

DEEP DIVE

DECARBONIZING AVIATION and MARITIME SHIPPING



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Questions and comments are welcome at givinggreen@idinsight.org.

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Summary

- **Emissions from aviation and maritime shipping:** Currently, aviation and maritime shipping constitute 6% of global emissions. However, given the rate of demand increase paired with lagging decarbonization efforts, these sectors are projected to account for more than 30% of global emissions by 2050 if left unmitigated while other sectors decarbonize.
- **Key technological interventions for decarbonization:** Decarbonizing aviation and maritime shipping will require a suite of technological interventions, some of which are in the early stages of development. We think that alternative fuels, especially e-fuels, are technologies that could play an outsized role in decarbonizing these sectors. There are various options for alternative fuels, each with distinct challenges and limitations.
- **Philanthropic strategies and funding need:** Nonprofits have worked on decarbonizing aviation and maritime shipping by creating plans for decarbonization, analyzing the development of enabling technologies, advocating for stricter policies, forming coalitions to strengthen political will for reduced emissions, aligning policies and standards, and testing new technologies. They have also used legal action and communication strategies to increase public awareness and pressure industry, governments, and investors to take action. Based on our analysis, we find policy advocacy to be among the most viable philanthropic strategies. We also favorably consider strategies to conduct technical analysis to identify critical technical and market gaps, build coalitions, and mount legal pressure.
- **Theories of change:** Decarbonizing aviation and maritime shipping will require policies directly regulating sector emissions, policies promoting clean, alternative fuel development, and industry commitments to purchase alternative fuels and transition existing fleets. Based on our analysis of the readiness of the requisite technologies, the ambition levels of current policies, and the status of private sector commitments, we have higher confidence in the potential effectiveness of policy measures and lower confidence in voluntary industry commitments in the absence of policy.
- **Key uncertainties and open questions:** Our key uncertainties include our concern regarding overreliance on biofuels, our evaluation of the influence of international governance bodies, funding need, and the general feasibility of decarbonizing aviation.
- **Bottom line / next steps:** We think it is important to direct more philanthropic funding toward reducing emissions from aviation and maritime shipping, given the challenges of decarbonization, the low level of funding these sectors have received historically, and synergies with other critical pathways for reducing emissions (e.g., decarbonizing heavy industry). As part of our 2023 investigation into aviation and maritime shipping, we classified [Opportunity Green](#) and [Clean Air Task Force](#) as two of our [top recommendations](#).



Overview

The transportation sector, which includes road transport, rail, maritime shipping, aviation, and pipelines, accounted for nearly 8 billion metric tons of CO₂ emissions in 2022, or about 20% of global emissions.¹ Emissions from this sector have been steadily increasing by 1.7% annually since 1990.²

According to analysis by the American Council for an Energy-Efficient Economy, the transportation sector holds the largest opportunity for electrification of any sector. The analysis projects that 75% of passenger vehicles and 50% of medium- and heavy-duty vehicles will be electrified by 2050.³ Consequently, despite constituting the bulk of the sector's emissions, it is our impression that road transport has a relatively straightforward path to reach zero emissions. In contrast, electrification is not as central to decarbonizing aviation and maritime shipping, which will depend heavily on more nascent technologies such as clean, alternative fuels. Consequently, aviation and maritime shipping are generally considered more difficult to decarbonize.

Aviation currently contributes 3% of annual global emissions, but given that demand is projected to triple in the coming decades, this transport sector could account for 22% percent of annual emissions by 2050 if left unabated while other sectors decarbonize.⁴ Challenges to decarbonization include rapid demand increase, limited technological options, the high cost of alternative fuels, and the international nature of the sector.⁵ Thus far, private sector efforts have focused on improving efficiency, buying offsets, and using bio-based sustainable aviation fuels (SAFs). However, our understanding is that achieving substantial decarbonization in the aviation sector may also require a combination of robust investment in synthetic jet fuel development, carbon removal, and initiatives to reduce demand.⁶

A 2023 report cites that 90% of global trade relies on maritime shipping and that while it accounts for 3% of annual global emissions today, it could rise to 10% of annual global emissions by 2050 under

¹ "In 2022 global CO₂ emissions from the transport sector grew by more than 250 Mt CO₂ to nearly 8 Gt CO₂, 3% more than in 2021." [IEA Transport Analysis](#)

² "Transport emissions grew at an annual average rate of 1.7% from 1990 to 2022, faster than any other end-use sector except for industry (which also grew at around 1.7%)." [IEA Transport Analysis](#)

³ "Our analysis includes electrification in several sectors. The largest amount of electrification is in the transportation sector: in our opportunity case, by 2050 electric vehicles ramp up to more than 75% of the passenger vehicle stock and 50% of the medium- and heavy-duty stock." [ACEEE \(2019\)](#)

⁴ "Global aviation is currently responsible for about 3% of total global, anthropogenic CO₂ emissions – having seen an increase by over a third between 2010 and 2019 alone. If aviation were unmitigated, it could be responsible for 22% of global emissions by 2050." [Mission Possible Partnership \(2022\)](#)

⁵ "Why is aviation hard to abate?" [Mission Possible Partnership \(2022\)](#)

⁶ "In summary, if aviation growth is sustained, fully mitigating the climate impacts caused by the European aviation sector this coming century through offsetting and the adoption of syn-jet fuel will simultaneously require CDR and significant amounts of energy, natural and financial resources..." [Sacchi et al \(2023\)](#)



business-as-usual, assuming other sectors decarbonize.⁷ Challenges to decarbonization include the diversity and longevity of vessels, the development of alternative fuels and requisite infrastructure, and the sector's international nature.⁸ Our understanding is that a combination of interventions will be needed to decarbonize maritime shipping – including electrification, alternative power, and improved efficiency – but the bulk of emissions reductions will be achieved through the transition to alternative fuels.

Technological Interventions

Decarbonizing aviation and maritime shipping will require a suite of technological interventions, including alternative fuels (e-fuels and biofuels), electrification, and improved efficiency. We briefly describe each of these intervention areas.

In particular, we think that low-carbon hydrogen-derived fuels have long-term, cross-cutting potential to reduce a substantial amount of emissions from both shipping and aviation, but these fuels are at a relatively early stage of technological readiness.⁹ For this reason, we have included an [Appendix](#) to describe a few relevant hydrogen-derived fuels, our understanding of the challenges, co-benefits, and adverse effects of scaling these fuels, and a cursory review of cost-competitiveness and maturity levels.

Alternative Fuels

While some lighter aircraft use aviation gasoline (Avgas), most aircraft are powered by kerosene-based jet fuel.¹⁰ Alternative fuels for aviation are often referred to as sustainable aviation fuels (SAFs) and described as low-carbon, drop-in ready fuels derived from both biological and non-biological feedstocks.¹¹ Our impression is that there has been more emphasis on bio-based SAFs and less, albeit growing, support for jet fuels derived from non-biological feedstocks, also called synthetic jet fuels. We think increased support for synthetic jet fuels is important because (i) they are in most need of

⁷ "About 90% of world trade utilizes maritime shipping, and nearly all vessels involved in moving goods around the world run on fossil fuels...Under its current trajectory, the sector could account for 10% of global greenhouse gas emissions by 2050." [Our Shared Seas \(2023\)](#)

⁸ "Some traits of the maritime industry make it especially difficult to cut down emissions..." [CTVC \(2023\)](#)

⁹ "Our analyses suggest that switching from low sulfur fuel oil (LSFO) to alternative fuels could reduce well-to-wake emissions by 80 to 100%." [Mærsk Mc-Kinney Møller Center for zero-carbon Shipping \(2022\)](#); "That's why ICCT's aviation 2050 report, which examined several decarbonization scenarios, concluded that SAFs are likely to contribute the majority of future CO2 reductions in a decarbonized future for aviation...." [ICCT \(2022\)](#)

¹⁰ "Kerosene, known as Jet A-1 in the aviation industry, is derived from refined and used in jet planes, large aircraft with propellers and turboprop engines, and certain helicopters." [Planete Energies \(2019\)](#)

¹¹ "Sustainable aviation fuels (SAF) are low-carbon fuels produced from biological (i.e., plant and animal materials) and non-biological (i.e., municipal solid waste, industrial waste gases) feedstocks, which have similar physical and chemical characteristics as conventional jet fuel but with a lower life-cycle carbon footprint." [IEA \(2019\)](#)



innovation, and (ii) they may circumvent certain land use constraints or competition for sustainable biomass feedstock.¹²

Most fuels currently used in shipping vessels are heavy fuel oils known as bunker fuels.¹³ While there is a variety of alternative, low-carbon fuel pathways applicable to this sector, we think ammonia and methanol (i) can have relatively low well-to-wheel emissions depending on energy sources and feedstocks, (ii) have the potential to be sustainable in the long term, and (iii) may be less land-use intensive as their production can circumvent reliance on biomass feedstocks.¹⁴ Unlike SAFs, however, engine modifications are needed to power shipping vessels with ammonia or methanol. We also note that there has been industry interest in transitioning to liquid natural gas (LNG), but studies indicate that given LNG's lifecycle methane emissions, it should not be considered a clean alternative.¹⁵

Using low-carbon hydrogen, especially [green hydrogen](#), in the production of synthetic jet fuel, ammonia, and methanol reduces climate impacts.¹⁶ Synthetic jet fuel and methanol production also require CO₂ as a feedstock; to reduce the climate impact of production, this CO₂ must be sourced through captured CO₂ and optimally from the atmosphere via carbon removal technologies such as direct air capture (DAC). We refer to synthetic jet fuel, ammonia, and methanol produced using these specific feedstocks as [e-SAFs](#), [e-ammonia](#), [e-methanol](#), and collectively, e-fuels. Given the requisite feedstocks, these fuels face challenges in reaching commercial scale, including high costs and limited supply.

