrastructure, unlocking significant emission reductions in the short run. However, intense cross-sectoral competition for the limited feedstock for sustainable biomass production is expected to hinder their large-scale adoption. Therefore, **synthetic fuels** such as ammonia, methanol and synthetic kerosene are expected to become the dominant sources of low-carbon fuels supply in the long run.

Deloitte Global's outlook, leveraging a data-driven and model-based quantitative analysis, explores the uptake of **synthetic fuels as key enablers of decarbonizing aviation and maritime shipping.** In this outlook, aviation experiences stagnating carbon dioxide (CO_2) emissions until 2030, and about 75% of emission reductions by 2050. Maritime shipping reaches almost net-zero by 2050, experiencing 95% emission reductions. These emission reductions are driven mainly by efficiency measures and the uptake of low-carbon fuels, especially synthetic fuels. Synthetic fuels, almost absent from the current fuel mix, would only play a marginal role in 2030, supplying 1.6 exajoules (EJ) out of the 26 EJ consumed. Nevertheless, in Deloitte's outlook they emerge as the main source of energy in the air and on the seas by 2050, accounting for almost 16 EJ of fuel consumption.

Reaching such levels of synthetic fuel supply requires about 150 million tons of sustainable hydrogen and 700 million tons of climate-neutral CO_2. This represents a major industrial and technical challenge as the clean hydrogen sector is still in its infancy and CO_2 capture technologies have not yet been developed at large scale. Moreover, hydrogen production, fuel synthesis, and direct air capture together require up to 10,000 terawatt hours (TWh) of clean electricity supply by 2050 — equating to a third of global power generation in 2023. This is more than the current global renewable power generation produced today and requires an extensive upscaling of renewable power capacity; well beyond the progress made to date.

Although synthetic fuels hold the key to decarbonization of aviation and shipping, they are still at an early stage of deployment with almost non-existent regulatory frameworks, and significantly higher costs compared to fossil fuels. A **globally harmonized regulatory framework is crucial** for developing the necessary synthetic fuels in the inherently international sectors of aviation and shipping. Without public support, however, synthetic fuels will remain two to 10 times more expensive than conventional fossil fuels because of limited availability of low-cost CO_2 feedstock, inherent energy inefficiencies in the processes, and inter-sectoral competition for clean hydrogen. Reaching such levels of synthetic fuel supply comes with significant investment needs; almost US$130 billion on average annually through 2050. While it remains a small fraction of the global fossil fuel investments (US$1.1 trillion in 2024), it is comparable with the overall spendings on aviation and maritime shipping fuels. An important and necessary lever to enhance their economic competitiveness is offered by global trade. By connecting the least-cost resource locations to demand centers with limited renewable and climate-neutral CO_2 endowment, **global trade can help mitigate geographical imbalances** between supply and demand, increase overall economic efficiency, and foster economic development.

Synthetic fuel cost competitiveness is only a piece of the broader technological challenges in decarbonizing aviation and maritime shipping. While the decarbonization of aviation does not require major modification in infrastructure or engine modification, decarbonizing shipping suggests a **multi-fuel future** consisting of methanol and ammonia. This requires both utilization of the existing infrastructure during the transition and development of new bunkering, engine technologies and refueling infrastructure. Technological challenges associated with decarbonization therefore go beyond fuel supply.

In summary, transitioning away from fossil fuels in aviation and maritime shipping will likely require coordinated and ambitious efforts from each participant in the aviation and maritime shipping value chains:

- **Policymakers** are pivotal in creating the starting conditions, the required regulatory framework and continuous momentum. They should create visibility through national and sectoral strategies, to help enable the offtake by creating the demand through mechanisms such as blending mandates, and reducing the economic hurdle on the supply chain actors by providing economic support for low-carbon fuels. Continuous evolution of mandates and economic support will likely be key to ensuring the transition in the long run.
- **International organizations** are ideally placed to support a coordinated global transition by establishing common rulesets. They can support value creation and therefore global uptake of synthetic fuels by robust certification, that can enable book and claim mechanisms. Harmonized and common definitions can support avoiding carbon leakage or arbitrage opportunities.
- **Fuel suppliers** may need to proactively secure low-cost sustainable energy feedstock, notably clean hydrogen and climate-neutral CO_2, for the growing demand for synthetic fuels, thanks to early investments and partnerships with upstream actors. During the build-up phase of the synthetic fuels value chain, by blending biofuels they can support the technology scale-up and the development of the necessary infrastructure.
- **Airplane manufacturers and shipbuilders** should adapt their offers to meet sustainability needs. This means ensuring that airplane engines can run on high blends of synthetic fuels, and vessels compatible with new fuels, notably ammonia and methanol. Moreover, they should develop efficiency measures through investments in research and development and integrate them into their manufacturing processes, reducing both fuel costs and CO_2 emissions.
- **Airports and port authorities** are instrumental in laying the foundations for the adoption of synthetic fuels by putting the needed refueling infrastructure in place and ensuring continuous fuel supply. While this requires no new specific infrastructure development for the airports, marine ports need to enable a multi-fuel infrastructure.
- **Airlines and shipping companies** are at the center of the transition, linking upstream activities to final consumers. By marketing sustainable shipping and travel options, they can initiate technology adoption, low-carbon fuels offtake and bring coordinated progress among all the supply chain actors. When they adopt operational efficiency measures in their activities, they can immediately unlock significant cost savings and emission reductions in the short run.

The window to bringing the world on course for net-zero is closing fast, and aviation and shipping remain almost entirely reliant on fossil fuels. Despite monumental complexities, the transition from fossil fuels in these sectors is achievable through targeted policymaking and coordinated action among key supply chain actors. Such collaboration can pave the way for a clean and sustainable future: one that supports global decarbonization, promotes a just transition, and fosters equitable economic development.

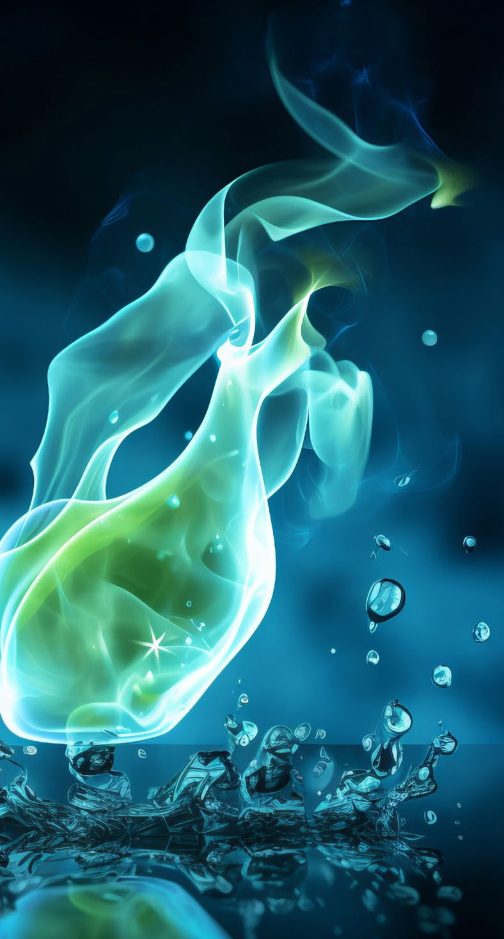
1. Net-zero requires significant quantities of low-carbon fuels

To limit global warming to 1.5°C requires net-zero greenhouse gas (GHG) emissions by no later than 2050.[1]

Given energy consumption and industrial processes represent more than 80% of global GHG emissions,[2] this entails full decarbonization of the whole energy system. A fundamental requirement for decarbonization of the energy system is therefore shifting from the current fossil fuel-centric model to a highly renewable and electrified energy system.[3] The existing literature on decarbonization underscores electrification, large-scale renewable development and efficiency improvements as the key technological solutions.[4]

Figure 1 shows global energy-related CO_2 emissions, and the key decarbonization options for the main economic sectors. Some sectors, such as buildings and light road transport, can almost fully rely on electrification for decarbonization. This electricity can come entirely from renewable sources such as hydro, wind and solar power.[5] Nevertheless, heavy industries such as steelmaking and cement production require solutions beyond electrification, at least for high-temperature heating and industrial feedstock demand.[3, 6] Moreover, most of heavy-duty transport applications, notably within aviation and shipping, need high energy density, making them difficult to electrify.[6, 7, 8]

Complementary to direct electrification, hydrogen, if produced from clean sources (electrolysis of low-carbon electricity or fossil fuels with abatement), can unlock significant emission reductions. For example, it can be used as a reduction agent for primary steelmaking, as feedstock to produce other molecules (such as synthetic fuels and chemical products), or as an energy source for producing heat and electricity.



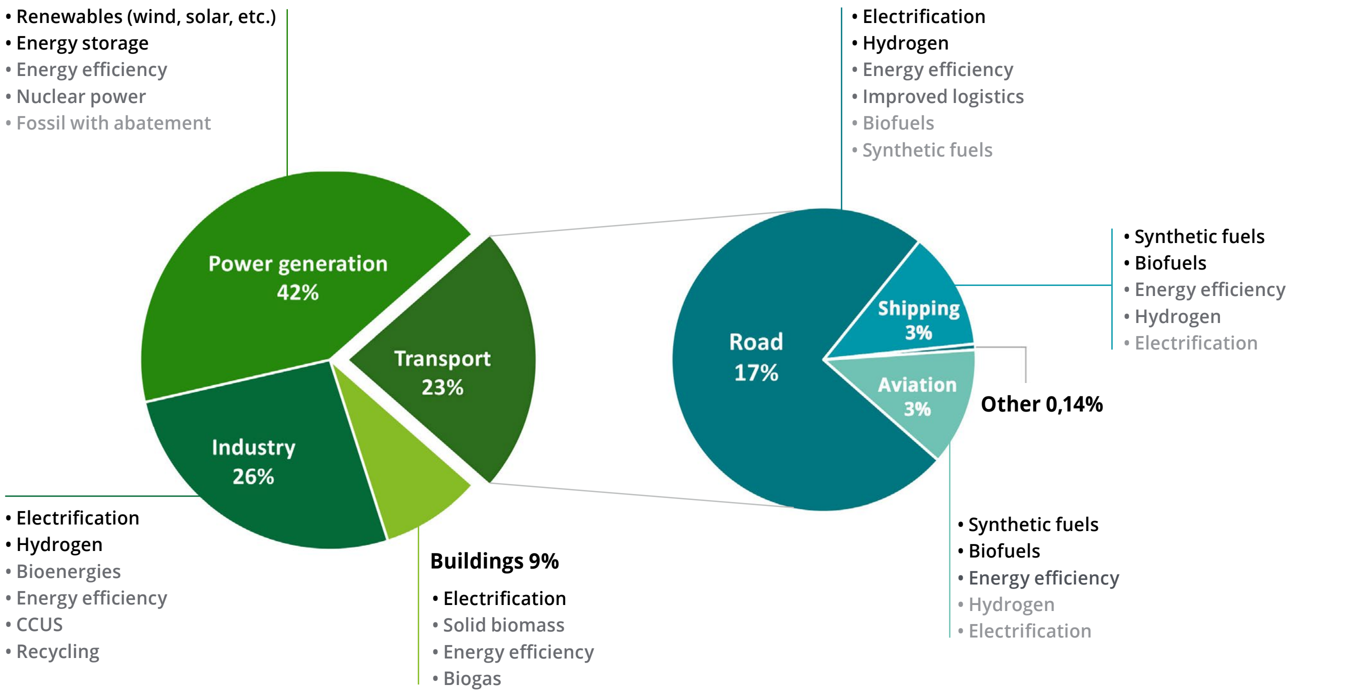
Alongside biomass and biogas, clean hydrogen has an important decarbonization potential in heavy industries. It can also contribute to decarbonization of heavy-duty road transport, overcoming limitations of electrification. However, its low energy density makes it less suitable as aviation fuel or shipping fuel for most appliances that require important energy density in small fuel storage reservoir volumes. Therefore, decarbonization of these heavy-duty transport sectors will rely on low-carbon fuels—biofuels and synthetic fuels—which have similar characteristics to fossil fuels, but are produced from low-carbon feedstocks.

As two of the most "hard-to-abate" sectors, aviation and shipping are each responsible for about 1 billion tons of annual CO_2 emissions (1 $GtCO_2$/year[11, 12] and represent about 6% of global CO_2 emission[13]). As important sources of GHG emissions, their decarbonization is particularly challenging: certain industries, such as steelmaking and chemicals, can manage emissions by relocating production to areas with abundant clean energy[14] and subsequently importing the end-products.[15] Nevertheless, in aviation and maritime shipping, emissions cannot be shifted elsewhere because the very nature of the industry involves planes flying and ships sailing around the globe, emitting GHG emissions directly into the atmosphere. Thus, unlike supply chain optimizations in other industries, the aviation and maritime shipping sectors should address emissions head-on. This necessitates a multi-faceted approach which includes improving planes' and ships' efficiency, optimizing logistics and most importantly, replacing conventional fossil fuels with cleaner alternatives such as biofuels and synthetic fuels.

Biofuels in the form of biodiesel, biokerosene, and bioethanol are renewable fuels derived from organic materials such as plant biomass, agricultural residues, and even algae.[16] The combustion of these fuels releases the CO_2 that was previously absorbed by the biomass during its growth, or was supposed to be emitted naturally.[17] When no other emissions occur during the fuel production process, biofuels can then be considered carbon-neutral. This closed carbon cycle helps mitigate the net increase of CO_2 in the atmosphere, making biofuels an attractive option for sustainable fuel alternatives. Nevertheless, the limited availability of sustainable biofuels calls for the need for other fuels to complement them, most notably in aviation and maritime shipping.[18]

Synthetic fuels are liquid or gaseous fuels produced through chemical reactions involving hydrogen as feedstock. If the used feedstock (including hydrogen) and energy for their production is low-carbon, these fuels can be considered clean alternatives to conventional oil products and have the potential to reduce CO_2 emissions in the transport sector. Among synthetic fuels, ammonia, methanol, and synthetic kerosene are widely viewed as the most promising solutions for decarbonizing aviation and maritime shipping.[19, 20] Ammonia can be produced from hydrogen and ambient nitrogen via the Haber–Bosch reaction (Figure 2).[21] Synthetic methanol and synthetic kerosene are synthesized from CO_2, and hydrogen through the methanol synthesis and Fischer-Tropsch reactions, respectively.[22]

Figure 1. Global CO_2 emissions from energy combustion across key economic sectors and the available decarbonization strategies for each



Source: Deloitte analysis based on Deloitte,[3] IEA[9] and Our World in Data[10]

While ammonia is a carbon-free molecule, the combustion of synthetic hydrocarbons such as methanol and synthetic kerosene is associated with CO_2 emissions, which releases the CO_2 used for their production. If this CO_2 has biogenic sources,[23] or is directly captured from the air using chemical processes (such as direct air capture - DAC), it can be considered low-carbon, or even climate neutral. In these cases, the GHG emissions resulting from the fuel combustion are offset as part of the carbon cycle by the captured/biogenic CO_2.

In short, low-carbon fuels (e.g., biofuels and synthetic fuels) are essential for decarbonizing the most hard-to-abate sectors, complementing electrification and hydrogen thanks to their high energy density.

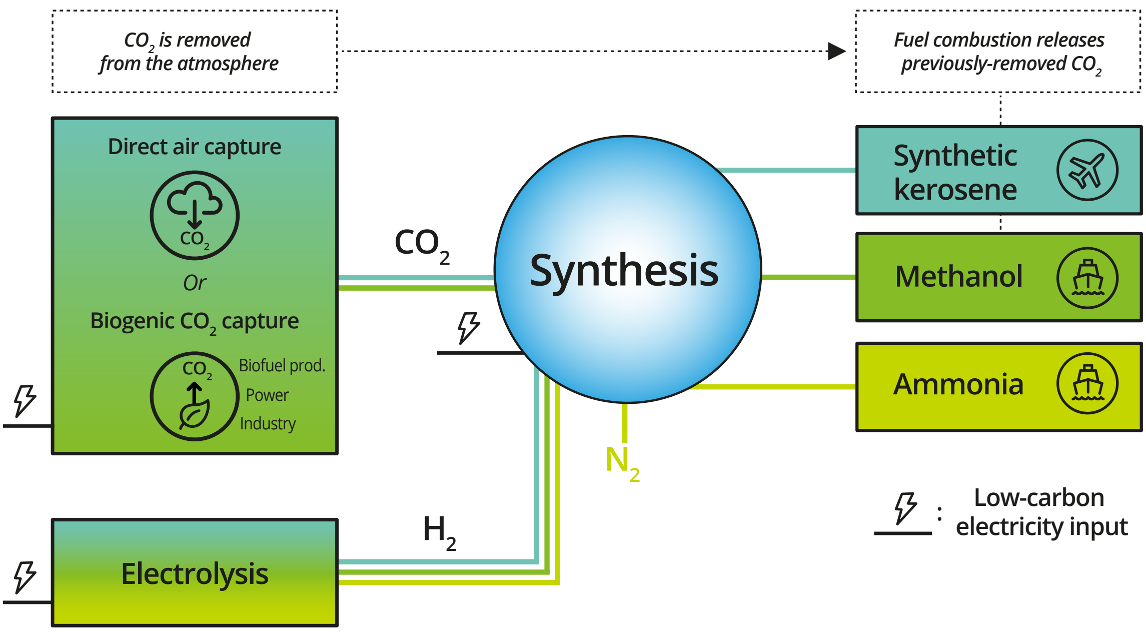
However, the future low-carbon fuel markets and their emergence are fraught with uncertainties surrounding key technological choices, the fuel-engine mix options, as well as the sourcing of these fuels and their feedstock. As they are relatively easy to transport, these fuels have the potential to significantly impact and reshape future energy trade flows, underscoring the need for a forward-looking assessment of their supply routes to maximize their overall potential.

This report presents Deloitte's outlook for low-carbon fuels and their role in the decarbonization of aviation and maritime shipping in a net-zero scenario.

Leveraging a data-driven and model-based approach, it offers a science-based vision for the development of these fuels. The analysis harnesses Deloitte's *Hydrogen Pathway Explorer* (see Appendix 1), a techno-economic model of the emerging hydrogen and low-carbon fuels market which has been validated through academic peer review and published in reputable scientific journals.[24, 25, 26]
Deloitte's scenario builds, amongst others, on the long-term perspectives of the International Energy Agency[27] and the Intergovernmental Panel on Climate Change (IPCC)[1] and is fully aligned with the objective of the Paris Agreement to limit global warming to 1.5°C. This scenario assumes a benign geopolitical environment, underpinned by an efficient financial sector and sees determined policy action to achieve the net-zero objectives that more than 140 countries have set for themselves.

Against this backdrop, this outlook aims at describing what would need to be true for low-carbon fuels to thrive and make their essential contribution to achieving climate neutrality. This scenario thus serves as a 'north star' for strategic decision making in the public and private sectors. It can also help by monitoring progress in establishing low-carbon fuels markets and identifying regulatory, economic and technological gaps to be addressed by leaders. It should not be viewed as the most probable future outcome.

Figure 2. Overview of low-carbon synthetic fuels production pathways



Source: Deloitte analysis based on Deloitte[6] and International Transport Forum[19]

2. Last mile decarbonization: shipping and aviation

Decarbonizing aviation and shipping relies on similar strategies and the same action levers.

Firstly, a modal shift to using transport that emits less GHG is needed[28] along with changes in consumer behavior[29] to limit potential increases in demand. Secondly, efficiency improvements on both the logistics and operations sides, as well as technical (physical) efficiency improvements, can further curb fuel consumption.

Both efficiency and behavioral measures are considered quick wins that can bring significant fuel savings and, therefore, can contribute to carbon emission reductions. However, they will not completely eliminate CO_2 emissions, and therefore achieving climate neutrality requires replacing conventional fossil fuels with low-carbon alternatives.

2.1 Decarbonization of aviation

Most of the air travel is passenger transport, with freight accounting for about 20% of air traffic,[30] measured in Revenue Ton-Kilometers equivalent (RTKeq).[31] Driven by economic growth and the falling cost of air transport, the aviation sector has rapidly expanded in recent years (about 70% for passenger transport and 40% for freight transport between 2010 and 2019).[30] This upward trend is set to continue as behavioral measures such as modal shifts and taking sufficiency measures are not expected to compensate for the increase in aviation demand. Total air traffic is expected to grow two-and-a-half fold between 2023 and 2050, with an annual average growth rate of 4%.[32] This is mainly due to increased global population growth and economic growth, notably in the emerging countries and increased global interconnectedness due to business, tourism, and international collaborations.

Efficiency gains from technology development and operational measures

In 2022, the average aircraft fuel consumption stood at 12.1 MJ/RTKeq, almost half compared to its early 2000s levels.[33] This is mainly the result of decades-long improvements in fuel efficiency (1%/year between 1960 and 2019 on average).[34] In the short run, efficiency gains can be obtained by gradually integrating the latest generation aircraft technologies into the fleet, as the new aircrafts are around 15% more efficient than the existing fleet average.[35] Given the small number of new aircraft design projects, it is likely that there will not be visible step-change in the efficiency of delivered aircrafts through the mid-2030s. Therefore, **Deloitte's analysis results in an expected efficiency improvement rate of 1.1%/year between 2022-2035** (see Appendix 2).

In the longer term, scientific progress on current research on aerodynamics (e.g., blended-wing body, active flow control), jet engines (e.g., open rotor technology) and lightweighting through advanced composites can make the next generation of airplanes 30% more efficient than the current ones.[36] Their gradual integration in the fleet entails technology efficiency improvement of 1.5%/year from 2035 to 2050.

In parallel, efficiency improvements linked to operational measures such as payload maximization[37] and route optimization[38] can bring a further 0.45%/year of fuel burn reductions each year until 2050 (see Appendix 2). Summing them up with technology related efficiency gains, **the average aircraft efficiency gains in this outlook can get as high as 1.6%/year in the period between 2022 and 2035, and almost 2%/year from 2035 onwards.** Therefore, an average aircraft in 2035 and 2050 would consume 18% and 39% less fuel respectively than the equivalent in 2022.

Need for low-carbon fuels

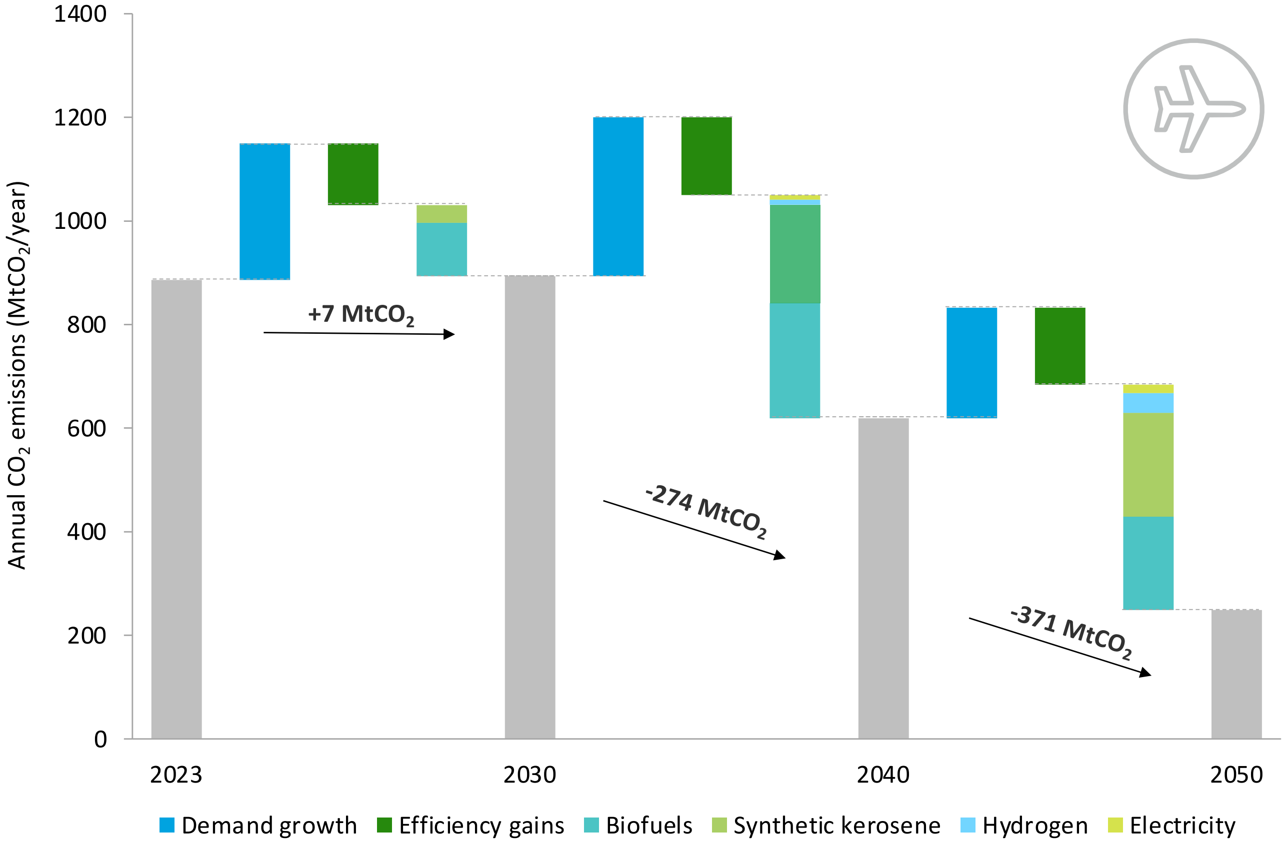
As fuel efficiency gains are outpaced by air traffic demand growth, GHG emissions from aviation are set to increase in the absence of fuel decarbonization.

Jet fuels derived from fossil kerosene currently supply almost all aviation energy needs, causing significant amounts of GHG emissions.[34] Achieving climate neutrality implies transitioning away from fossil fuels,[3] with the aviation industry being no exception. There are two viable alternative fuel options for aviation: one involves adopting fuels that necessitate significant changes to aircraft design and propulsion technologies, such as batteries and hydrogen. The other focuses on using drop-in fuels, which require replacing conventional fuels with biofuels or synthetic alternatives.

Hydrogen and battery-powered airplanes are only compatible with lightweight and small distance air traffic and can therefore replace fossil fuels only to a small extent.[39] The sectoral transition away from fossil fuels, therefore, relies mainly on the use of Sustainable Aviation Fuels (SAF), which have very similar chemical and physical properties to the conventional kerosene-based jet fuels.[40] These fuels can be readily used as drop-in replacements for conventional fuels by injecting them into the existing infrastructure and engines.[39]

Low-carbon aviation fuels are still at an early stage of development. In Deloitte's outlook their ramp-up starts in the 2030s. In 2030, fossil fuels still represent around 90% of the fuel mix (13.2 EJ), falling to about 20% in 2050 (3.7 EJ). Due to their limited compatibility with most of the applications, direct use of hydrogen and electricity are restrained to regional segments, representing only 7% and 3% of final aviation energy consumption in 2050 respectively. **SAF, accounting for 43% of its energy consumption in 2040 and 70% in 2050, is the key enabler of decarbonization in aviation.** Among different low-carbon fuels, biokerosene is the fastest to be developed, exceeding 1.2 EJ before 2030. Its deployment, however, is limited by the availability of input biomass feedstock (see Box 1). This makes synthetic kerosene the dominant source of supply by 2050, representing 6.8 EJ (almost 40%) of aviation fuel supply in 2050. As a result, emissions in the aviation sector are set to remain stable until 2030, before dropping to 240 MtCO_2 in 2050. This corresponds to a 75% decrease compared to today's emission levels (Figure 3).[41]

Figure 3. Evolution of aviation CO_2 emissions and the impact of different emission-reduction levers from 2023 to 2050



Source: Deloitte analysis based on the efficiency improvements described in Appendix 2 and Deloitte's scenario described in section 2.3.