Fuels derived from biomass-based feedstocks are also considered viable options for aviation and maritime shipping and are already in use.¹⁷ Biofuels can be produced from various feedstocks, including sugars, starches, algae, woody residues, agricultural residues, oils, and municipal solid waste.¹⁸ While the cost is lower and the technological readiness is higher than that of e-fuels, there are concerns about

¹² "Limits on the availability of biomass and arable land could create competition with other agricultural sectors, and the reallocation of farmland and other agricultural inputs to biofuel production could exacerbate food insecurity." [CATF \(2022\)](#)

¹³ "Fuels used by marine vessels are known as bunker fuels. Those commonly used today are typically produced by refining crude oil—heavy fuel oils are essentially what's left after the distillation process that separates out kerosene or gasoline, which contributes to the lower prices—and are differentiated by their sulfur content." [CTVC \(2023\)](#)

¹⁴ Well-to-wheel is used as the fuel-cycle emissions analog to cradle-to-grave. Well-to-wheel indicates a full life cycle analysis including extraction, production, and use.

¹⁵ "The authors use a representative life-cycle emission factor as well as the 100-year and 20-year global warming potentials (GWPs) for methane included in the Intergovernmental Panel on Climate Change's Fifth Assessment Report. The 20-year GWP better reflects the need to reduce GHGs quickly, in order to meet the International Maritime Organization's (IMO) climate goals, and the results show that when combined with a trend toward higher leakage, there is no climate benefit from using LNG, regardless of the engine technology." [ICCT \(2020\)](#)

¹⁶ Conventional methods produce hydrogen from natural gas through a process called steam methane reforming. When some of the resulting emissions are mitigated via carbon, capture, and storage (CCS), the produced hydrogen is often referred to as "blue hydrogen." Hydrogen can also be produced by splitting water into hydrogen and water through a process called electrolysis; this is often referred to as "green hydrogen." Given that the production of both blue and green hydrogen produces fewer emissions than conventional methods, they are often both categorized as low-carbon hydrogen.

¹⁷ "The first flight using blended biofuel took place in 2008. Since then, more than 150,000 flights have used biofuels." <https://www.iea.org/commentaries/are-aviation-biofuels-ready-for-take-off>

¹⁸ "A Menu of Sustainable Feedstocks for Producing SAF..." [DOE, Bioenergies Technology Office](#)



overreliance on biofuels. One reason is that there is high uncertainty when calculating full life cycle emissions and ecological impacts of biofuels and biofuel production, and it is our impression that this continues to be an area of investigation.¹⁹ Another is that there are concerns that growing demand will result in increased land use for dedicated energy crops, detracting from land used for growing food, consuming water and other resources, and perpetuating impacts of further land use change.²⁰ For a decarbonization scenario heavily reliant on biofuels, it is estimated that by 2050, 20-40% of sustainable biomass stocks will be used for biofuel production – the majority for the aviation sector.²¹

Electrification, alternative power, and improved efficiency

For aviation, additional interventions include electrification, route optimization, fleet renewal, and even cabin densification. The benefit of these interventions is that they are relatively inexpensive and, in certain instances, may even generate revenue. However, these pathways would achieve only some of the necessary emission reductions.²²

In maritime shipping, there are a variety of additional interventions to help reduce emissions of the sector, such as optimizing route planning and fleet strategies, electrification of engines, integrating waste heat recovery systems, modifying hull and propeller design, and incorporating wind-assisted propulsion. One advantage is that most of these interventions are at a high technological readiness level. However, the associated emissions reductions for these pathways are minimal compared to alternative fuels' impact.²³

The Current Policy Landscape

Decarbonizing aviation and maritime shipping will require a combination of sector-specific policies and regulations and general policies and regulations for enabling technologies such as alternative fuels and the requisite feedstocks (e.g., hydrogen, DAC). To help inform our [theory of change](#), we briefly describe relevant governing bodies and some existing policies and policy gaps.

¹⁹ "Biofuel supply chains (BSCs) face diverse uncertainties that pose serious challenges. This has led to an expanding body of research focused on studying these challenges." Habibi, F., Chakraborty, R. K., & Abbasi, A. (2023). Towards facing uncertainties in biofuel supply chain networks: a systematic literature review. *Environmental Science and Pollution Research*, 1-31

²⁰ "For biofuels, the track record of investments without satisfying results is causing some to ask, wouldn't we have cracked this the first time around if it was a good solution? The feedstock issues, including competing with food and the expense of transporting biomass, make it a challenging pathway to scale." [CTVC \(2023\)](#)

²¹ "Therefore, 20%–40% of the indicative globally available sustainable biomass would be used in biofuel production facilities, to primarily serve the aviation sector." [Mission Possible Partnership \(2022\)](#)

²² "Actions are classified by three categories: operational measures (including air traffic management), fleet renewal, and SAF." <https://www.mckinsey.com/industries/aerospace-and-defense/our-insights/decarbonizing-aviation-executing-on-net-zero-goals>

²³ "Energy efficiency levers, their potential impact and current uptake." [Mærsk Mc-Kinney Møller Center for zero-carbon Shipping \(2022\)](#)



Aviation and maritime shipping

International Maritime Organization (IMO)

The [International Maritime Organization \(IMO\)](#) is a UN agency that regulates shipping globally and, combined with national and subnational policies, is considered to be a highly effective and comprehensive avenue for establishing ambitious emissions standards.²⁴ The IMO recently revised its climate strategy to reflect a net-zero emissions goal by 2050, accompanied by shorter-term reduction goals for 2030 and 2040. Beginning on January 1, 2023, ships will be required to calculate their Energy Efficiency Existing Ship Index (EEXI) and annual operational Carbon Intensity Indicator (CII). The EEXI measures a ship's efficiency relative to a baseline, the Energy Efficiency Design Index (EEDI), and provides a metric to ensure minimum efficiency standards. The CII ranks ships from A (highest) to E (lowest), and there are certain guidelines and timelines under which ships with low ratings must implement improvements. New ships must be manufactured to meet the baseline EEDI. The intention is to measure progress in 2026 and amend implementation measures to ensure that the sector is on track to meeting the goals outlined in the strategy.²⁵ While the IMO's strategy and regulations are the most progressive policies for the maritime shipping sector to date, they do not align with 1.5°C Paris goals.²⁶

International Civil Aviation Organization (ICAO)

The [International Civil Aviation Organization \(ICAO\)](#) is a UN agency that regulates aviation. In 2016, ICAO established the Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA) to temper the sector's emissions. The only mandatory component is for airlines to monitor and report emissions. It further encourages improved operational efficiency, the use of SAFs, and the purchase of carbon credits. In 2022, ICAO released a long-term global aspirational goal for international aviation to reach net-zero emissions by 2050.

In the context of biofuels, our understanding is that CORSIA's life cycle emissions estimates include higher emissions projections due to indirect land use change relative to other methodologies such as [GREET](#). Because of this, we think CORSIA is valuable in providing guidance for incentives such as the IRA SAF tax credit.²⁷ However, we are skeptical of CORSIA's effectiveness as a direct regulatory body, given that the implementation measures are voluntary, as well as the trend for airlines to rely heavily on offsetting in their climate strategies. In addition, ICAO has been criticized for its lack of transparency,

²⁴ "The global scope of the IMO presents a unique opportunity to develop consistent, comprehensive global policy solutions for decarbonization." [Global Maritime Forum \(2022\)](#)

²⁵ EEXI and CII - ship carbon intensity and rating system. [IMO \(2023\)](#)

²⁶ "Shipping Regulator Falls Short of 1.5C-Aligned Climate Goals." [Bloomberg \(2023\)](#)

²⁷ "As shown in the brown bars in the figure below, the supply chain LCA emissions estimated in GREET and CORSIA are closely aligned. But emissions from indirect land-use changes (ILUC) and soil organic carbon credits from land-management practices differ widely due to assumptions in the underlying models. These indirect emissions cannot be easily verified by regulators like the Treasury Department or easily demonstrated by producers, and thus there is the risk that using GREET would widely diverge from the CORSIA approach and existing U.S. fuel policies. Adopting GREET as a "similar" LCA methodology for SAFs in the IRA could incentivize fuel pathways with uncertain GHG reduction benefits." [ICCT \(2023\)](#)



exclusion of scientists and civil society, and prioritization of private sector interests.²⁸ For these reasons, some advocacy groups do not currently consider ICAO to be a key political lever.

EU

The [Fit for 55 package](#), which aims to reduce the EU's emissions by 55% by 2030, contains the [ReFuelEU aviation and FuelEU maritime initiatives](#) targeted toward increasing the use of sustainable fuels.

The ReFuelEU Aviation regulation mandates that airport fuel suppliers incrementally increase the amount of SAFs to 70% by 2050, with sub-targets specifically for e-SAFs.²⁹ It also requires EU airports to develop the necessary infrastructure to supply SAFs to airplanes leaving from EU airports. It requires aircraft to fuel with only the exact amount of fuel needed for a given flight (some aircraft carry extra if it's more expensive to refuel at the destination). Lastly, a consumer-facing labeling system will indicate operators using SAFs.