Box 1. Biofuels production and potential

Chemically similar to conventional fossil fuels, biofuels can be used as drop-in fuels in existing jet engines and fuel infrastructure. **As such, biofuels can contribute significantly to the decarbonization of the transport sector—including road transportation, aviation, and maritime shipping.** Some biofuel processes are already quite mature and are already integrated into energy systems.[42] In 2022, biofuels supply reached 4.3 EJ and accounted for 3.5% of energy consumption in the transport sector. Almost all current production volumes (biodiesel and bioethanol) are geared toward the road transport sector, but in a net-zero scenario, biofuels demand would double by 2030 and extend to other transport segments including aviation and shipping.[27]

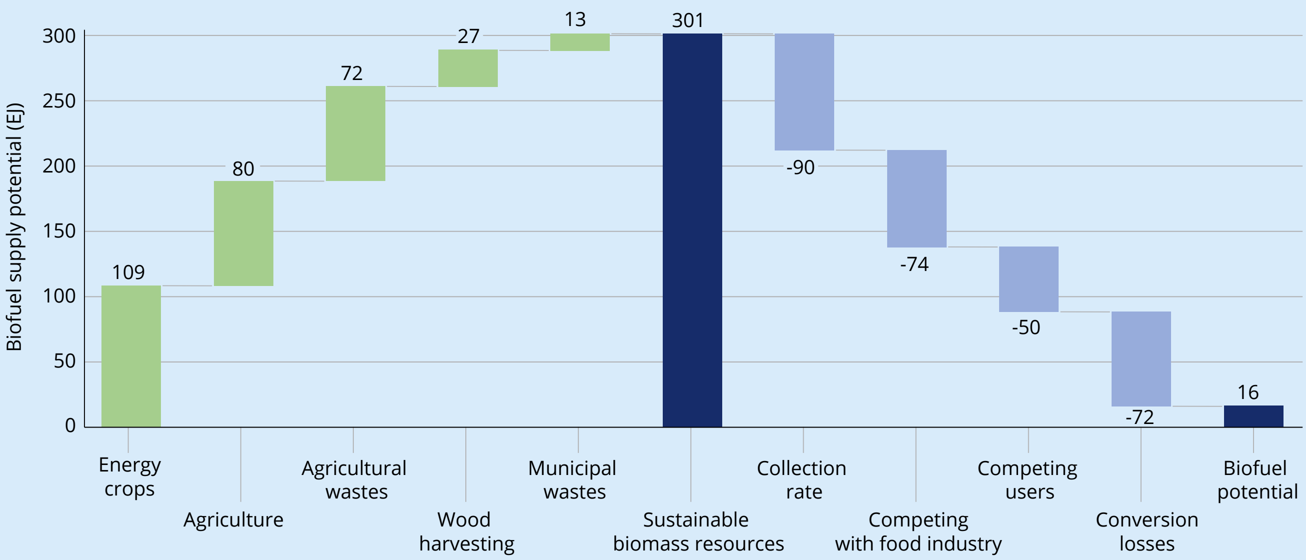
Nonetheless, biofuel deployment faces several challenges that limit its uptake and prevent it from being the sole low-carbon fuel option for decarbonization of the heavy-duty transport sector:

- Biofuel production can divert feedstock from agricultural use which could disrupt food supply.[43, 44] To promote sustainability, the utilization of such biofuels should be limited to feedstocks that are sustainable and do not compete with the food sector. As such, many regulations restrict biofuels production from edible oil or feedstocks (sugar cane, soybean, palm, etc.), which strongly limits the potential of cost-competitive biofuel supply.
- The changes in land-use (such as deforestation) or additional energy consumption for growing feedstock (such as fertilizers used) or fuel synthesis can significantly impact the biofuels environmental lifecycle assessment, reducing the available volume of biofuels compatible with climate neutrality.[45, 46]

Biological feedstock used in biofuel production can be divided into five main categories:

- Energy crops,
- Agricultural residues,
- Agricultural waste,
- Forest residues, and
- Municipal solid waste (MSW).

The sustainable biomass potential for production of different bioenergies is estimated to reach around 300 EJ (see the figure below). Access to fats, oils, and greases (FOGS) can be limited due to their availability and collection rate. According to IRENA, the potential of total used cooking oil reaches around 0.8 EJ globally, where only 0.2 EJ is collected.[45] Additionally, despite its availability, only half of MSW is estimated to be from biogenic resources, and advanced treatments should be made to increase the quality of feedstock.[46] Therefore,accounting for competition with other energy uses, the food sector, collection limitations and conversion losses, approximately 16 EJ of biofuel is estimated to be available for the transport sector (see Appendix 3), which would account for only 20% of the projected transport demand in the IEA's Net-Zero scenario by 2050. Therefore, although biofuels hold considerable promise for reducing GHG emissions, they need to be complemented with synthetic fuels to maximize emission reductions across the transport sector, notably aviation and shipping.



Source: Deloitte analysis based on the methodology detailed in Appendix 3

2.2 Decarbonization of shipping

Maritime shipping plays a critical role in global trade, accounting for more than 80% of world freight transport volume.[47] Driven by economic growth and globalization, shipping demand is expected to grow steadily until 2050, with an average annual growth rate of approximately 2%/year in t.km.[48] There is a large variety of different use cases and their underlying segments within the shipping sector, each with its own vessel design requirements and forms, route characteristics and decarbonization challenges. Nevertheless, around 75% of emissions result from the long-distance goods transport in tankers, dry bulk and general cargo carriers and container ships.[49] Like aviation, decarbonization of shipping relies on efficiency measures, consumer-side behavior change and switching to cleaner energy sources.

Efficiency gains from technology development and operational measures

Due to massive cargo volumes per vehicle (through optimized logistics) and relatively low speeds, maritime shipping already has significantly lower energy consumption per t.km of goods transported, compared to other freight transport options: around 0.1 MJ/t.km,[50] which is approximately 10 times more efficient than trucking[51] and 100 times more than aviation.[33] Nevertheless, there is still room for efficiency improvements in shipping, and the International Maritime Organization has set an ambitious efficiency standard—the Energy Efficiency Design Index—which requires all new ships brought to market after 2025 to be 30% more efficient compared to vessels delivered in the period between 2000 and 2010.[52]

Efforts for improving energy efficiency focus mostly on optimizing hydrodynamics (e.g., hull design and air lubrication) and improving propulsion efficiency (e.g., engine waste-heat recovery and wind-assisted propulsion in the longer run). However, due to the long lifetime of vessels (more than 30 years), the integration of the latest technical improvements in the operating fleet take place gradually, and slowly. Fleet renewal and new vessels additions entail technological efficiency improvement of around 0.7%/year through to 2050 (see Appendix 2).

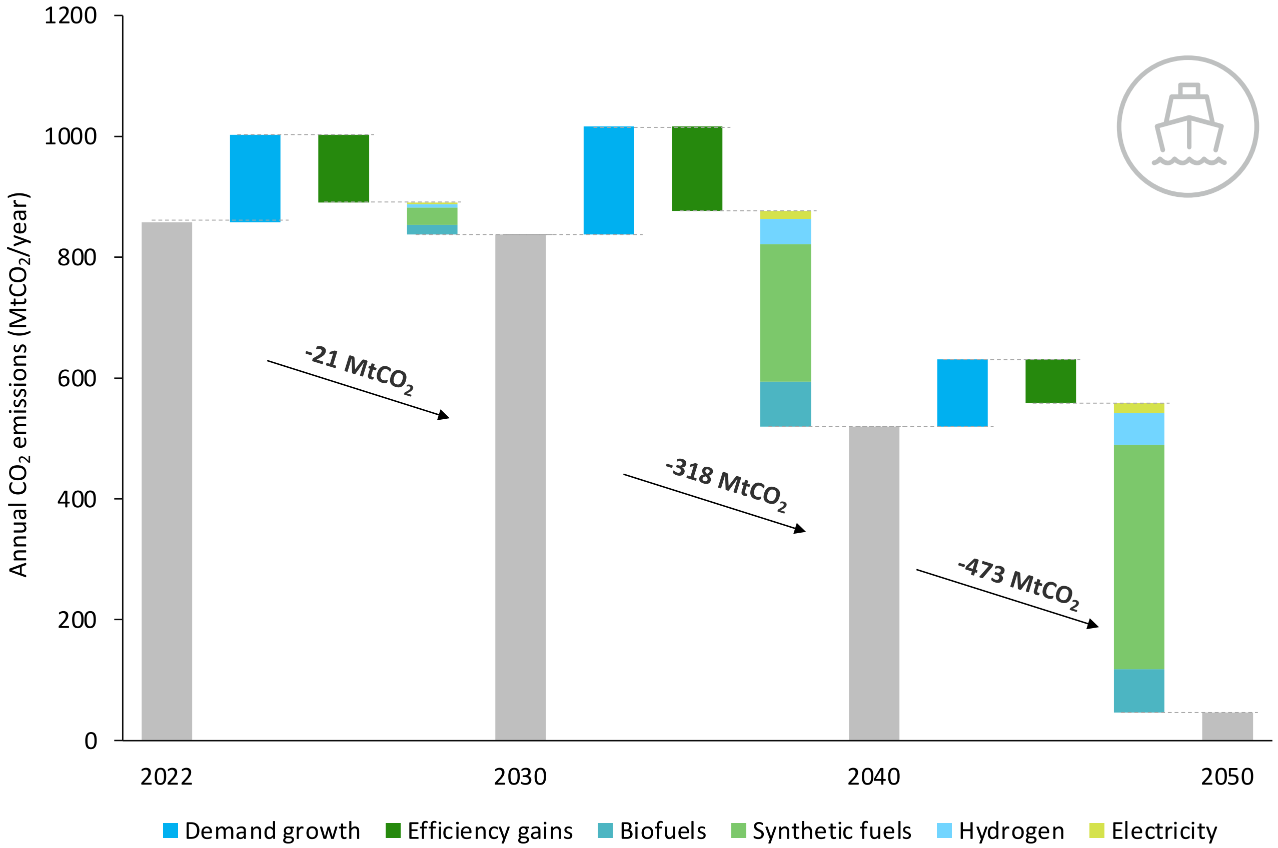
In the short run, the greatest potential for maritime shipping energy efficiency improvements lies in operational measures.[53] Thanks to digitalization and advanced software development, the freight payloads, routing and speed can be optimized to reduce overall energy consumption, leading to efficiency improvements of up to 38% for individual ships.[54] **Summing up both technological and operational efficiency measures, energy intensity of maritime transport is expected to drop by 13% between 2022 and 2030, and to fall below 0.06 MJ/t.km by 2050,** improving the average fleet efficiency by a third compared to current levels.

Need for low-carbon fuels

Like in aviation, the anticipated efficiency gains through technological and operational improvements in shipping are likely to be outpaced by increasing demand. Thus, decarbonization in this sector necessitates a shift to clean energy sources. While electricity and hydrogen can power some vessels, the extensive journeys typical of international shipping require liquid fuels due to their higher energy density and superior storage capabilities over long durations. Only small boats that can frequently recharge at ports, such as ferries and coastal vessels, are amenable to electrification. Hydrogen, despite having a higher gravimetric energy density compared to batteries, is impractical for long voyages due to its low volumetric energy density and the high cost of storage in liquefied form. Consequently, in Deloitte's outlook, electricity and hydrogen account for 0.4 EJ (3% of fuel mix) and 1.3 EJ (10%) of sector's energy consumption by 2050 respectively. Liquid biofuels present a feasible option for maritime use, being compatible with existing engines and infrastructure. By 2030, biofuels constitute 6% (0.6 EJ) of the maritime shipping fuel supply, mainly through blending with fossil fuels. However, intense cross-sectoral competition for sustainable biomass limits their large-scale adoption (see Box 1). The growth of biofuel use in shipping slows down after 2030, reaching 13% (1.7 EJ) of the sectoral fuel mix by 2050.

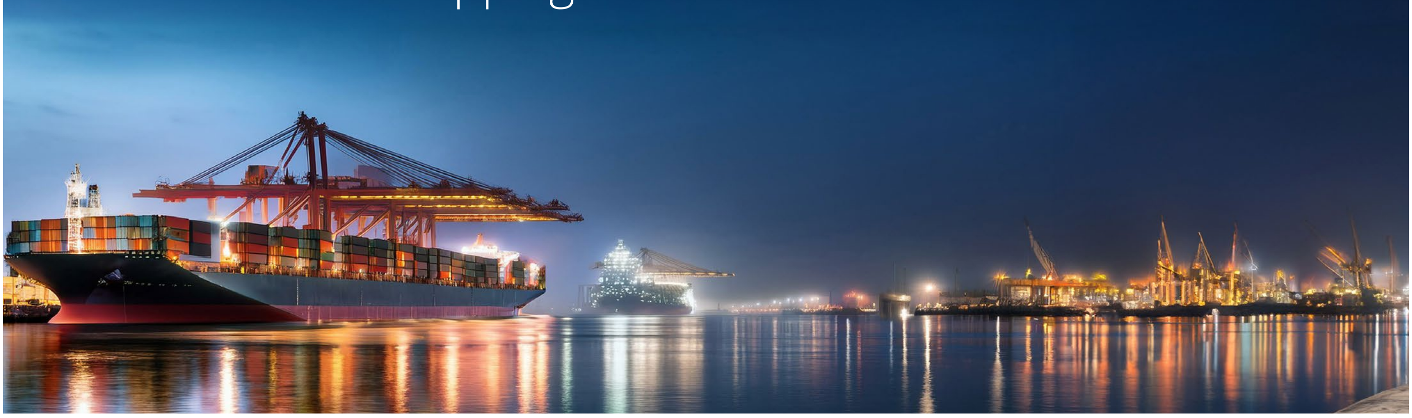
The frontrunning fuel decarbonization options in the maritime sector are synthetic liquid fuels, notably methanol and ammonia. Combined, they account for 8.9 EJ of maritime shipping fuel consumption by 2050 (70% of fuel mix), bringing more than 600 MtCO_2 of emission reductions by then (Figure 4). Neither ammonia nor methanol are drop-in fuels and their adoption requires new propulsion engines as well as the development of dedicated infrastructure and supply chains. Therefore, their integration into the fuel mix requires long-term planning and concerted investments across the maritime ecosystem. Whether the industry ultimately settles for a dominance of ammonia or methanol, or a more-balanced multi-fuel approach is still unclear (see Box 3 in Section 3.1 for a detailed comparison). This uncertain environment risks discouraging infrastructure investment in light of the fear of stranded assets.

Figure 4. Evolution of CO_2 emissions from maritime shipping and the impact of different emission-reduction levers, from 2022 to 2050



Source: Deloitte analysis based on the efficiency improvements described in Appendix 2 and Deloitte's Net-Zero scenario

"Maritime shipping reaches almost net-zero CO_2 emissions by 2050, largely thanks to the synthetic fuels, that start taking important shares of the maritime fuel mix by 2040. Ammonia and methanol alone represent 70% of the fuel mix in maritime shipping in 2050."



2.3 Deloitte's outlook on decarbonization of aviation and shipping

In Deloitte's outlook, aviation experiences stagnating CO_2 emissions until 2030 and about 75% of emission reductions by 2050, mainly thanks to efficiency measures (30% of emission reductions) and the uptake of low-carbon fuels (65%). This brings the annual CO_2 emissions of the sector down to 220 $MtCO_2$ by 2050. **Maritime shipping experiences almost net-zero by 2050, with about 45 $MtCO_2$ of residual emissions by this date.** The residual emissions of both sectors result from the fact that not all countries have a target of reaching net-zero by 2050. For instance, the largest and the third largest CO_2 emitters, China and India, aim to reach net-zero by 2060 and 2070 respectively.[55] Moreover, given the global and cross-sector nature of net-zero, these emissions are among the most difficult to abate which would require offsetting negative emissions from other sectors, through direct air capture and bioenergy with carbon capture and storage.

Synthetic fuels are indispensable for long-term decarbonization of aviation and maritime shipping. Efficiency gains from advanced technologies and operational improvements can slow the growth in fuel consumption and biofuels' potential is insufficient to cover a big proportion of fuel demand in these sectors. Almost absent from the current fuel mix, synthetic fuels would only have a marginal role in 2030 (supplying 1.6 EJ of the 26 EJ consumed), but would be the main source of energy in the air and on the seas by 2050, accounting for almost 16 EJ of fuel consumption (Figure 5). **Such levels of synthetic fuel production require more than 150 Mt of clean hydrogen and almost 700 $MtCO_2$ of DAC-based or biogenic CO_2.** This represents a major industrial and technical challenge as the clean hydrogen sector is still in its infancy and CO_2 capture technologies have not yet been developed at an industrial scale.

Figure 5. Demand for low-carbon fuels in aviation and shipping sectors in Deloitte's outlook

Fuel type	Fuel	Demand in aviation (EJ)				Demand in shipping (EJ)			
		2023	2030	2040	2050	2022	2030	2040	2050
Biofuels	Maritime biofuels	-	-	-	-	0.0	0.6	1.3	1.7
	Biokerosene	0.0	1.2	3.9	6.1	-	-	-	-
Synthetic fuels	Ammonia/methanol	-	-	-	-	0.0	1.2	3.9	8.9
	Synthetic kerosene	0.0	0.4	3.3	6.8	-	-	-	-
Fossil fuels	Kerosene	13.1	13.2	9.1	3.7	-	-	-	-
	Marine fuel oil	-	-	-	-	9.4	9.1	5.7	0.5

Source: Deloitte analysis based on aviation and shipping demand evolution estimated in sections 2.1 and 2.2, efficiency gain estimations in Appendix 2 and top-down resource allocation

"In Deloitte's scenario, emissions from aviation and maritime shipping stagnate by 2030, thanks to biofuels and efficiency measures that compensate for the increase in air and maritime traffic demand. Synthetic fuels, absent from the current aviation and shipping fuel mix, represent almost 60% of it by 2050, emerging as the key enablers of decarbonization."

3. Unlocking the decarbonization potential of synthetic fuels

Low-carbon fuels, especially synthetic fuels, are still at a nascent market stage, with nonexistent or unstable regulatory frameworks (see Figure 6). Despite some net-zero targets announced by international organizations,[56] there are no legally binding targets for the production or use of low-carbon fuels at the global level. However, at national level, an increasing number of countries are introducing regulations.

For instance, EU regulation requires ship operators to remain below carbon intensity thresholds with their fuels, and respect strict SAF blending mandates in aviation fuel.[57]

While the existing regulatory framework has initiated pilot projects, the market still faces significant uncertainties: as of January 2024, of the 230 synthetic fuel production projects announced globally, only 15% reached final investment decision stage.[58]

Figure 6. Country-wise decarbonization policy environment in shipping and aviation

Australia
- SAF included in roadmaps and initiatives
- A "Maritime Emissions Reduction National Action Plan" is in preparation

Brazil
- Expected to implement a SAF mandate by 2027
- RenovaBio regulation including low emissions fuels for transport

Canada
- "Aspirational" goals for SAF blending
- SAF present in British Columbia's fuel regulation

China
- Potential SAF mandate envisioned
- An important pilot project for SAF flights has been announced.

Europe
- ReFuelEU Aviation regulation: SAF mandate and synthetic fuels sub-targets
- FuelEU Maritime regulation: carbon intensity of fuel legal targets
- UK and Norway aligned with the EU

India
- Potential SAF mandate envisioned

Indonesia
- Potential SAF mandate about to be implemented

Japan
- SAF mandate about to be implemented in the aviation
- National plan for the maritime sector, encompassing low-emission fuels (but no mandates)

Malaysia and Singapore
- Potential SAF mandate envisioned in Singapore, already implemented in Malaysia

United States
- Production goals for SAF (SAF Grand Challenge), supports for production and use (IRA) and e-fuels included in some states clean fuel programs
- Clean shipping act in discussion

Legend

- Strong policy on aviation + maritime sectors
- Strong policy on aviation sector
- Existing policy for aviation + maritime sectors (not necessarily binding)
- Existing policy for aviation (not necessarily binding)

Source: Deloitte analysis based on IEA Policy database,[59] International Transport Forum,[60] World Trade Organization (WTO)[61] and regional and national regulations

"As a first step, globally harmonized regulatory and certification frameworks are essential for the global uptake of the inherently international aviation and shipping sectors."

3.1 Significant technological barriers yet to overcome

Processes to produce synthetic fuels are not yet deployed on a large-scale and depend on the availability of clean hydrogen and, in the case of hydrocarbons, sustainable CO_2. Although electrolytic hydrogen production benefits from a high technologic maturity and holds significant promise, the challenges associated with its storage and transport impede its broader adoption and scale-up.[6] While CO_2 point capture has long been deployed at the industrial scale, other carbon removal technologies, notably DAC, due to their nascent development stage suffer from substantial uncertainties which in turn casts doubt on their ability to secure an adequate supply of sustainable CO_2 . This wide range of technological maturity in synthetic fuels production also means that they are not all certified for use in the existing engines. Obtaining certifications takes years and both investors and potential offtakers of uncertified synthetic fuels may postpone their commitments. Moreover, for some synthetic fuels such as ammonia and methanol, uncertainties around corresponding downstream technologies such as engines, particularly in shipping, which are also in the early stages of development, amplify these uncertainties (Figure 7). They can entail significant technical risks (e.g., underperformance, cost overruns and construction delays) for the whole value chain in maritime transport and aviation, increasing the financial costs and delaying investment decisions.[62] Additionally, for the case of fuels with no drop-in characteristics such as ammonia and methanol, the interdependent deployment timeline between fuel supply, infrastructure development, and compatible engine technology (a triple "chicken-and-egg" dilemma) further exacerbates the existing challenges and elevates the associated risk premiums.

Figure 7. Technology readiness level (TRL) of different technologies for decarbonization of aviation and shipping

Category	Sub-category	Main Solutions	TRL	Comment
Fuel production	Synthetic fuel production	Synthetic kerosene production	6	Produced by Fischer-Tropsch synthesis (using H_2 and CO_2)
		Methanol production	7	Produced using H_2 and CO_2
		Ammonia production	8	Produced by Haber-Bosch (using H_2 and Nitrogen)
Feedstock	H_2 production	Electrolysis	9	Green hydrogen - electrolysis using renewable energy
	CO_2 capture	Solid direct air capture	7	Direct air capture based on solid adsordents (at low temperature)
		Liquid direct air capture	6	Direct air capture using aqueous solution (at high temperature)
		Sustainable biogenic CO_2	11	Sustainable CO_2 from point capture (concentrated sources)
Engine technology	Aviation	Electric aircraft	5	Battery or Hybrid electric plane
		Hydrogen-fueled aircraft	5	Fuel cell or direct hydrogen combustion
		Kerosene-fueled aircraft	11	Commercial engines
	Maritime	Hydrogen-fueled ship	4-5	Combustion engines fuelled with hydrogen
		Ammonia-fueled ship	6	Combustion engines fuelled with ammonia
		Methanol-fueled ship	9	Combustion engines fuelled with liquefied methanol
		Biogas-fueled ship	9-10	Combustion engines fuelled with liquefied biogas
		Electric ship	8	On-board battery electric ships

Source: Deloitte analysis based on IEA Clean Technology Database[63]

Sourcing sustainable CO_2 for synthetic fuels production

Production of both synthetic kerosene and methanol requires significant amounts of sustainable CO_2. Accounting for an important part of their total cost, the origin of the CO_2 used has a major impact on the cost-competitiveness of these fuels.[39] The challenge however, is not only of an economic nature: as the capture pathway for CO_2 is crucial to ensure the compatibility of these fuels with a net-zero economy, the availability and geographical distribution of low-cost and sustainable CO_2 is determining. CO_2 captured from fossil sources, if recycled, can benefit the technology scale-up and the development of the necessary infrastructure. Nevertheless, since this CO_2 is not climate-neutral within the carbon cycle, it cannot be used to produce synthetic fuels in a sustainable manner. The focus of this study is therefore on synthetic fuels derived from biogenic CO_2 and air-captured CO_2 based on DAC, allowing for a closed carbon-neutral cycle assessment which complies with net-zero ambitions.

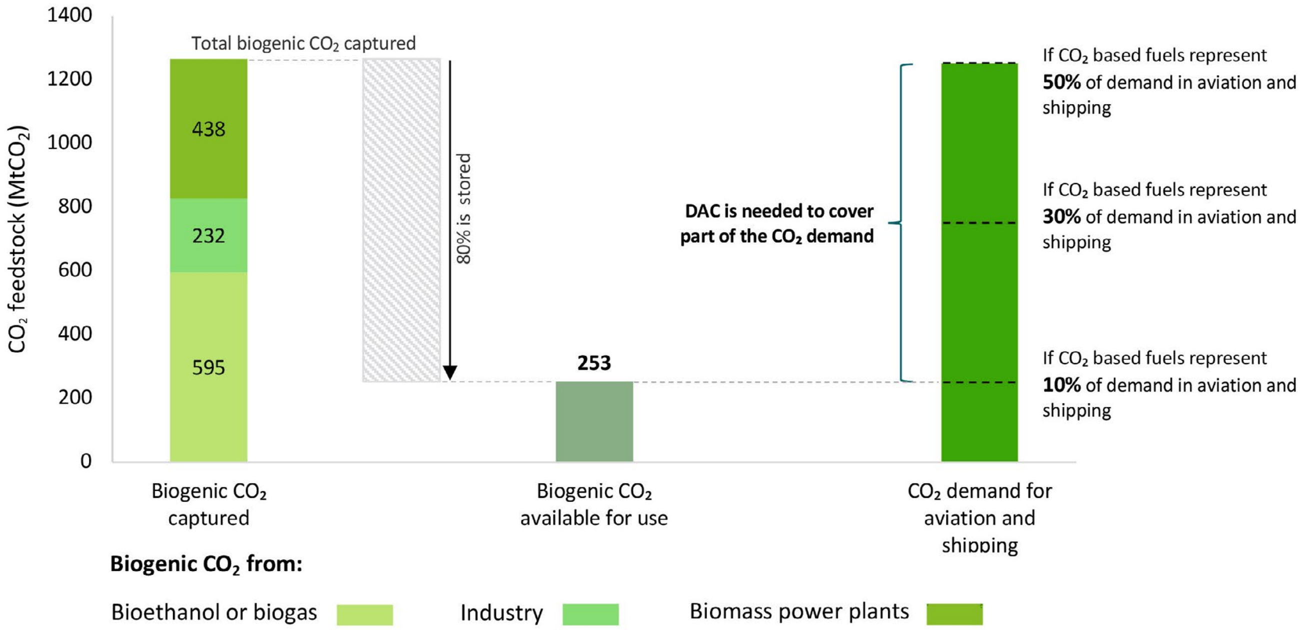
Biogenic CO_2 refers to the carbon that is sequestered through natural and biological processes, such as animal digestion and plant respiration. It is part of the natural carbon cycle, which means its release into the atmosphere does not add to anthropogenic CO_2 emissions. Two main sources of biogenic CO_2 are the CO_2 captured from bioenergy (e.g., during bioenergy combustion, notably in the industry and power sectors), and process by-product CO_2 sequestration. From about 2 $MtCO_2$ of biogenic CO_2 sequestered and currently utilized each year, 90% originates from bioethanol installations as a by-product.[39] Biogenic CO_2 from upgrading biogas to biomethane is another promising source which currently remains marginal.[39] Given that CO_2 is nearly the sole by-product of these processes (with a 99% concentration among the by-products), and its purification and collection incur minimal costs, it is one of the most economical sources of CO_2 at approximately US\$30/tCO_2.[64]

The potential of biogenic CO_2 is unevenly distributed across the world and its availability in the medium and long term is highly uncertain. Moreover, biogenic CO_2 is needed both for negative emissions to offset unavoidable GHG emissions in the most hard-to-abate sectors,[65] and for synthetic carbon-based fuels production. Nevertheless, the available amount of biogenic CO_2 remains far below the required levels for providing both negative emissions and producing synthetic fuels.

Figure 8 shows the available biogenic CO_2 and the level of demand for CO_2 storage and synthetic fuels in aviation and maritime shipping. Given the competition for biogenic CO_2, achieving important levels of synthetic fuels penetration in the aviation and maritime shipping sectors will likely require other sources of low-carbon CO_2, notably DAC.

Direct air capture, unlike biogenic CO_2, theoretically offers an unlimited low-carbon CO_2 supply potential, presenting a complementary supply option. However, DAC is still an emerging technology, which currently costs more than US$1000/t$CO_2$.[67] Even with significant long-term cost reductions, it is unlikely to become competitive with biogenic CO_2, and it is expected to remain at least five times more expensive (see Box 2). Therefore, DAC should be considered only as a complement to biogenic CO_2, or where biogenic CO_2 is not available.