The FuelEU Maritime regulation, adopted in July 2023, includes objectives to reduce the carbon intensity of certain vessels' onboard energy use by 80% by 2050, mandating incremental reductions starting in 2025. Also included are regulations regarding plugging into onshore electric power sources when possible. Recent modifications include the inclusion of maritime shipping emissions in the [EU emissions trading scheme \(ETS\)](#) for the first time. Marine fuels sold and used in the EU became subject to tax in 2023; taxes are on a sliding scale based on pollution.³⁰ Despite being an improvement to existing EU regulations, these mandates are even less ambitious than those of the IMO.

Countries

IMO and EU policies are among the most ambitious, despite a growing patchwork of country-level initiatives. In the US, a [Clean Fuel Production Credit](#) was passed in the Inflation Reduction Act (IRA), which allocates credit amounts for SAF and non-SAF fuels corresponding to emissions factors. In addition, the Departments of Energy, Agriculture, and Transportation have coordinated a [Sustainable Aviation Fuel Grand Challenge](#) to scale SAF production to meet 100% demand by 2050. Supporting the SAF Grand Challenging, the Department of Energy (DOE) announced a [Clean Fuels & Products Shot](#), which includes meeting 50% of projected maritime shipping fuel demand by 2050. See [IEA's list](#) for more examples of country-level policies relevant to decarbonizing aviation and shipping.

Our impression is that there has been an uptick in policies supporting the decarbonization of aviation and maritime shipping. However, even in the presence of existing policy, these sectors remain off track in

²⁸ "In the past few years ICAO has faced criticism and been seen rightly or wrongly as an outlier even in the UN system for its lack of transparency in decision-making, its lack of access to information by the media, undue influence of industry ("captured by producer interests": *The Economist*), restricted involvement of civil society and independent scientists, and its political interference in the culture and workings of the Secretariat." [Centre for Aviation \(2021\)](#)

²⁹ "70% of jet fuels at EU airports will have to be green by 2050." [European Parliament \(2023\)](#)

³⁰ "All marine fuels sold in and used within the EU will be taxed from January 2023. In this way, marine fuels with serious pollution will be taxed the most." [Dong, J. et al \(2022\)](#)



terms of progress toward net-zero emissions. We think that increased policy adoption and ambition will be critical to meeting climate goals.³¹

Enabling technologies

Hydrogen

By the end of 2022, 32 countries had adopted national hydrogen strategies; see [this database](#) for a comprehensive list of hydrogen policies. According to the IEA, China is leading in electrolyzer capacity. The EU, UK, and US lead with respect to policy frameworks.³²

The US, for example, has committed \$8 billion for hydrogen hubs and has included a tax credit for low-carbon hydrogen production, [45V](#).³³ Also, the Department of Energy (DOE) launched an “energy earthshot” in 2021 to reduce the cost of green hydrogen by 80% in 10 years.³⁴

The EU has included hydrogen in its Carbon Border Adjustment Mechanism (CBAM).³⁵ Germany has created a [market-shaping initiative](#) to reduce financial risk, encourage investment, and increase the supply of low-carbon hydrogen and its derivatives.

The development and scaling of fuels such as methanol, ammonia, and e-SAFs are intimately linked to the progress and policy of hydrogen, given that the production of these fuels relies on hydrogen as a feedstock and because some of these fuels could serve as hydrogen carriers. Despite growing policy efforts, incentives remain insufficient to scale low-carbon hydrogen production, especially green hydrogen, to meet cross-sector climate goals. In particular, most policies address supply-side push, but advocates argue that more demand-side policy is needed.³⁶

³¹ “New technologies, fuels and operational measures can help reduce the industry’s greenhouse gas emissions, but without appropriate laws and policies, it will be difficult to achieve the targets set by the industry.” [Dong, J. et al \(2022\)](#); “The role of policy in enabling an industry transition to support aviation’s goal to reach net zero carbon emissions by 2050, is key. Only with a predictable policy framework, encompassing all aspects of regulation, can all industry stakeholders confidently invest the amounts required to bring revolutionary, carbon-saving technologies to market with the necessary speed...” [IATA \(2023\)](#)

³² “The United States and the European Union lead policy action, while China has taken the lead in deployment.” [IEA Hydrogen Analysis](#)

³³ “As part of a larger \$8 billion hydrogen hub program funded through the Bipartisan Infrastructure Law, the H2Hubs will be a central driver in helping communities across the country benefit from clean energy investments, good-paying jobs and improved energy security.” [DOE, Office of Clean Energy Demonstrations](#)

³⁴ “The first Energy Earthshot, launched June 7, 2021—Hydrogen Shot—seeks to reduce the cost of clean hydrogen by 80% to \$1 per 1 kilogram in 1 decade (“1 1 1”).” [DOE, Hydrogen and Fuel Cell Technologies Office](#)

³⁵ “The CBAM will initially apply to imports of certain goods and selected precursors whose production is carbon intensive and at most significant risk of carbon leakage: cement, iron and steel, aluminium, fertilisers, electricity and hydrogen.” [European Commission](#) n.d.

³⁶ “However, creating the green hydrogen market necessary for decarbonization requires sufficient demand-side policy that incentivizes that change. For the green hydrogen market to really scale, these policies will need to exist in the form of sectoral standards or sector-based or economy-wide carbon policies.” [Rhodium Group \(2023\)](#)



DAC

While an increasing number of countries have begun adding carbon removal technologies to their climate strategies, the US is leading in government investment. For example, US policies that promote direct air capture (DAC) innovation specifically include California's [Low Carbon Fuel Standard \(LCFS\)](#), the federal tax credit [45Q](#), and the recent allocation of [\\$3.5 billion for four regional DAC hubs](#).

Uses for certain technologies such as DAC are projected to include a variety of CO₂ markets, including alternative fuels, as well as durable carbon removal via geologic storage. Our understanding is that to meet these demands at scale, deployment must grow to reach billions of tons of CO₂ capture capacity per year by mid-century and that policy efforts are crucial to reaching these targets.³⁷

Industry Commitments

While we believe that policy will be the most critical lever to ensure that aviation and maritime shipping meet climate targets, we also think that industry action will be necessary for decarbonization. Below, we briefly outline some industry-level efforts and commitments.

In the aviation sector, there has been an increase in SAF offtake agreements; ICAO hosts a [public dashboard](#) tracking these agreements. One notable example is the MOU signed by Alaska Airlines, Microsoft, and Twelve to advance the use of e-SAFs.³⁸

The International Air Transport Association (IATA), the trade association for airlines, passed a resolution for the global air transport industry to be net zero by 2050.³⁹ The European aviation sector, representing aircraft manufacturers, airlines, airports, and air navigation service providers, released [Destination 2050](#), outlining a strategy toward net zero.

[Cargo Owners for Zero Emission Vessels \(coZEV\)](#), started by the Aspen Institute, is a platform to bring together shipping industry customers to help accelerate the sector's decarbonization. Members of this initiative include Amazon, IKEA, Unilever, Target, and Patagonia.

³⁷ "The scale-up that can be achieved by this novel, immature technology is heavily dependent on the policy and regulation landscape of the future." [Transport & Environment \(2022\)](#)

³⁸ "Under the Memorandum of Understanding (MOU) agreement Twelve will also work with the companies toward a demonstration flight proving viability of commercial use of e-fuel, and to provide low carbon jet fuel for Microsoft's business travel on Alaska." [Alaska Airlines \(2022\)](#)

³⁹ "The International Air Transport Association (IATA) 77th Annual General Meeting approved a resolution for the global air transport industry to achieve net-zero carbon emissions by 2050." [IATA \(2021\)](#)



The Global Maritime Forum has created the [Getting to Zero Coalition](#), an alliance that includes 160 companies, to push private sector and policy action, including developing green corridors – routes where policy incentives align to test new technologies and build partnerships.⁴⁰

Mærsk, one of the largest container shipping companies, has recently ordered 6 mid-size container vessels with engines compatible with methanol; it now has ordered a total of 25 methanol-powered vessels.⁴¹ At COP27, Mærsk signed the [Joint Statement on Green Hydrogen and Green Shipping](#), a commitment to accelerate the adoption of green hydrogen-based fuels.

Assessment of Philanthropic Strategies

We think decarbonizing aviation and maritime shipping requires policies to regulate emissions, policies to support enabling technologies such as alternative fuels, private sector commitment, and, in the case of aviation specifically, demand reduction.⁴² From what we've observed, nonprofits have supported these efforts in the following ways:

- Conducting technical and market analysis for enabling technologies such as alternative fuels
- Coordinating across stakeholders to align emissions accounting standards and certifications for alternative fuel pathways
- Advocating for more ambitious IMO targets
- Advocating for more ambitious ICAO targets
- Advocating for governments to regulate aviation and shipping emissions
- Advocating for policies to scale enabling technologies such as alternative fuels
- Coordinating private sector coalitions to align on emissions reduction targets, commit to alternative fuel offtake agreements, and/or advocate for policies and regulations
- Promoting green shipping corridors, strategically chosen geographic regions in which policies, partnerships, and technologies can be tested
- Mounting legal pressure on the aviation industry, governments, financial institutions, and/or investors
- Crafting communications strategies to build consumer awareness.