Figure 8. Availability of CO_2 feedstock compared to the expected demand for aviation and maritime sector in 2050



Source: Deloitte analysis based on IEA net-zero scenario figures[27] and World Energy Outlook 2023[66] for CO_2 captured from different sources

Box 2. CO_2 feedstock supply through direct air capture

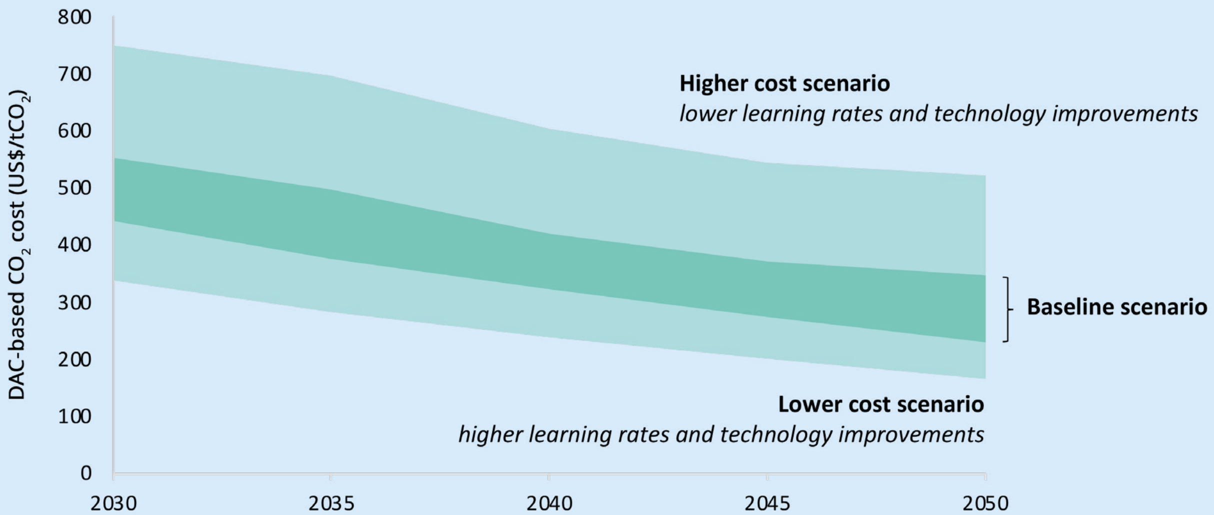
Direct air capture from the atmosphere is a promising source of low-carbon CO_2 to produce synthetic fuels, as it represents an unlimited potential and can be located independently from industrial installations as long as there is enough low-carbon electricity available to power the process. However, DAC remains an emerging technology, which still requires significant development before being deployed on a larger scale. As of today, close to 30 DAC facilities are operational, with most located in the US, Europe and Canada. These plants represent a total of 10 kt of CO_2 captured in 2023.[68]

Today's DAC technologies rely mainly on two methods: liquid sorbents (Liquid DAC or L-DAC), primarily developed by Carbon Engineering, and solid sorbents (Solid DAC or S-DAC), mainly developed by *Climeworks*. Both methods have their unique characteristics, with one key difference being the required process temperature: while L-DAC requires temperatures up to 900°C, S-DAC temperature requirements do not exceed 120°C.[69, 70] Given the numerous supply possibilities of low-temperature heat by renewable technologies compared to the provision of high-temperature heat, S-DAC seems a more suitable option in a low-carbon energy system dominated by renewables. Therefore, this analysis focuses on the use of S-DAC, with the heat provided by heat pumps.

As the technology is still emerging and not yet at scale, its cost and development are associated with important uncertainties.[71] In addition to the high overnight cost (CAPEX)of this technology, one key cost driver is the energy procurement. Given the low concentration of CO_2 in ambient air (0.04%)[72] compared to other sources such as biogenic sources or industrial facilities, the technology requires more energy within the capturing process leading to overall higher operational costs (OPEX).

Despite significant uncertainties linked to these elements, the cost of DAC-based low-carbon CO_2 supply is expected to fall in the coming decades due to economies of scale, technological innovation and falling energy costs.[67] Expected cost ranges resulting from both techno-economic uncertainties and regional discrepancies (mostly differences in power and capital costs) are illustrated in the figure below. In Deloitte's scenario, the average cost of DAC falls from around US$500/t$CO_2$ in 2030 to slightly above US$300/t$CO_2$ by 2050. Even under the most optimistic cost development assumption, this cost remains above US$200/t$CO_2$, which accounts for about a third to half of the cost of synthetic hydrocarbons by 2050 (see Section 3.2).

Direct air capture cost evolution and uncertainties (Solid DAC)



Source: Deloitte analysis based on IEA,[70] IEAGHG,[73] and TNO,[74] data

The cost uncertainties surrounding the future development of direct air capture also impact the projected transition landscape. Currently, methanol is seen as a more promising synthetic fuel option for maritime shipping compared to ammonia, due to its higher maturity and storability in ambient conditions. Almost 10% of new vessels under construction are designed to run on methanol, whereas the number of ammonia-fueled ships under construction or in operation remain marginal.[75] However, if the CO_2 used in methanol production is sourced from DAC, it becomes significantly more expensive (see Box 3). Consequently, **ammonia is also a promising long-term fuel option for the maritime shipping sector,** as it relies solely on the cost of hydrogen and is less affected by the highly uncertain development of DAC technology.

Box 3. Methanol or ammonia: What are the key competition drivers?

While a transition of the maritime sector to synthetic fuels is inevitable to meet the long-term climate targets, the composition of the future fuel mix remains highly uncertain with both methanol and ammonia considered as potential dominant options.

In the near-term, methanol is expected to be used earlier and faster than ammonia due to its technological maturity. As it can be stored at ambient temperatures and pressure, only minor modifications are required to existing infrastructure and operational processes. **The path to the widespread use of methanol in shipping is already paved:** its use as a marine fuel received IMO approval in 2020, around 20 ships are already fueled with methanol, and more than 120 ports propose a corresponding refueling infrastructure.[76] Conversely, **ammonia deployment in shipping still faces several technical hurdles** as ammonia engines are not commercially available yet, and the molecule toxicity and low-temperature requirements (-34°C) create new challenges for its bunkering and storage.

Methanol vessels provide fleet operators with an increased flexibility in managing their environmental transition. As powering ships using fossil methanol still reduces GHG emissions compared to conventional marine fuels, this option offers a hedge against potential shortfalls of synthetic methanol. It provides the opportunity for ships' gradual transition from fossil to synthetic fuels, allowing better control of the transition. The current vessels order book confirms this preference in investing in methanol-fueled ships (see the figure below). Ship owners invest preferentially in methanol solutions with more than 240 orders being registered compared to 26 ammonia ships. **These sale numbers confirm that methanol has a short-term advantage over ammonia.**

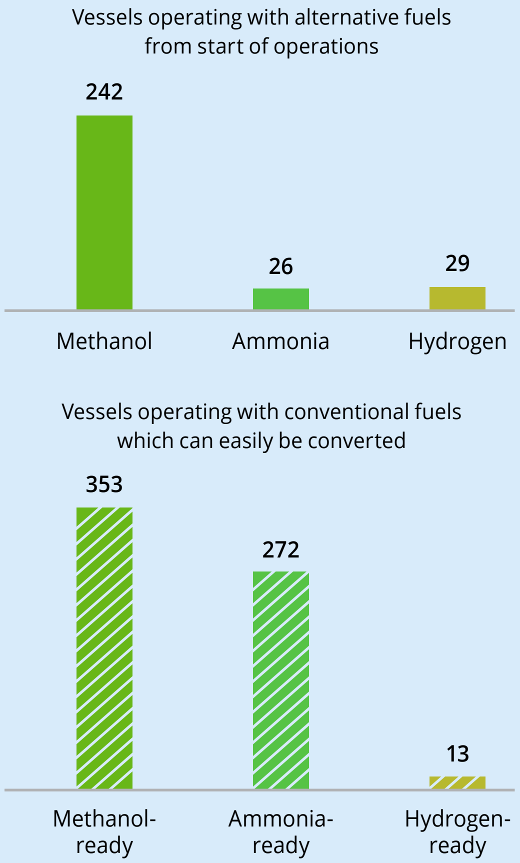
Shipbuilders also commercialize vessels with optionality, ships that are equipped with conventional engines specifically designed to be easily retrofitted to an alternative fuel. In this category, 272 "ammonia-ready" ships were ordered, only just behind the orders for "methanol-ready" solutions (353).[75] This suggests that the medium-term race between methanol and ammonia is highly undecided, with no industrial consensus on which solution to favor. In the longer-term, however, the outlook for methanol is clouded due to concerns about the availability of affordable climate-neutral CO_2.

Methanol can only remain cost-competitive with ammonia if it is produced from low-cost biogenic CO_2, with any resource limitation strongly favoring ammonia deployment. The figure below shows the relative cost of methanol and ammonia as a function of the cost of the input CO_2.

Methanol production can cost more than twice as much as ammonia production when relying on CO_2 from DAC. **Therefore, as the availability of biogenic CO_2 is likely to be insufficient to meet expected CO_2 demand for chemicals and fuel production (Figure 8), the potential for synthetic methanol in shipping remains limited.**

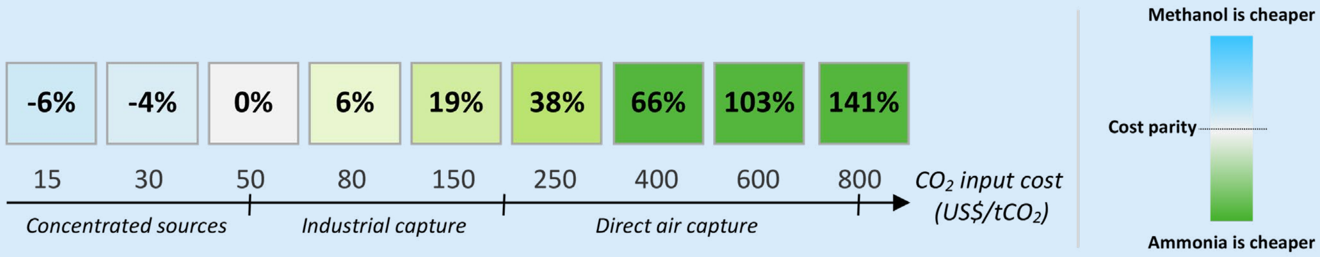
There are fewer technical constraints associated with methanol handling compared to ammonia. As such, the investment and operational costs of methanol vessels are slightly below those of ammonia-based options. However, the cost disparity is so significant that DAC-based methanol will remain considerably more expensive than ammonia, even when evaluated within a total cost of ownership framework.[39]

Hydrogen-based alternative fuel vessels in current order book (as of July 2024)



Source: Deloitte analysis based on Clarksons research[75]

Cost difference between Methanol and Ammonia



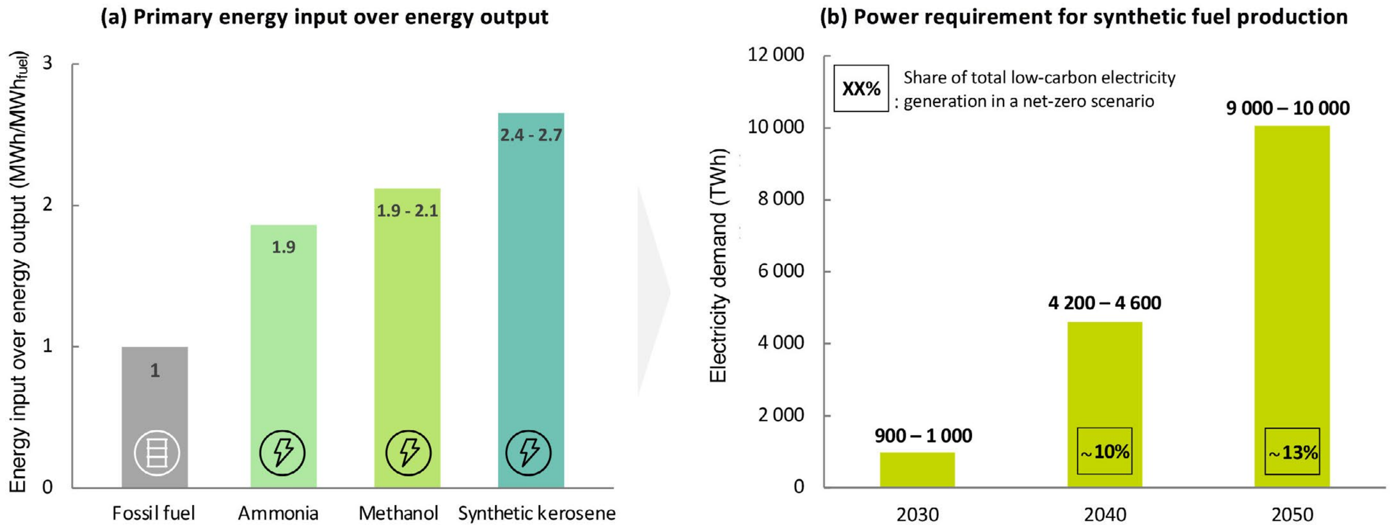
Source: Deloitte analysis based on HyPE results

Energy implications of synthetic fuels production

Synthetic fuels require considerably high primary energy inputs. Hydrogen production, fuel synthesis, and DAC are all highly energy-intensive processes, with synthetic fuel production requiring a primary electricity input equivalent to 1.9 to 2.7 times the final energy content of the produced fuel (Figure 9(a)). As synthetic fuels become a viable decarbonization option for the aviation and maritime sectors, they will require additional clean electricity supply capacities. However, given that widespread electrification is a major part of the energy transition, synthetic fuels are expected to constitute a manageable part (up to 13%) of the overall clean electricity demand, which is expected to grow significantly in a net-zero future (Figure 9(b)).

The infrastructural challenges of scaling up synthetic fuels production go beyond additional power generation capacities. **Deploying synthetic fuels necessitates the simultaneous development of an integrated infrastructure,** including hydrogen production and distribution, CO_2 capture and transportation, as well as new storage and bunkering facilities for methanol and ammonia, though synthetic kerosene can be stored, transported and fueled through existing infrastructure.

Figure 9. Energy needs for producing synthetic fuels in 2030, 2040 and 2050



Source: Deloitte analysis based on Danish Energy Agency,[77] Global CCS Institute,[78] IEA.[27] The ranges correspond to the difference in energy intensity between production from biogenic-CO_2 and from DAC-based CO_2. Total power requirements are based on Deloitte's outlook described in section 2.3.

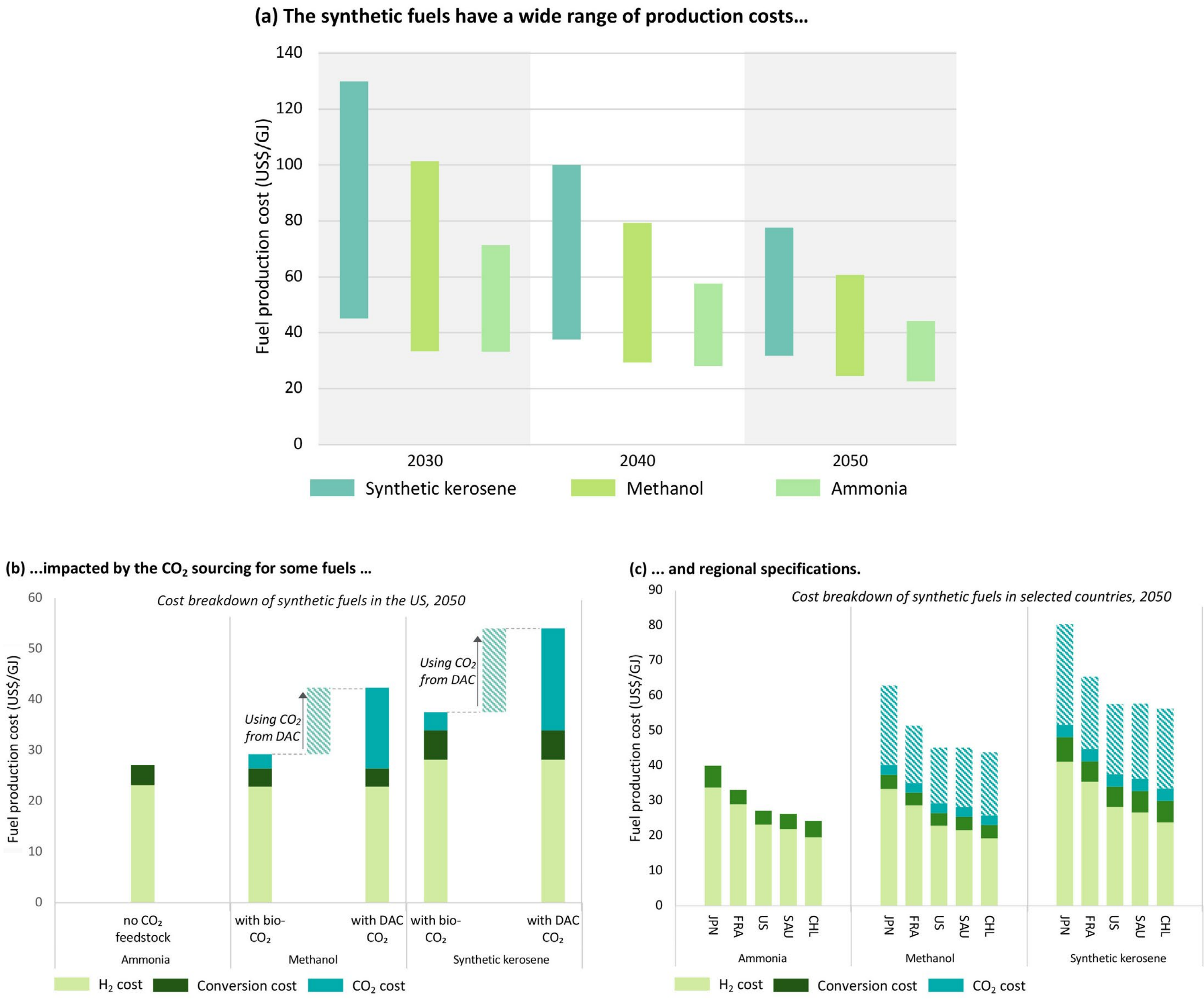
"To unlock the decarbonization potential of synthetic fuels, an extensive upscaling of renewable power capacity is essential, reaching as high as 10,000 TWh of annual production by 2050. This exceeds current global renewable production, surpassing the progress made in the last 20 years."

3.2 Navigating the high costs of synthetic fuels

As the fuel cost is a key cost component in both aviation and maritime shipping, the cost competitiveness of synthetic fuels is a major obstacle for their widespread adoption (Figure 10(a)). As ammonia production requires only hydrogen as feedstock, its cost is mostly driven by the hydrogen production cost. Synthetic hydrocarbons such as methanol and synthetic kerosene, however, require CO_2—and their costs are highly sensitive to the source of low-carbon CO_2. Using CO_2 from DAC instead of biogenic CO_2 can increase the production cost of methanol by 45%, and that of synthetic kerosene by 44% (Figure 10(b)).

Resources are not distributed evenly across the globe, and regional differences in the availability of natural resources (e.g., clean hydrogen and biogenic CO_2), technology costs and financing conditions lead to differing costs (Figure 10 (c)). In particular the levelized cost of green hydrogen, as one key cost driver, depends on the cost and availability of low-carbon electricity supply which is driven by the quality of renewable sources. As a result, the production costs of synthetic fuels vary widely across geographies. Due to further learning, technological development and economies of scale, the main drivers of synthetic fuel costs are expected to drop significantly in the coming decades, enhancing their competitiveness.

Figure 10. Variability in production costs for synthetic fuels by technology, region and year



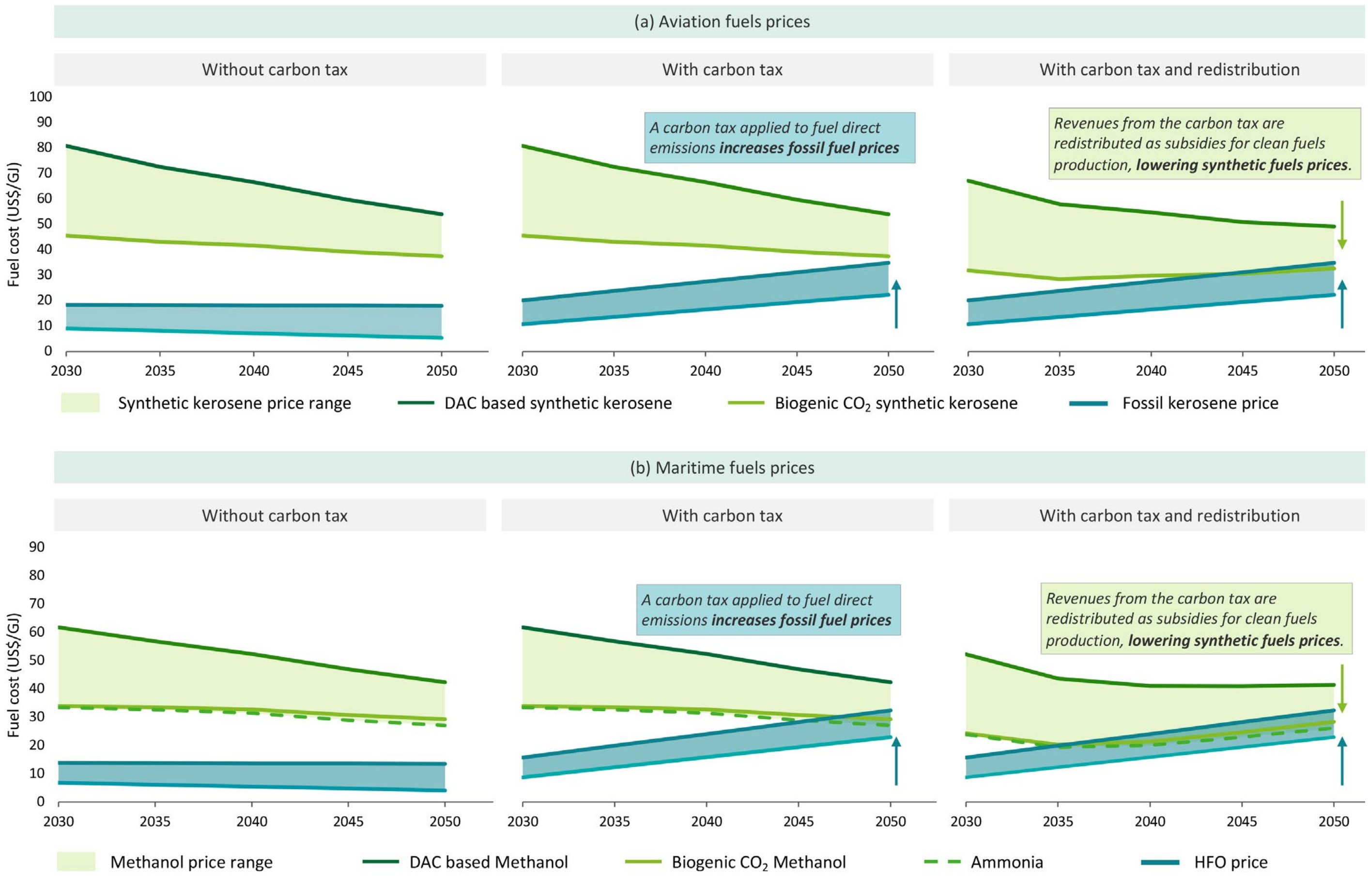
Source: Deloitte analysis based on techno-economic modeling and HyPE results

Synthetic fuels are significantly more expensive than conventional fossil fuels. Depending on the geography and the source of CO_2, producing synthetic fuels can cost two to ten times the average fossil fuel prices, both in aviation and maritime shipping (Figure 11, left). Despite the expected decline in the costs of synthetic fuels, in the absence of substantial policy intervention this price disparity will likely persist, even in the long run.

With the integration of a carbon component into fossil fuel prices,[79] synthetic fuel production costs can only intersect with fossil prices in the maritime sector after 2045 (Figure 11, middle). Adding a support component to the cost of synthetic fuels, using the generated revenue from carbon pricing to subsidize synthetic fuels production, would both decrease and flatten production costs over time.

In the short-run—when the cost gap is at its widest—the carbon revenues would be concentrated on a limited number of synthetic fuels projects. Conversely, in the long-term, although carbon prices would be higher, they would apply to less emissions due to the decreasing use of fossil fuels. Such a support scheme would reduce the cost gap and accelerate the transition to synthetic fuels. In a few cases, cost competitiveness can be achieved as early as 2035 in maritime shipping, and 2045 in aviation (Figure 11, right). Nevertheless, **due to limited availability of low-cost CO_2 feedstock and inter-sectoral competition for both clean hydrogen and sustainable CO_2, an important share of synthetic fuels supply (notably synthetic kerosene and methanol) will remain more expensive than conventional fossil fuels, even in the long run.**

Figure 11. Fuel cost difference between fossil fuels and synthetic fuels in aviation and shipping over time



Source: Deloitte analysis based on techno-economic modeling and HyPE results. Fossil fuels price ranges are based on IEA data[39] with trends for crude oil from the net-zero and stated-policies scenarios.[66] Carbon tax: linearly increasing from US\$25/tCO_2 in 2030 to reach US\$250/tCO_2 in 2050, in line with IEA's Net-Zero scenario. Synthetic fuel prices are based on modeled costs for the US.

The production of synthetic fuels requires an additional, but limited, financial effort in terms of investment costs compared to their fossil counterparts. The supply chain to produce 16 EJ of low-carbon fuels for the aviation and shipping industries would require the development of 2,500 GW of wind and solar capacities, 2,000 GW of electrolyzers and 700 Mt of climate-neutral CO_2, on top of the conversion plants. Altogether, the corresponding investment needs reach US$3.2 trillion cumulatively over the period 2050. Remaining below US$130 billion/year, these investment needs remain comparable to the current spendings on aviation and maritime shipping fuels,[80] once scaled over the same supply quantities and represents a small fraction of current investments in the fossil fuels industry (US$1.1 trillion expected in 2024[81]).

Given the tight margins shipping companies and airlines operate on, the additional costs of switching to low-carbon fuels will likely be passed on to final consumers. Nevertheless, the effect of synthetic fuels adoption in the aviation and maritime shipping sectors remain highly uneven (Figure 12). **Fuel costs represent an important part of air travel fares,** accounting for about 25-30% of airplane ticket prices.[82] Replacing fossil kerosene with synthetic kerosene at US$35/GJ[83] could increase the cost of a seven-hour flight from London to New-York by more than US$150.[84] If the CO_2 for its production is derived from DAC, the cost hike would more than double, adding around US$380 to the ticket. Nevertheless, synthetic fuels integration is expected to be very gradual and simultaneous to continued production cost decrease. This could help ease the economic impact on consumers and airlines in both the short and long term. **In contrast, since transport costs make up a small fraction of the final price of goods shipped by sea, end consumers are far less impacted by fuel price fluctuations in the maritime sector.** The cost increase stemming from switching to ammonia or methanol will therefore hardly be noticeable for the end consumers. For instance, shipping a kilogram of rice from Thailand to the United States costs around 3.5 US cents,[85] corresponding to less than one percent of its retail price (about US$4/kg). Switching fuel, even for a fuel costing twice the conventional one, would result in less than a 1% increase of additional costs (Figure 12). To sum up, **the impact across transport sectors varies significantly, with the maritime industry more readily able to pass cost increases on to end consumers compared to the aviation sector.**