⁴⁰ "Green maritime shipping corridors are an avenue for coordinating across stakeholder groups in specific high-potential geographies to align incentives, test-drive new technologies, target investments, and build public-private partnerships." [Our Shared Seas \(2023\)](#)

⁴¹ "By ordering additional six vessels, Mærsk now has 25 methanol-enabled vessels on order." [Mærsk \(2023\)](#)

⁴² "Thus, from a physical standpoint, reducing air-traffic demand is a good short- to mid-term solution. It drastically reduces the scale of the environmental and economic effort needed to limit the impact of aviation on the climate. Doing so gives society time to develop other, possibly longer-term, sustainable solutions (e.g., navigational avoidance, hydrogen-powered and battery-electric aircraft, and other CDR options), which may be combined with the ones addressed in our work." [Sacchi et al \(2023\)](#)



We evaluate each strategy's scale, feasibility, and funding need (see table below). See [Giving Green's Research Overview](#) for more information on these metrics and our research process.

Sector(s)	Strategy	Scale	Feasibility	Funding Need	Notes
Aviation & Shipping	Conducting technical and market analysis for enabling technologies such as alternative fuels	Medium	High	Medium	Scale: While we think that these resources are foundational to advocacy efforts, we think that they can only achieve high impact when paired with advocacy efforts to promote policy or private sector action. Feasibility: As evidenced through the citations in this report, we think that nonprofits and think tanks have generated a robust collection of reports that articulate to policymakers what is needed to decarbonize shipping and aviation. Funding Need: We think that the many nonprofits working in these sectors actively publish analyses related to decarbonization. However, we still think there may be room for funding, given the ongoing need for market analysis to identify the gaps and potential mechanisms to address these gaps as the nascent market for alternative fuels and enabling technologies grows and evolves.
Aviation & Shipping (broader applicability)	Coordinating across stakeholders to align emissions accounting standards and certifications for alternative fuel pathways,	High	Medium	Medium	Scale: Our impression is that the impact of having a standardization across accounting and certification schemes could help reduce the perceived risk of investment and help to align policies and incentives to facilitate the growth of a global market. A lack of clarity around accounting schemes can also compromise the efficacy of policy initiatives, especially ones based on life cycle emissions or carbon intensity factors; an example of this lack of clarity arose in the development of guidance for the 45V tax credit for hydrogen included in the IRA. Feasibility: We think feasibility is medium, given that accounting methodologies often rely on highly uncertain or subjective assumptions. We see this, for example, in life-cycle emissions estimates for corn ethanol-to-jet fuel. Funding need: While there is significant effort on this front, we think that more pressure from civil society can move stakeholders (i) more quickly and (ii) toward standards that ensure climate impact is reduced. In addition, our impression is that the current analysis is more concentrated in academia and lacks broad civil society engagement.
Shipping	Advocating for more ambitious IMO targets	High	Medium	Medium	Scale: The IMO is a key political lever given its relatively ambitious policies, the recent success of advocacy in shaping and improving these standards, and its authority to implement measures to achieve its policy targets. Feasibility: We are unsure how effective nonprofits' advocacy efforts will be given that IMO policy is already the most ambitious to date and that it might be difficult to influence certain member states that are less progressive.



					Funding Need: Our impression is that most nonprofits working on decarbonizing maritime shipping include IMO advocacy centrally in their efforts. Therefore, we think funding need is medium given that sources of funding are already present but that continued funding remains important. ⁴³
Aviation	Advocating for more ambitious ICAO targets	High	Low	Medium	Scale: Given the international nature of the sector, ambitious and binding targets from ICAO could achieve large-scale emissions reductions. Feasibility: We rank feasibility as low given that current implementation measures are voluntary and that airlines have thus far relied heavily on offsetting in their climate strategies. In addition, there is low confidence in ICAO as a neutral governing body, given its lack of transparency and close ties with the private sector. Funding need: Despite low feasibility, the high potential for impact indicates that civil society advocacy may be an important counterbalance to private sector pressure. Therefore, while we don't consider this a focal point for advocacy, we assess funding need as medium to ensure some level of engagement.
Aviation & Shipping	Advocating for governments to regulate aviation and shipping emissions	High	Medium	High	Scale: Given the international nature of both shipping and aviation, we think that a patchwork of international, national, and subnational policies will be critical to decarbonizing these sectors, requiring a global advocacy effort. Feasibility: Policy ambition levels for aviation and maritime shipping have lagged behind those of other sectors, and the shipping and aviation industries have lobbied against emission regulations. This increases the difficulty of achieving policy progress. However, we think it's possible that civil society could provide a credible, balanced voice that may have the potential to positively and tangibly influence these efforts. Funding need: Given the above, we think that civil society efforts are especially needed to advocate for policies aligned with climate goals. In particular, our impression is that advocacy efforts have been underfunded relative to other strategies.⁴⁴
Aviation & Shipping (broader applicability)	Advocating for policies to scale enabling technologies such as alternative fuels	High	High	Medium	Scale: Policy advocacy efforts for enabling technologies such as alternative fuels complement sector-specific regulations. We think the scale is high given that the emission reductions resulting from such policies span multiple sectors. Feasibility: We rank feasibility as high, given that cross-sector applicability results in a broader ecosystem of advocates. Funding need: While policy efforts in this direction are growing, we think more funding for civil society policy advocacy will ensure that key innovation needs and market gaps are addressed. We think funding need is medium given that while more funding is needed, groups representing multiple sectors are engaged in this work.

⁴³ Private communication with civil society groups. (2023)

⁴⁴ Private communication with civil society groups. (2023)



Aviation & Shipping	Coordinating private sector coalitions to align on emissions reduction targets, commit to alternative fuel offtake agreements, and/or advocate for policies and regulations	High	Medium	Medium	Scale: We think that partnerships between civil society and the private sector could be powerful given that (i) civil society may push the private sector toward more ambitious climate stances and purchase commitments and (ii) the private sector has a strong influence over market shaping and certain policy-making processes. Feasibility: We are uncertain about how far the ambition level of private sector companies can be pushed, especially given the current high cost of certain climate interventions like alternative fuels. Funding need: Some efforts are underway to create private sector coalitions, for example, coZEV, Getting to Zero Coalition, and SASHA. We think that continued efforts from civil society to pressure the private sector are important given the potential scale of impact.
Shipping	Promoting green corridors to align policies, create partnerships, and test new technologies	High	Medium	Medium	Scale: Green corridors are strategically chosen geographic regions where policies, partnerships, and technologies can be tested. This could be an effective strategy as it recreates what is needed globally on a more localized and manageable scale. Feasibility: We think the concept is theoretically strong, but given the lack of concrete measures taken to formalize implementation, we have medium certainty regarding the initiative's feasibility. In August 2023, the US and UK began the scoping phase for a shipping corridor between the two countries.⁴⁵ However, bilateral or multilateral government relations may be difficult to achieve and sustain. Funding need: Our impression is that funding need is low, given that it is a relatively targeted intervention pursued by both coZEV and the Getting to Zero Coalition.
Aviation & Shipping	Mounting legal pressure on industry, governments, financial institutions, and/or investors	Medium	Medium	High	Scale: We think the legal action with the most chances for success might be more targeted and local in scope. We are unsure how broadly such cases will influence the industry at large. An indirect effect of legal pressure could be consumer awareness via media coverage. Feasibility: We think that there is a chance that certain targeted legal cases can be won, but given the cost and inherent risks associated with this strategy, we have medium certainty regarding its feasibility. Funding need: It is our understanding that it is uncommon for NGOs outside of the US to have lawyers on staff, signaling funding need for this strategy if executed globally.

⁴⁵ "To address the decarbonization goals of the global shipping industry the U.S. Department of Energy, with support by the U.S. Department of State and the U.S. Department of Transportation, and the United Kingdom (UK) government's Department for Transport are releasing simultaneous, but separate, *Development of Green Shipping Corridors between the United States and the United Kingdom Requests for Information* (RFI) seeking to understand the issues related to the establishment of at least one green shipping corridor between the two countries." [DOE \(2023\)](#)



Aviation & Shipping	Crafting communications strategies to build public awareness	Medium	Low	High	Scale: We have medium certainty that increased public awareness will lead to significant behavior change or pressure on industry and/or policymakers to impact measures to reduce emissions. In the case of shipping, the consumer is often far removed from the industry, except for cruise lines. In the case of aviation, we think that there are often no viable alternatives to air travel. However, we think there are opportunities to influence demand reduction policies for short-haul flights and convince corporate consumers to choose shipping as an alternative. Feasibility: We have low certainty that communication campaigns will lead to widespread public awareness. We think that it may be more feasible to increase public and consumer awareness through media attention as a result of legal pressure (see above). Funding need: Our impression is that communication strategies, particularly consumer-targeted communication about aviation emissions, are not generally well-funded.
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Table 1: Scale, feasibility, and funding need of various approaches nonprofits use to promote the decarbonization of aviation and maritime shipping.

Based on the above evaluations, we think the most viable philanthropic strategies center on policy advocacy. We also favorably consider strategies to conduct technical analysis to identify critical technical and market gaps, build coalitions, and mount legal pressure. We explore these approaches further by developing theories of change that illustrate the pathways through which these strategies could lead to emission reductions.

Theory of Change for Philanthropic Engagement

Based on the readiness of the requisite technologies, the ambition levels of current policies, and the status of private sector commitments, we develop high-level theories of change for how philanthropic actors can push for decarbonization of the aviation and maritime shipping sectors. This enables us to better understand the pathways of influence, the likelihood of each pathway, and avenues of greatest impact for philanthropic and civil society efforts.

We also discuss and evaluate the main assumptions related to each theory of change and rank whether we have **low**, **medium**, or **high** certainty for each assumption.⁴⁶ Our assessment is based on both primary and secondary evidence, as well as our general impression of the plausibility of the assumption. Importantly, a number of the stages of this theory of change may not be amenable to easy measurement or quantification, are not supported by a robust evidence base, or are expected to occur in the future but have not occurred as of yet.