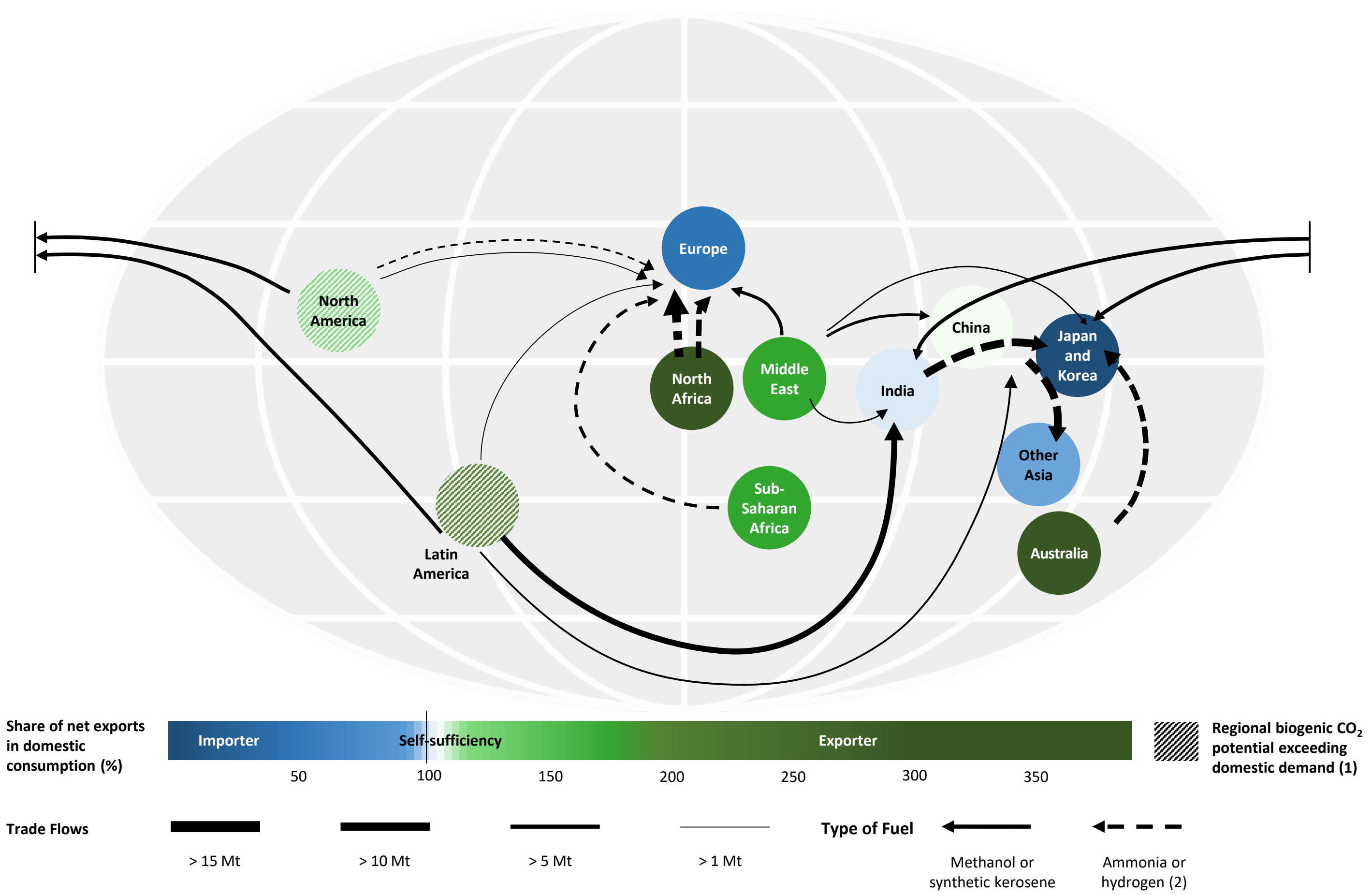
Figure 12. Cost implications of switching to synthetic fuels in aviation and shipping on transportation costs and final products

Source: Deloitte analysis based on the HyPE model. Synthetic fuels costs modeled correspond to the 2040 production cost average in the United States.

3.3 The role of trade in connecting supply and demand

As the most favorable production locations are not necessarily located near demand hubs, and transport costs of synthetic fuels are low compared to their production costs, **global trade can reduce the costs and mitigate regional imbalances.**[6] Regions with abundant renewable energy sources and biogenic CO_2, such as North and South America, are well-positioned to become leading producers of synthetic fuels, notably synthetic kerosene with higher value end-product but lower transport costs (Figure 13). Their significant biogenic CO_2 potential provides a competitive advantage in producing these fuels. Meanwhile, regions with excellent renewable potential but limited biogenic CO_2, such as North and Sub-Saharan Africa, are best placed to focus primarily on producing and exporting ammonia as a synthetic fuel with no CO_2 component. Lack of biogenic CO_2 restricts their ability to export carbon-based synthetic fuels. Nevertheless, their excellent renewable endowments can place them as the dominant exporters of ammonia.

Figure 13. Trade of hydrogen derivatives by end-use molecule in 2050



(1) Availability of biogenic CO_2 is assessed at a regional level.

(2) Ammonia can be used as a carrier to transport hydrogen over long distances. The second flow of hydrogen from North Africa to Europe is pure hydrogen transported via pipelines.

Source: Deloitte analysis based on HyPE modeling results.

Infrastructure availability is a key driver regarding the trade of synthetic fuels. Despite no major biogenic CO_2 potentials, the Middle East emerges as a prime candidate to export methanol, underpinned by its existing export infrastructure, combined with substantial low-carbon hydrogen potential and economic capacity to deploy DAC. Leveraging its geographical proximity to key demand hubs like Europe, the region is well-positioned to export methanol, which, though higher in transport costs than synthetic kerosene, remains economically more viable over shorter distances. Unlike other regions with high demand such as Europe, Japan and Korea that are likely to act as demand hubs, China and India are endowed with significant renewable energy potentials. Nevertheless, because of lack of sufficient biogenic CO_2, they will likely engage both in imports and exports: importing substantial quantities of methanol and synthetic kerosene, while exporting ammonia and hydrogen, thereby achieving a balanced and near self-sufficient energy economy.

The strategic global trade of synthetic fuels, driven by regional characteristics and resource endowments, infrastructure availability and economic strength, is crucial for balancing supply and demand. This intricate network of trade not only mitigates regional imbalances but can also enhance overall economic efficiency by optimizing resource allocation.

As the world moves toward a net-zero future, global trade of synthetic fuels will likely be crucial in ensuring energy security, economic viability, and environmental sustainability for all participating nations.

4. A call for action

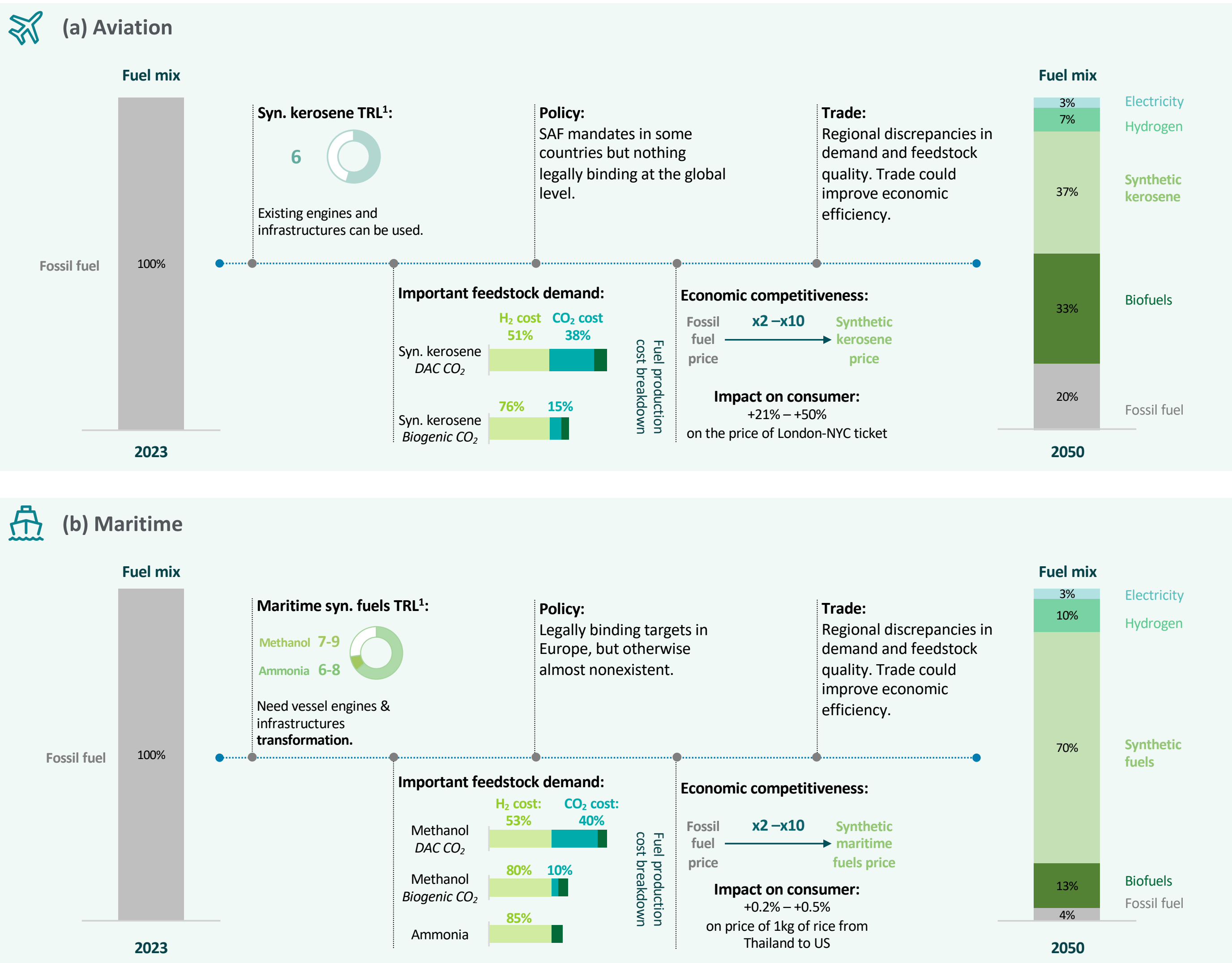
Decarbonization of aviation and maritime shipping requires significant amounts of synthetic fuels production, that reach 1.6 EJ in Deloitte's outlook by 2030 and almost 16 EJ by 2050. The latter corresponds to more than 150 Mt of clean hydrogen and almost 700 $MtCO_2$ of DAC-based and biogenic CO_2. Hydrogen production, fuel synthesis, and direct air capture together require between 9,000 TWh and 10,000 TWh of clean electricity supply by 2050 (one-third of global power generation in 2023), depending on the source of the low-carbon CO_2 used. Achieving such levels of clean electricity supply is a significant challenge, and exceeds the current global renewable power supply by more than 1,000 TWh.[86] Therefore, to unlock the decarbonization potential of synthetic fuels, an extensive upscaling of renewable power capacity is essential, surpassing the progress made in the last 20 years.[86]

4.1 Challenges ahead for the takeoff of low-carbon fuels

Currently, aviation and maritime shipping are predominantly reliant on fossil fuels. Synthetic fuels hold the key to their decarbonization, yet their relatively low technology readiness levels and their high production costs constrain their rapid adoption. Concerning aviation, the existing infrastructure and aircraft technologies are largely compatible with synthetic kerosene, but its production remains at a nascent stage (Figure 14.a). Conversely, ammonia and methanol are considered more mature but necessitate the development of new bunkering and engine technologies, as well as fueling infrastructure (Figure 14.b).

Beyond regional and national policies, a globally harmonized regulatory framework is crucial for these inherently international sectors to decarbonize effectively. In essence, transitioning away from the current fossil-centered aviation and maritime shipping sectors requires coordinated and ambitious efforts from all stakeholders in these sectors, including policymakers, international organizations, fuel suppliers, manufacturers, port and airport authorities, airlines, and shipping companies.

Figure 14. Decarbonization of aviation and maritime shipping—summary of the needs and means



[1]*TRL = Technology readiness level*

Source: Deloitte synthesis based on the findings of previous sections

4.2 The way forward

Policymaking to lay the foundations for regional market creation

Policymakers play a pivotal role in creating the conditions, the regulatory environment and continuous momentum for an effective transition toward low-carbon fuels. They should develop clear strategies, such as energy and climate strategies and sectoral roadmaps to provide industrials with much needed visibility, so they can tackle the uncertainties and the associated risks with their investments. By implementing the enabling regulatory instruments such as quotas or blending mandates, they can initiate the offtake of these fuels and their progressive scale up, mobilizing all actors in the supply chain to take action expensive than their fossil counterparts for a long time. Concerning economics, while mandates or quotas are essential for the offtake, in the long run, policymakers can bridge the cost gap by introducing taxes and support schemes. As these measures might not be sufficient to completely overcome the cost gap, the introduction of additional mechanisms (such as fossil fuel pricing) and channeling these revenues to low-carbon fuels can help synthetic fuels to break even with fossil fuels sooner.

Establishing common rules to create global markets

International organizations, including industrial associations and related agencies, are central in defining common rules and standards to help enable a coordinated transition across the world. Robust certification schemes are instrumental for value creation over the whole value chain of low-carbon fuels by providing credible sustainability guarantees. Harmonized rule sets and targets around the globe, such as taxonomies, definitions and carbon pricing practices, can help avoiding carbon leakage or arbitrage opportunities, as the carbon footprint of synthetic fuels can vary drastically depending on different production pathways and different regions.[87] For instance, a harmonized global sustainable fuel definition would help prevent abuse as seen historically when environmental regulation in maritime has been undermined by 'flagging' [88] practices as part of firms' cost minimization strategies.[89]

Proactive securing of sustainable feedstock

The decarbonization of aviation will rely on SAF, a drop-in fuel option, while the maritime sector will mostly use ammonia and methanol. The early development stage and complex supply chain of these fuels entail considerable lead times in their provision. **Fuel suppliers** will build new supply chains from scratch, and they must secure low-cost clean hydrogen and CO_2 feedstock by investing early in strategic sites, as well as entering into partnerships with upstream supply chain actors.

Technical and market uncertainties entail significant risks, adding to the financing costs of production and transport facilities and hindering their development. De-risking measures, such as long-term offtake contracts and different guarantee mechanisms (performance, revenues, etc.), can partially mitigate these risks, enabling investments and reducing financing costs. Finally, during the build-up phase of synthetic fuels supply chains, blending biofuels can benefit the technology scale-up and the development of the necessary infrastructure and help to meet decarbonization targets, with synthetic fuels gradually increasing in the fuel mix of aviation and maritime shipping.

Adequate infrastructure and adapted propulsion technologies

Port authorities and airports are the key enablers of adopting synthetic fuels in aviation and shipping, as they are responsible for putting the necessary refueling infrastructure in place. While current airport infrastructure can already be used with minimal adjustments, adapting port infrastructure to low-carbon fuels presents greater challenges. Port authorities should carefully weigh which fuels to supply, when to supply them, and in what quantities. They need to develop multi-fuel infrastructure that can support the continued refueling of conventional fossil ships, while also enabling progressive shipping companies to refuel vessels running on methanol and ammonia.