⁴⁶ We describe our certainty as low/medium/high to increase readability and avoid false precision. Since these terms can be interpreted differently, we use rough heuristics to define them as percentage likelihoods the assumption is, on average, correct. Low = 0-60%, medium = 70-80%, high = 80-100%.



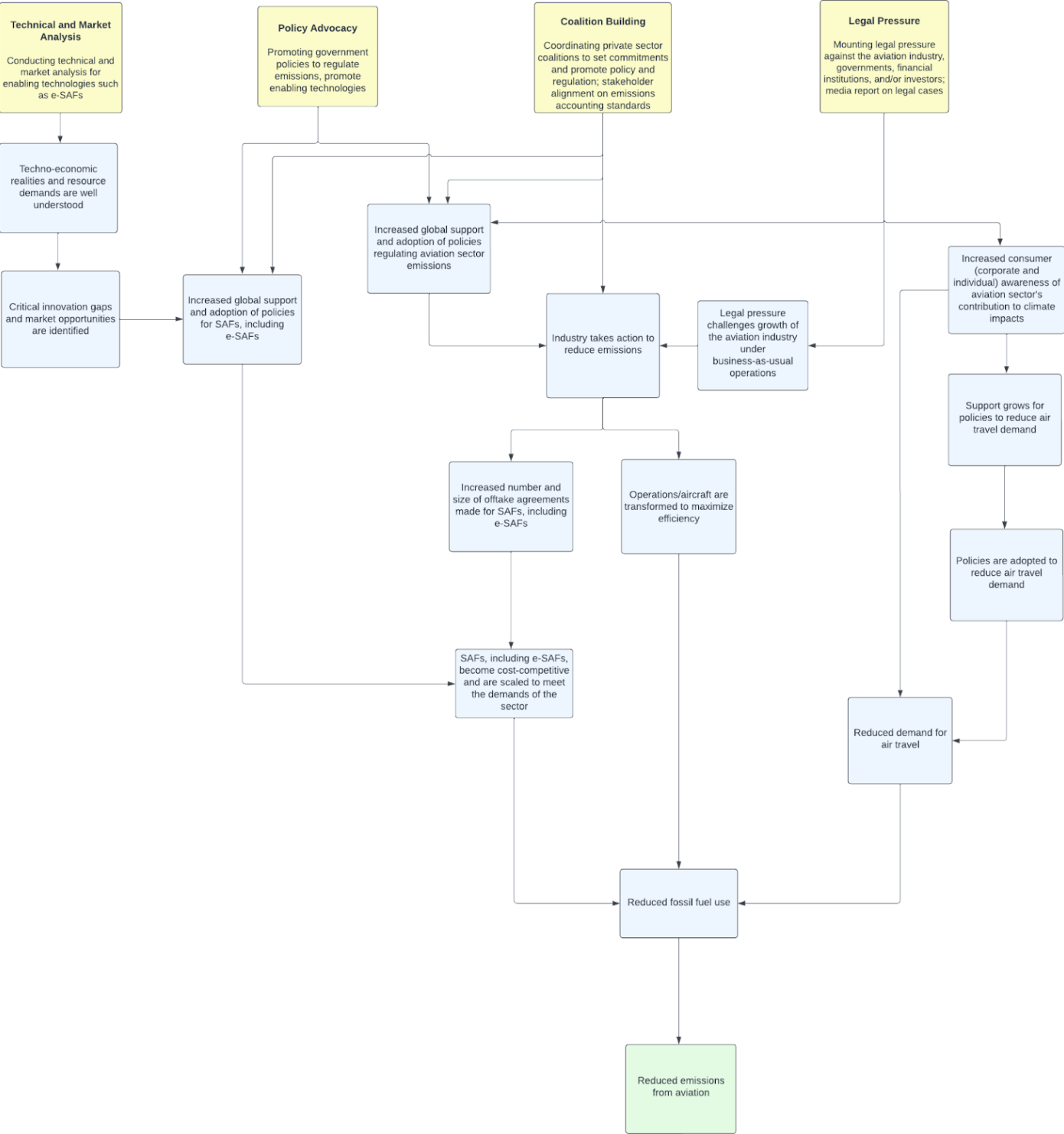


Figure 1: Theory of change diagram for reducing aviation sector emissions



Evaluating key assumptions

1. Advocacy efforts push governments to adopt policies to regulate aviation sector emissions in line with climate targets. (medium certainty)

Our impression is that [ReFuelEU Aviation](#) regulation is the most progressive policy to date. However, we think reaching net-zero sector emissions will require binding international commitments or a patchwork of robust national or regional measures. A growing number of countries have signaled intentions towards mandating or encouraging increased use of SAFs.⁴⁷ We have high certainty that momentum for such policies will continue, but we have low certainty regarding the ambition levels. This is based on our impression of (i) the [lack of confidence in ICAO](#), (ii) the international nature of the sector, (iii) the complexity of decarbonization pathways, and (iv) lobbying efforts by the aviation sector against ambitious climate policy.⁴⁸

2. Advocacy efforts push governments to adopt policies to promote enabling technologies such as alternative fuels. (high certainty)

We have high certainty that governments will adopt policies to promote enabling technologies such as alternative fuels given cross-sector applicability and, in some cases, economic potential. Green hydrogen will be critical to the decarbonization of heavy industry in addition to transportation. Given that green hydrogen production will rely heavily on renewable energy, our understanding is that the economic benefits of production could be widely distributed based on wind and solar potential. We think this is evidenced by the growing number of countries adopting hydrogen strategies.

3. Absent policy, private sector coalitions will set commitments and promote policies to regulate aviation sector emissions. (low certainty)

Initiatives like [IATA's resolution](#) and [Destination 50](#) signal some industry intent, but our impression is that there may be a reluctance to set ambitious commitments or promote policies that regulate sector emissions. We think that this is mainly because of the high cost of interventions. While some airlines have entered into offtake agreements to purchase SAFs (mostly from bio-based feedstocks), the demand signal remains insufficient to bring the fuels to scale – especially given the price gap between SAFs and conventional fuels. We think the most likely way for the private sector to take action is through a combination of policy and legal pressure, in which case direct corporate advocacy would not be additional.

In addition, we think that this evaluation depends on the composition of the coalitions. For example, we think coalitions with representation from alternative fuel producers (e.g., green hydrogen, e-SAFS) are more likely to support policies and regulations that include fuel standards or targets.

⁴⁷ "In the Asia Pacific region, in 2022 Japan proposed legislation mandating that SAF must account for 10% of aviation fuel by 2030. In the same period the Civil Aviation Administration of China also set ambitions to increase SAF use and lower GHG emissions intensity." [IEA Aviation Analysis](#)

⁴⁸ "The research further shows that many airlines have initiated extensive, climate-focused PR campaigns to deflect growing concern from governments and the public over the sector's climate footprint." [Influence Map \(2021\)](#)



4. Climate litigation will increase industry perception of risk associated with business-as-usual operations and catalyze industry efforts toward decarbonization (medium certainty)

While climate-focused legal action has had mixed success, we think that strategic litigation against a targeted sector could potentially spur private sector action by increasing industry perception of risk to business as usual operations. While winning a case would have a maximal impact, we think that even the media attention around legal cases could significantly influence corporate and consumer behavior.⁴⁹ In addition, our understanding is that litigation targeting a specific sector has been a critical tool in changing regulation and behavior in other contexts.⁵⁰

5. Increased consumer awareness can directly reduce air travel demand or increase support for demand reduction policies. (medium certainty)

Although we are not optimistic about the potential for voluntary behavior change in individuals, we see more potential for demand reduction resulting from policy or corporate action. For instance, we think that France's legislation to ban short-haul domestic flights (2.5 hours or less) is replicable, especially in countries with substantial rail infrastructure.⁵¹ Second, it is our impression that corporate consumers that ship products by air could lead to notable demand reduction if they transition to other forms of transport. For example, Apple has stated that it will begin to rely more on maritime shipping and rail to ship its products.⁵² Third, we think there may be growing momentum to target "elite flyers" like private jet users and infrastructure projects like airport expansions.

6. Policies and industry offtake agreements enable alternative fuels such as e-SAFs will become cost-competitive and scale to meet the needs of the aviation sector (low certainty)

Production cost of e-SAFs will depend on the cost of low-carbon and, optimally, green hydrogen and CO₂. The most climate-beneficial sources of CO₂ may either be through carbon removal technologies like DAC, which are currently quite expensive, or sustainable biomass, for which feedstocks are limited. E-SAFs are among the most costly fuels, given the price of feedstocks and the various reactions involved in the production process. We think that it will require broad and ambitious incentives for e-SAFs to become cost-competitive with conventional jet-fuel or biomass-based sustainable aviation fuels, and we think it is possible that they may be unable to scale to meet the needs of the sector. We address this as a [key uncertainty](#).

⁴⁹ "Delta Air Lines faces lawsuit over \$1bn carbon neutrality claim." [The Guardian \(2023\)](#)

⁵⁰ "Tobacco litigation has transformed the prospects for tobacco control, first in the United States and more recently worldwide." [Daynard et al \(2000\)](#)

⁵¹ "Rutherford says there's a sweet spot: For trips of less than 500 miles, replacing a flight with high-speed rail could put a dent in air travel. Flights of less than 500 miles make up [about a quarter](#) of the United States' domestic air traffic." [Washington Post \(2023\)](#)

⁵² "The company is shifting more product volume to shipping modes that are less carbon-intensive than air transport, such as ocean or rail. Apple's carbon footprint methodology shows that shipping the same product by ocean emits 95 percent fewer emissions than by air." [Apple \(2023\)](#)



Maritime Shipping

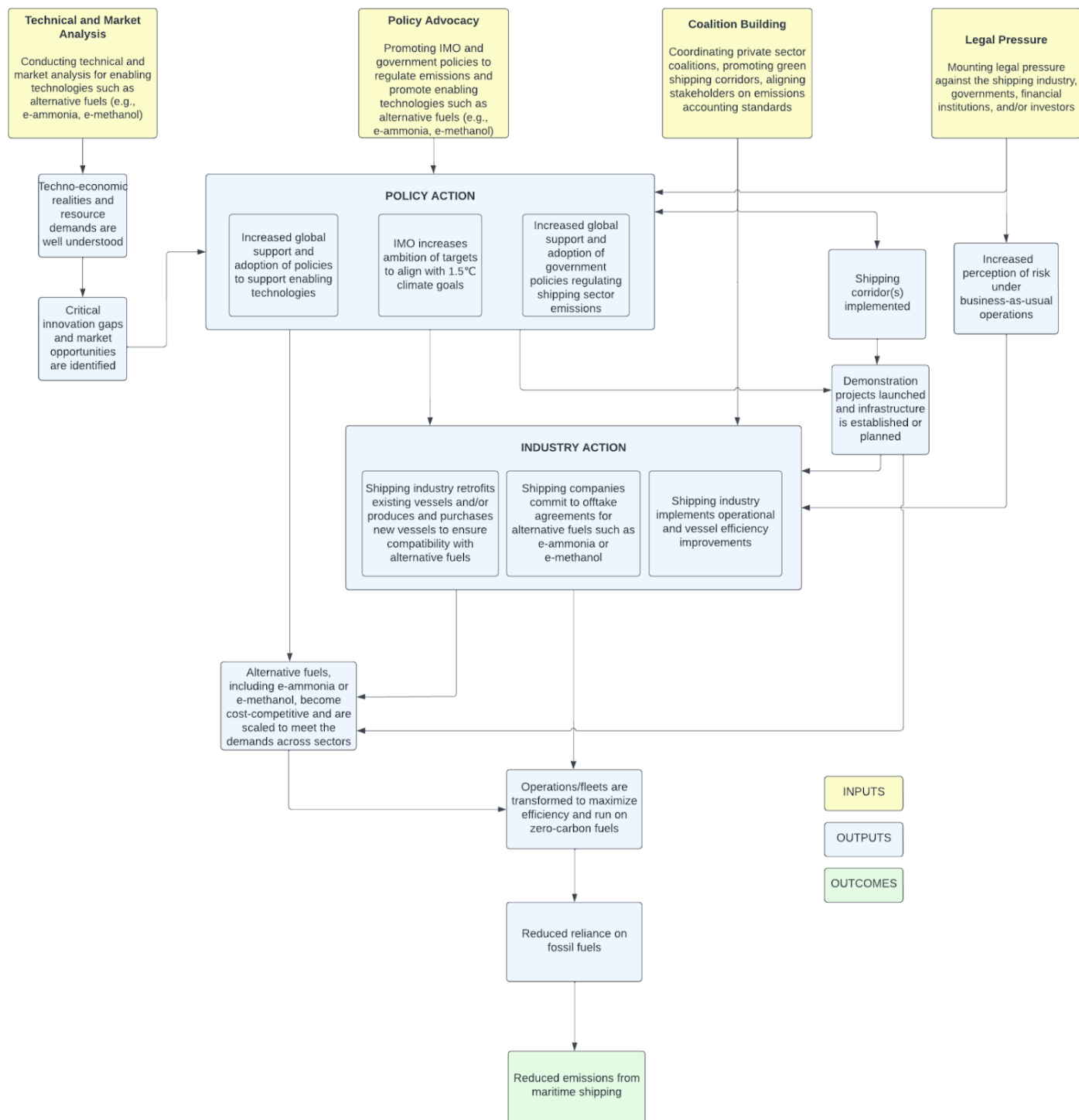


Figure 2: Theory of change diagram for reducing maritime shipping sector emissions



Evaluating key assumptions

1. Advocacy efforts result in revised IMO targets. (medium certainty)

While the [targets of the IMO](#) remain the most progressive to date, to align with climate goals, it needs to incorporate stronger commitments and clarity to ensure advancement toward its stated targets.⁵³ On one hand, it is our impression that the IMO is a key political lever given its relatively ambitious policies, the recent success of advocacy in shaping and improving these standards, and its authority to implement measures to achieve its policy targets. However, we also think that given such recent progress (July 2023), it may be unlikely to expect another revision in the short term. Lastly, as is currently happening at the EU level, governments may be pressured to pass policies that are at least as ambitious as the IMO's. We think this could dissuade member states from voting for stricter measures.

2. Advocacy efforts push governments to adopt policies to regulate shipping sector emissions in line with climate targets. (medium certainty)

While we think that the IMO policy will greatly influence other international, national, and subnational policies, our impression is that not all member states intend to match or exceed IMO ambition levels in their own policies. For example, [FuelEU Maritime](#) is less progressive than IMO targets. Given that the IMO targets still fall short of climate targets, we have medium certainty that government policies will generally achieve the level of ambition to meet climate goals.

3. Advocacy efforts push governments to adopt policies to promote enabling technologies such as alternative fuels. (high certainty)

Same as aviation assumption 2.

4. Private sector coalitions will set commitments, promote policies to regulate shipping emissions, and/or support the formation of green shipping corridors (medium certainty)

While Mærsk has been a notable private sector leader, we think that shipping companies may be generally reluctant to voluntarily set commitments to reduce emissions or promote policies that regulate emissions for reasons including the longevity of existing vessels, the high cost of new vessels that can run on alternative fuels, and the high cost and limited supply of alternative fuels such as e-methanol and e-ammonia. However, we think they might be slightly more supportive of green shipping corridor initiatives if they are located in contexts where policies and regulations are either likely to pass or already in place.

In addition, we think that this evaluation depends on the composition of the coalitions. For example, we think coalitions that have representation from alternative fuel producers (e.g., green hydrogen,

⁵³ "The IMO's strategy isn't currently binding, and it lacks specific measures to achieve its stated targets. Nevertheless, it represents significant progress from previous positions. However, the absence of alignment with the 1.5° C target is a major shortfall." [ClimateWorks \(2023\)](#)



e-ammonia, e-methanol) are more likely to support policies and regulations that include fuel standards or targets.

5. Policies and industry offtake agreements enable alternative fuels such as e-ammonia and e-methanol to become cost-competitive and scale to meet the needs of the shipping sector (medium certainty)

The cost trajectories of e-ammonia and e-methanol are highly correlated to the cost of green hydrogen. Given cross-sector demand and the [uptick in supply-side hydrogen policy initiatives](#), we have medium certainty that green hydrogen can become cost-competitive and be scaled to meet the needs as a feedstock for these fuels. We think it may be more difficult for [e-methanol to scale, as it also depends on sourcing captured CO₂](#). According to a 2019 study, while e-methanol and e-ammonia are more expensive than their fossil fuel counterparts at present, they could become cost-competitive by 2040 and even cheaper by 2050.⁵⁴

Is There Room For More Funding?

According to ClimateWorks' data, transportation has only received \$65 million (~3.8%) of the \$1.7 billion foundation support for climate change between 2015 and 2021.⁵⁵ For reference, this is similar to the amount given for industry (\$55 million), which [Giving Green evaluated to be a neglected sector](#).⁵⁶

The vast majority of general transportation funding has gone to road transport. This is evidenced by Climateworks' 2022 annual report; \$55.9 was directed toward road transport, \$7.8 million was directed toward maritime shipping, and \$3 million was directed toward aviation.⁵⁷ Based on this funding information, we think that efforts to decarbonize aviation and maritime shipping have been relatively underfunded with respect to other climate interventions.

Key Uncertainties and Open Questions

- **The role of biofuels:** Given their technological readiness, uncertainties regarding full life-cycle emissions, and concerns around sources and availability of sustainable biomass, we have emphasized the role of e-fuels in decarbonizing aviation and maritime shipping to protect against overreliance on biofuels. We may be wrong about this, especially if (i) similar land-use constraints arise in the context of renewable energy and (ii) e-fuels are unable to become cost-competitive and scale to meet the demands across sectors.

⁵⁴Fuel production cost estimates and assumptions. [Lloyd's Register \(2019\)](#)

⁵⁵ Page 6. [Funding trends 2022: Climate change mitigation philanthropy \(2021\)](#)

⁵⁶ While annual global emissions are higher from industry than from maritime shipping and aviation, the sectors share similar features including relatively complex and difficult pathways to decarbonization and rapid demand increase.

⁵⁷ Page 6. [ClimateWorks Annual Report \(2022\)](#)



- **Evaluation of international bodies:** We may have overestimated the IMO and underestimated ICAO in terms of influence as a regulatory body. If this is the case, it would affect our analysis of aviation, given that we did not include ICAO advocacy in our theory of change.
- **Funding need:** We have only included estimates for philanthropic funding directed specifically toward decarbonizing aviation and maritime shipping. We recognize that efforts to promote alternative fuels and other enabling technologies could potentially influence the decarbonization of these sectors, but do not include this funding because (i) it is difficult to estimate given cross-sector applicability and (ii) we do not think that this would significantly change our assessment of funding need.
- **Feasibility of decarbonizing aviation:** Aviation is one of the most difficult sectors to decarbonize as there is no clear, viable technological pathway. Given the limitations of sustainable biomass supply for SAFS and the high cost of producing e-SAFs, we think that a possible scenario is that the aviation sector cannot fully decarbonize and could, for some time, rely on carbon removal to compensate for these unabated emissions.⁵⁸

Bottom Line / Next Steps

In summary, aviation and maritime shipping are projected to account for more than 30% of global emissions by 2050 if left unmitigated.⁵⁹ Given the evaluation of philanthropic strategies, the relevance of the strategies to many of the critical pathways in our theories of change, and the relatively low level of funding these sectors have received, we think it is important for more philanthropic funding to be directed toward aviation and maritime shipping.