Airplane manufacturers and shipbuilders should ensure the availability of ships and airplanes running on low-carbon fuels. In aviation, this requires ensuring that aircraft engines are compatible with high blends of synthetic and bio-based fuels. However, the transition is more complex for shipbuilders, as they need to develop vessels compatible with methanol and ammonia that have hitherto not been used as fuel in shipping. To mitigate the risk of stranded assets, **airlines and shipping companies** need to proactively adapt their fleets to meet transition requirements. For instance, "dual-fuels" or "synthetic fuels-ready" vessels can be suitable options by providing the flexibility of running on both fossil and low-carbon fuels, by or enabling the shift to a low-carbon fuel at a later stage. Moreover, large shipping companies with fixed harbors can take the geographical characteristics into account in their fuel sourcing strategies given the uneven distribution of the available sustainable CO_2 and clean hydrogen feedstock around the globe.

Efficiency measures as low-hanging fruit

In the long run, the only way to achieve climate goals is to transition away from fossil fuels to low-carbon fuels.[1,27] Nevertheless, the required technology is not fully mature yet, and the urgency to address climate change calls for quick decarbonization. Efficiency improvements, both operational and technical, can significantly curb fuel consumption, reducing associated operational costs (maintaining competitiveness) and GHG emissions. **Airlines and shipping companies** can capture this quick win by investing in operational efficiency measures such as route optimization, speed control and logistics optimization, which require minimal upfront investments. On top of emission reductions, such measures can also maintain competitiveness by reducing expensive synthetic fuels consumption, even in the long run.

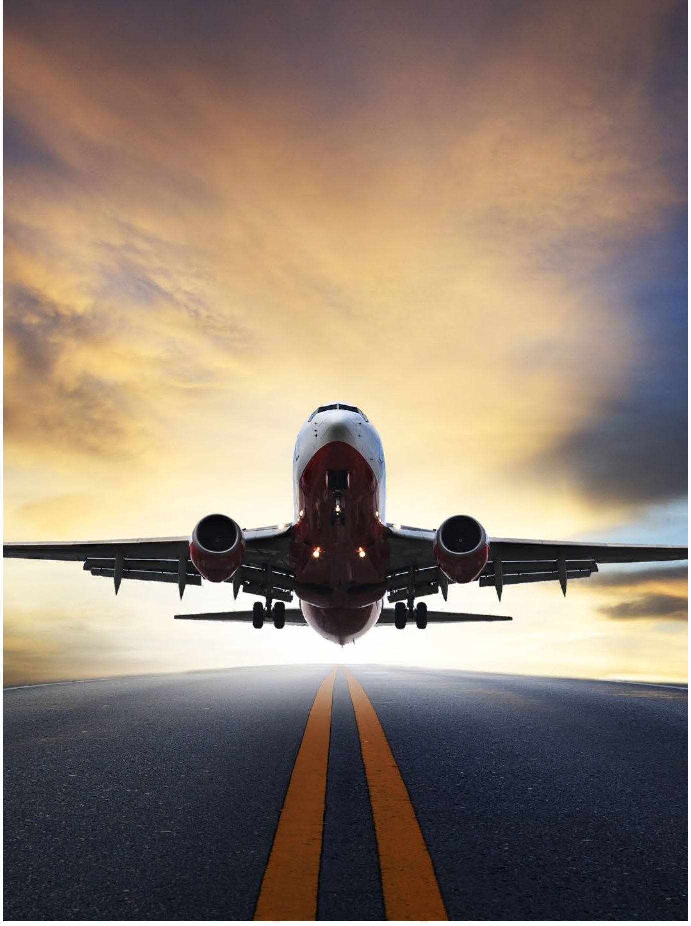
Technical efficiency improvements, through enhanced aerodynamic and hydrodynamic designs, more efficient motorization technologies, and lightweighting the vehicles require upfront investments in aircraft and ship technologies. This will require **airplane manufacturers and shipbuilders** to invest in research and development, innovation and adapt their designs to accommodate the future fuel mix efficiently.

Coordinated action through strategic decision-making and innovative business models

Airlines and shipping companies take the center stage as they link all stakeholders, connecting vehicle manufacturing and fuel supply (upstream), ports and airports (midstream) and consumers (downstream) with each other. Airlines and shipping companies play an important role in stimulating change across the value chain through the introduction of sustainable commercial offerings. Addressing the triple chicken-and-egg problem in aviation and maritime shipping necessitates coordinated action across the whole ecosystem. This requires strategic partnerships among **fuel suppliers** and other upstream **feedstock production and processing actors, airplane manufacturers and shipbuilders, airports and port authorities and airlines and shipping companies** and the engagement of **end customers.**

Decarbonization of aviation and maritime shipping, including the uptake of synthetic fuels, is a tremendous technical, economic and financial challenge, necessitating concerted efforts from all stakeholders. Despite the complexities, this monumental endeavor is achievable through targeted policymaking and coordinated action among key actors. Such collaboration can pave the way for a clean and sustainable future that supports global decarbonization, promote a just transition, and foster economic development, particularly in the Global South that generally benefits from important renewable endowments but often lacks access to the required low-cost capital.[62] This could help enable the creation of a resilient and thriving low-carbon economy for generations to come.

> Decarbonization of aviation and maritime shipping, including the uptake of synthetic fuels, is a tremendous technical, economic and financial challenge, necessitating concerted efforts from all stakeholders. Such collaboration can pave the way for a clean and sustainable future that supports global decarbonization, promotes a just transition, and fosters economic development.



Appendices

Appendix 1. HyPE model updates

HyPE (Hydrogen Pathway Explorer) is Deloitte's global hydrogen and hydrogen-based synthetic fuels supply and trade optimization model. It finds cost-efficient pathways to balance point-to-point hydrogen and its derivative synthetic fuels demand (methanol, ammonia and synthetic kerosene), and supply and optimize transport between different regions from 2025 to 2050. As such, its insights can be used as an outlook on the future of synthetic fuels. More information on the HyPE model can be found in Deloitte's latest global clean hydrogen outlook,[6] and the relevant scientific publications.[25]

This study considers the HyPE modeling data used in the previous studies mentioned, including the latest Deloitte publication on the impact of low-carbon hydrogen regulation in the EU,[90] by slight modifications on the hydrogen and its derivatives' demand data, overnight cost of the considered technologies and the cost of CO_2 and power sourcing for production of synthetic fuels. Figure 15 summarizes the updated cost values used as input data in the modeling exercise with HyPE.

Following the trends in hydrogen development and the latest public announcements and outlooks, the demand values have been revised downwards compared to the 2023 global clean hydrogen outlook study. In Deloitte's 2024 scenario utilized in this study, the demand for pure hydrogen in the industry sector reaches 89 Mt in 2030 and 189 Mt in 2050. In the power sector, it reaches 13 MtH_{2eq} and 62 MtH_{2eq} by 2030 and 2050 respectively. The trajectory of demand for the aviation and maritime sectors were also recomputed resulting in demand for synthetic fuels reaching 75 MtH_{2eq} and 154 MtH_{2eq} by 2030 and 2050 respectively. Overall, the global demand for clean hydrogen and its derivatives was reduced to 130 MtH_{2eq} and 480 MtH_{2eq} by 2030 and 2050 respectively (vs. 170 MtH_{2eq} and 598 MtH_{2eq} in Deloitte's 2023 global clean hydrogen outlook).[6]

Figure 15. Update of technology cost data

Technology cost		Unit	2030	2050
Alkaline electrolyzer	CAPEX*	**US$/kW$_e$**	620 – 960[91]	400 – 680[77]
Wind turbines	CAPEX*	**US$/kW**	1050 – 1350[92]	1000 – 1250[92]
Solar PV	CAPEX*	**US$/kW**	400 – 750[93]	300- 550[93]
Conversion costs				
Ammonia synthesis	CAPEX	**US$/[t$NH_3$/year]**	878[77]	551[77]
	Fixed OPEX	**US$/[t$NH_3$/year]**	26[77]	17[77]
	Variable OPEX	**US$/[t$NH_3$]**	0.1[77]	0.1[77]
Synthetic kerosene synthesis	CAPEX	**US$/[t$C_{12}H_{26}$/year]**	2325[94]	1369[94]
	Fixed OPEX	**US$/[t$C_{12}H_{26}$/year]**	93[94]	55[94]
	Variable OPEX	**US$/t$C_{12}H_{26}$**	30[94]	30[94]
Methanol synthesis	CAPEX	**US$/[t$CH_3OH$/year]**	739[77]	591[77]
	Fixed OPEX	**US$/[t$CH_3OH$/year]**	21[77]	18[77]
CO_2 costs				
DAC	CAPEX DAC plant only	**US$/t$CO_2$/year**	585[73]	398[73]
	Fixed OPEX DAC plant only	**US$/t$CO_2$**	24[73]	18[73]
Biogenic CO_2	Levelized cost of capture	**US$/t$CO_2$**	30[64]	30[64]

Source: Deloitte analysis, based on the sources provided in the table.

** These cost data include regional discrepancies. All cost data is provided in US$$_{2022}$.*

Appendix 2. Calculation of efficiency improvements of aviation and shipping

The modeling of efficiency gains for aerial and maritime transport in Deloitte's outlook includes both technical and operational efficiency improvements. It is based on literature review of the potential of different emission reduction levers and modeling of fleet evolution. The scenario is intended to be rather conservative: it excludes technologies with the lowest TRLs and uses median potentials where the net gains are still uncertain.

In aviation, different generations of airplanes with different efficiencies are modeled. The "previous generation" corresponds to airplanes that have been delivered prior to 2015. They currently represent around 70% of the fleet, and it is assumed that they will be gradually phased-out with the last airplanes being retired in 2040. The "upcoming generation" corresponds to today's best-in-class airplanes assumed to be 16% more efficient than the current fleet average. New aircrafts of this kind are assumed to enter the fleet each year until 2040. By then, all new sales would be of the "future generation". This third generation should enter the market in about 2035 and is expected to be 30% more efficient than the previous generation. Deloitte's estimates of fleet renewal and new aircrafts integration leads to a fleet composition of 60% "future generation" and 40% "upcoming generation" by 2050.

Air travel operational efficiency gains are drawn from ICCT's "Transformation" scenario,[95] encompassing both payload and traffic efficiency improvements, but not including formation flying.

In the maritime sector, new vessels added to the fleet from 2025 onwards are assumed to be 20% more efficient than the current average vessel. This rather conservative assumption is in line with the Energy Efficiency Design Index requirement,[96] consistent with various technical assessments[8, 48, 53] and can be achieved without even developing technical solutions which have not yet progressed beyond the pilot stage.[97] The long asset lifetime found in the maritime sector implies that deployment in the fleet is progressive. Such vessels represent around 20% of the fleet in 2030, 57% in 2040 and 93% in 2050.

The total potential for operational efficiency gains in the maritime sector is estimated to be 19% of fuel consumption reduction by 2050.[54] Capturing operational efficiencies in the maritime sector requires limited investment, mainly in deploying digitalization solutions. Deloitte's scenario therefore assumes that 80% of operational energy improvements are achieved before 2040.

Appendix 3. Calculation of sustainable feedstock availability for biofuel supply

There is a wide range of estimates on the potential supply of biomass feedstocks for bioenergy use. These differ based on various assumptions: key dimensioning assumptions include the economic potential of wastes and residues as input feedstock, adherence to sustainability requirements, and estimates of land allocation for energy crops given uncertainties regarding future food demand.[43, 45] Sustainable biomass potential is calculated based on considering different feedstock categories, with values taken from a mix of studies.

a. Starting with energy crops, which are primarily grown for producing biofuels, biogas, or power generation. These include plants with high biomass yield and fast growth rates such as switchgrass, miscanthus, and some types of willows and poplar trees.[27] These crops should preferably be grown on land that is not used for food purposes, such as contaminated and marginal land, to avoid competition with food sector. The potential for energy crops is estimated to be between 7 EJ and 700 EJ by 2050, with the average value of 109 EJ considered in this study.[45]

b. For agricultural feedstocks, production should occur without limiting food availability or causing significant land-use changes, while ensuring positive sustainability assessments regarding biodiversity and water availability and quality.[45] The IEA estimates that the range of potential for agricultural feedstocks will vary from 60 EJ to 100 EJ, while this value is estimated at around 80 EJ for 2033 by OECD and FAO.[43, 98]

c. The agricultural waste category comprises by-products from harvesting major crops like maize, cereals, rice, and sugar cane, as well as residues from processing them in mills. The agro-industry should ensure a balance by reserving some resources for animal feed and maintaining sufficient residues for soil protection. The estimated potential for agricultural wastes ranges from 46 to 95 EJ by 2060 as per the IEA's estimates.[43]

d. Wood harvesting includes woody biomass within a sustainable forestry plan, where protected areas are excluded to maintain soil health.[27] Its potential is estimated to be between 15 EJ and 30 EJ by 2060 according to the IEA.[43] According to the IRENA, this potential varies from 5 EJ to 95 EJ by 2050.[45]

e. Municipal waste includes materials that have no other useful purpose but must be collected and managed. Utilizing wastes such as the biogenic fraction of municipal solid waste (MSW) as fuel or feedstock offers an alternative environmental treatment option (replacing landfill). According to the IEA estimations, the potential for municipal waste ranges from 10 to 15 EJ in 2060.[43]

After summing these values up to calculate the total sustainable feedstock availability, other factors are applied to derive the potential of biofuel production: collection rates are applied on a part of municipal solid wastes, notably used oil, estimating an average collection rate of 26% based on the analysis carried out by the IRENA.[45] About half of the other municipal solid waste is from organic wastes, which is assumed to be sustainable and suitable for biofuels production. [27]

Other categories such as agriculture and forest residues are subject to competition with other sectors like the food, manufacturing, and industrial sectors. Approximately 8% of agricultural commodities[98] and 11% of energy crops are estimated to be available to produce biofuels.[43, 94]

Conversion rates account for energy losses when transforming feedstocks into biofuels. Municipal waste transformation is considered to rely on a combination of gasification/Fischer-Tropsch (50%) and Hydro-processed Esters and Fatty Acids (HEFA) routes, yielding 20% and 90% of conversion rates respectively. Other crops are assumed to rely on a combination of 50% gasification/Fischer-Tropsch and 50% alcohol-to-jet routes, yielding 20% and 13% biofuels respectively.[27]

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