As part of our 2023 investigation into aviation and maritime shipping, we classified [Opportunity Green](#) and [Clean Air Task Force](#) as two of our [top recommendations](#).

Acknowledgments

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⁵⁸ "This is difficult in practice, and CDR could start well before 2050 to accommodate a more feasible trajectory of emissions reduction. It is followed by an increasing removal effort due to the rising RF induced by the fleet." [Sacchi et al \(2023\)](#)

⁵⁹ "If, as in the past, the ambition of these sectors continues to fall behind efforts in other sectors and if action to combat climate change is further postponed, their CO2 emission shares in global CO2 emissions may rise substantially to 22 % for international aviation and 17% for maritime transport by 2050, or almost 40% of global CO2 emissions if both sectors are considered together." [EU \(2015\)](#)



Appendix

Green hydrogen

Overview

Hydrogen can be used as a direct fuel or feedstock for other fuels, such as ammonia and methanol. Hydrogen is considered a clean fuel because when used in a fuel cell, the byproducts are electricity, oxygen, and heat.⁶⁰ While it is also considered a zero-carbon fuel, it can produce secondary greenhouse gas (GHG) effects when combusted instead of used in a fuel cell.⁶¹ Conventional methods produce hydrogen from natural gas through steam methane reforming.⁶² When some of the resulting emissions are mitigated via carbon, capture, and storage (CCS), the produced hydrogen is often referred to as “blue hydrogen.”⁶³ Hydrogen can also be produced by splitting water into hydrogen and water through a process called electrolysis; this is often referred to as “green hydrogen.” Given that the production of blue and green hydrogen produces fewer emissions than conventional methods, they are often both categorized as low-carbon hydrogen. In this appendix, we will focus only on green hydrogen produced using clean energy as it avoids fossil fuels and should be favored in the long term.

Our impression is that green hydrogen’s role in decarbonizing shipping will be predominately as a feedstock to produce ammonia or methanol rather than as a direct fuel itself. In aviation, green hydrogen could potentially be used as an energy source for fuel cells, combusted in modified gas-turbine engines, or utilized as a feedstock for other synthetic fuels.⁶⁴ Advancements in fuel cells, engine modifications, and requisite infrastructure for transportation and airport storage are needed to use green hydrogen in aviation.⁶⁵ There is also emerging interest in zero-emission planes (ZEPs) for short-haul flights powered by

⁶⁰ “A fuel cell uses the chemical energy of hydrogen or other fuels to cleanly and efficiently produce electricity. If hydrogen is the fuel, the only products are electricity, water, and heat.” [DOE, Hydrogen and Fuel Cell Technologies Office](#)

⁶¹ “However, during hydrogen or ammonia combustion, nitrogen oxides (NOx) can be formed as it happens when fossil fuels are combusted with air. Although Nox themselves are not greenhouse gases, they lead to the formation of ozone through secondary reactions causing an indirect GHG effect.” [CATF \(2022\)](#)

⁶² “In steam-methane reforming, methane reacts with steam under 3–25 bar pressure (1 bar = 14.5 psi) in the presence of a catalyst to produce hydrogen, carbon monoxide, and a relatively small amount of carbon dioxide.” [DOE](#)

⁶³ “Blue hydrogen is produced mainly from natural gas, using a process called steam reforming, which brings together natural gas and heated water in the form of steam. The output is hydrogen, but carbon dioxide is also produced as a by-product.” [National Grid](#)

⁶⁴ “The study found that hydrogen – as a primary energy source for propulsion, either for fuel cells, direct burn in thermal (gas turbine) engines or as a building block for synthetic liquid fuels – could feasibly power aircraft with entry into service by 2035 for short-range aircraft.” [Clean Aviation](#)

⁶⁵ “Such disruptive innovation will require significant aircraft research and development, further development of fuel cell technology and liquid hydrogen tanks, and also investment into fleet and hydrogen infrastructure and accompanying regulations and certification standards to ensure safe, reliable and economic hydrogen-powered aircraft can take to the skies.” [Clean Aviation, EU](#)



hydrogen and electricity. However, this technology is in the very early stages, and there is uncertainty regarding the feasibility of development and adoption.⁶⁶

Green hydrogen has important applications outside the transportation sector. For example, green hydrogen is seen as vital to decarbonizing current hydrogen production and use, as well as heavy industry, specifically in the production of steel, cement, glass, and chemicals.⁶⁷ Potential end uses also include heating and power generation.⁶⁸

Challenges and limitations

Storing, transporting, and distributing hydrogen are major challenges. Given hydrogen's low energy density, it must be transported in either a compressed or liquid form. Developing cost-effective and safe methods and infrastructure to address these challenges is important to scaling hydrogen as a fuel and feedstock.⁶⁹

Electrolysis is more energy-intensive than traditional methods of producing hydrogen, and the main cost driver of green hydrogen is the energy use needed for production. Electrolyzer efficiency is improved when run continuously, potentially benefiting from firm yet more expensive power sources like nuclear. Given costs and other constraints, wind and solar are projected to dominate as green hydrogen production energy sources even though more generation capacity will be required given their intermittent nature.⁷⁰ At present, green hydrogen is more expensive than its alternatives: fossil fuels and hydrogen produced from natural gas. Another cost driver is electrolysis technology. Electrolysis happens within a unit called an electrolyzer, and our understanding is that an increase in electrolyzer innovation and production will be needed to bring down costs and meet projected hydrogen demand.⁷¹

⁶⁶ "Zero-emission planes (ZEPs) are an emerging technology that uses hydrogen and electricity as power sources. Due to the weight of current batteries, electric aircraft will be limited to short-range commuter missions before 2050...The successful development and deployment of these aircraft are not guaranteed." [ICCT \(2022\)](#)

⁶⁷ "The industrial processes used in the production of things like steel, cement, glass, and chemicals all require high temperature heat. Currently, this heat is produced by burning fossil fuels. For these hard-to-abate sectors, there is essentially no way to reach net-zero emissions at the scale required without using hydrogen." [RMI \(2020\)](#)

⁶⁸ See Figure 1. Green hydrogen production, conversion and end uses across the energy system. [IRENA](#) n.d.

⁶⁹ "Hydrogen storage, transportation and distribution are key challenges for utilising hydrogen as an energy carrier, as it has very low volumetric energy density at room temperature and also has the ability to permeate metal-based materials." [Hren, R. et al \(2023\)](#)

⁷⁰ "The most efficient sources of energy are those that can run electrolyzers continuously, which is why hydropower and even nuclear power have been proposed as potentially ideal power supplies for green hydrogen. In practice, however, cost and siting constraints mean green hydrogen hubs will likely be powered by wind or solar. And because wind and solar each have a lower capacity factor (the measure of a generation resource's output over the course of a year) than hydro or nuclear, a lot more generation would need to be installed to meet a given electrolyzer output target." [Canary Media \(2021\)](#)

⁷¹ "Electrolysis capacity is growing from a low base and requires a significant acceleration to get on track with the Net Zero Emissions by 2050 (NZE) Scenario, which requires installed electrolysis capacity to reach more than 550 GW by 2030." [IEA Electrolyser Analysis](#)



Co-Benefits

Green hydrogen, especially when used directly to power a fuel cell, may result in lower air pollutants other than greenhouse gases (GHGs) and may even enable quieter aircraft engines.⁷²

Global South countries with abundant renewable energy are well-positioned to become green hydrogen producers. This could lead to a more equitably distributed market and help to promote sustainable growth in emerging economies.⁷³

Adverse Effects

Hydrogen, like other fuels, is very flammable. Since the gas is odorless and colorless, leaks are difficult to detect. Hydrogen fires are also invisible, making it more difficult to notice the danger.⁷⁴ In addition, hydrogen has indirect radiative effects when released into the atmosphere. The potential leakage associated with increased hydrogen production and use could adversely affect its climate benefits; it is our understanding that the climate effects from leakage remain an ongoing area of investigation.⁷⁵

Certain policies and incentives intended to scale low-carbon hydrogen production could be used to subsidize more carbon-intensive forms of hydrogen, especially in the absence of clear and standardized guidance on calculating climate impact. For example, concerns arose regarding the tax credits included in the Inflation Reduction Act.⁷⁶

⁷² “The powertrain being developed by the project turns the hydrogen into torque to turn the propeller. It is highly efficient and also quiet to run, producing about the same amount of noise as an internal combustion engine in a car – meaning passengers should have a pleasant, quiet flight.” [Horizon, European Commission \(2020\)](#)

⁷³ “At the same time, the transition towards green hydrogen is seen as a potential for sustainable development in the Global South. Many developing countries in Africa, Latin America and Asia are endowed with very large potentials of solar radiation, wind and – sometimes – geothermal energy. These comparative advantages could help to open market opportunities in the North.” [Rural 21 \(2023\)](#)

⁷⁴ “Hydrogen used in the fuel cells is a very flammable gas and can cause fires and explosions if it is not handled properly. Hydrogen fires are invisible and if a worker believes that there is a hydrogen leak, it should always be presumed that a flame is present.” [OSHA](#)

⁷⁵ “The future leakage rate of hydrogen into the atmosphere is a major uncertainty and our assessment of the climate impact of an hydrogen economy transition is performed assuming different leakage rates.” [Hauglustaine, D. et al \(2022\)](#)

⁷⁶ “The worries, shared by the Clean Air Task Force, the Environmental Defense Fund and the Union of Concerned Scientists, are grounded in a study from a team of scientists at Princeton University. It concludes the looser accounting guidelines influential industry players are seeking would enable them to make the energy-intensive fuel without adding enough new clean power to local electricity grids to produce it.” [Washington Post \(2023\)](#)



E-methanol

Overview

Methanol (CH_3OH) is an alcohol produced by using a catalyst to react hydrogen with CO_2 .⁷⁷ Much of the emissions associated with methanol production are a result of producing hydrogen feedstock.

E-methanol is considered to be “net zero” if it is produced from green hydrogen and CO_2 captured from negative emissions technologies like direct air capture (DAC).⁷⁸ Methanol has a higher energy density than both ammonia and hydrogen, is considered relatively safe in its liquid form to transport and store, and is also already available at a large number of ports worldwide.⁷⁹ Methanol is used in a variety of applications, such as fabrics, building materials, pharmaceuticals, and agrochemicals.⁸⁰ Given its relatively high energy density and consequently the ease of transport and storage, e-methanol is also being considered for use as a hydrogen carrier – a material that can be used to transport hydrogen.⁸¹ Given its cross-cutting applicability, scaling e-methanol production could lower emissions across sectors.

E-methanol is growing in popularity as an alternative fuel for maritime shipping, especially given that the technology to retrofit engines to run on methanol is relatively advanced. In fact, private sector orders for methanol-powered vessels are outpacing those for ammonia-powered vessels.⁸² Earlier this year, Mærsk placed orders for methanol-powered vessels and signed an agreement with Equinor for green methanol supply. (Initially, this will be biomethanol produced from biogas from manure, but the long-term plan is to transition to e-methanol).⁸³

Challenges and limitations

It is our impression that scaling the production of e-methanol has two major challenges: feedstock availability and cost. Large-scale e-methanol production will rely on the scale-up and cost of green hydrogen and carbon removal technologies such as direct air capture (DAC).⁸⁴ This is because in order for

⁷⁷ “Methanol (CH_3OH), also known as wood alcohol, is considered an alternative fuel under the Energy Policy Act of 1992. As an engine fuel, methanol has chemical and physical fuel properties similar to ethanol.” [DOE, Energy Efficiency & Renewable Energy](#)

⁷⁸ “To produce net zero-carbon methanol, the CO_2 can be obtained directly by direct air capture (DAC) or from biomass.” [Global Maritime Forum \(2022\)](#)

⁷⁹ “As a liquid product, methanol is safe to transport, store, and bunker using regular safety procedures.” [Methanex](#)

⁸⁰ “Methanol and its derivative products such as acetic acid and formaldehyde created via chemical reactions are used as base materials in acrylic plastic; synthetic fabrics and fibers used to make clothing; adhesives, paint, and plywood used in construction; and as a chemical agent in pharmaceuticals and agrochemicals.” [Mitsubishi Gas Chemical](#)

⁸¹ “Methanol has the highest hydrogen to carbon ratio of any liquid fuels, allowing it to be a highly efficient carrier of hydrogen.” [Methanol Institute](#)

⁸² “The technology [for methanol] is ready now and we have to move this decade,” a spokesman for the company told *Hydrogen Insight*. “We can’t wait for ammonia.” [Hydrogen Insight \(2022\)](#)

⁸³ “Equinor and Mærsk partner up to ensure continued green methanol supply for the world’s first methanol-enabled container vessel.” [Mærsk \(2023\)](#)

⁸⁴ “High cost of DAC feedstock; long-term competition for bio-based CO_2 feedstock (point source bio energy carbon capture).” [Global Maritime Forum \(2022\)](#)



it to be considered carbon neutral or low carbon, the CO₂ feedstock must be sourced directly from the atmosphere.

Co-Benefits

E-methanol use as a fuel would result in lower air pollutants like sulfur oxides (SO_x) with respect to the use of conventional marine fuels.⁸⁵

Adverse Effects

Similar to hydrogen, methanol flames are invisible. This increases difficulty in detection and may pose a safety hazard. In addition, our impression is that methanol's toxicity may also be a safety concern, especially as production and use are scaled.⁸⁶

E-ammonia

Overview

Under the Haber-Bosch process, hydrogen is reacted with nitrogen at high temperatures and pressure to produce ammonia (NH₃). Most of the associated emissions are a result of hydrogen production and can be mitigated through the use of green hydrogen; ammonia produced using green hydrogen is referred to as e-ammonia.⁸⁷ The Haber-Bosch process is also energy-intensive, and there is ongoing research into more sustainable ammonia production processes.⁸⁸ Ammonia's energy density is lower than that of oil but higher than that of natural gas and hydrogen, and it can be easily liquified.⁸⁹ Consequently, ammonia is easier than hydrogen to transport and store. In fact, given that it is already widely used in other applications (e.g., fertilizer), some transport and storage infrastructure already exists.⁹⁰

⁸⁵ "Methanol can reduce SO_x and PM emissions by more than 95 per cent, and NO_x by up to 80 per cent compared to conventional marine fuels." [Methanex](#)

⁸⁶ "It's toxic, like any other fuel, and it will require different safety procedures. For example, methanol burns with an invisible flame." [Wallenius Sol \(2020\)](#)

⁸⁷ "However, the process of making ammonia is currently not a "green" process. It is most commonly made from methane, water and air, using steam methane reforming (SMR) (to produce the hydrogen) and the Haber process. Approximately 90% of the carbon dioxide produced is from the SMR process." [The Royal Society \(2020\)](#)

⁸⁸ "Due to the important role of ammonia as a fertilizer in the agricultural industry and its promising prospects as an energy carrier, many studies have recently attempted to find the most environmentally benign, energy efficient, and economically viable production process for ammonia synthesis." [Ghavam et al \(2021\)](#)

⁸⁹ "In contrast, ammonia provides solutions for several problems linked with hydrogen. On the other hand, ammonia entails solutions for several problems that hydrogen poses. It entails a high density and can be easily liquefied allowing significant ease in storage as well as transportation." [Ishaq et al \(2021\)](#)

⁹⁰ "With its relatively high energy density of around 3 kWh/litre and existing global transportation and storage infrastructure, ammonia could form the basis of a new, integrated worldwide renewable energy storage and distribution solution." [The Royal Society \(2020\)](#)



Increased production of e-ammonia may also help decarbonize other sectors of the economy, including agriculture, heavy industry, and even power.⁹¹ Given that it's more energy-efficient to transport, e-ammonia could potentially be used as a hydrogen carrier.⁹² E-ammonia is considered to be an alternative fuel for maritime shipping, although ammonia-fueled engines are not yet commercially available.⁹³ Small ammonia-powered vessels are projected to be delivered by 2024, and larger vessels by 2030.⁹⁴ However, our understanding is that certain technical and safety challenges remain in the context of ammonia-powered engines and fuel cells.⁹⁵

Challenges

Cost is a major challenge for e-ammonia production.⁹⁶ A secondary challenge is the intermittency of renewable energy sources. The Haber-Bosch process requires a "steady state operation mode," and disruption to the energy supply could damage the catalyst used for the reaction.⁹⁷ Firm power sources such as nuclear could be considered as alternatives to wind and solar.⁹⁸

Co-Benefits

Co-benefits of e-ammonia beyond its potential for cross-sector emissions reductions through direct use or as an energy vector for hydrogen include its use as a chemical storage medium for renewable energy.⁹⁹

⁹¹ "Since ammonia does not emit carbon dioxide (CO₂) when burned, by replacing the coal and natural gas currently used as the fuel for power generation with ammonia, a large-scale reduction in CO₂ emission is anticipated." Japan [Science and Technology Agency \(2019\)](#)

⁹² "Ammonia is being considered as one of the best potential options for a one-way carrier. Ammonia is one of the only materials that can be produced cheaply, transported efficiently and transformed directly to yield hydrogen and a non-polluting byproduct." [DOE \(2006\)](#)

⁹³ "There are currently no in-service ships using ammonia as fuel. Ammonia-fueled engines are not yet commercially available, and no existing vessels are equipped for ammonia propulsion." [Bureau Veritas](#)

⁹⁴ "By comparison, first orders for small ammonia vessels will begin in 2024 with delivery in 2026, Mærsk said, with deliveries of medium- to large-sized ammonia-powered vessels not expected until 2030." [Hydrogen Insight \(2022\)](#)

⁹⁵ "For ammonia-fueled shipping to become a reality, though, several things need to go right. Manufacturers and engineers must overcome key technical hurdles and safety issues in the design of ammonia engines and fuel cells." [IEEE Spectrum \(2021\)](#)

⁹⁶ "Ammonia is touted as the low-emissions fuel of the future and there are multiple proposed projects – and more announced almost by the day – that appear to lend credence to this view. But there are significant challenges linked to the costs..." [CRU Group \(2022\)](#)

⁹⁷ "The main current obstacle to large scale implementation of e-ammonia plants, is dealing with the inherent intermittency and unpredictability of the RE [renewable energy] sources which does not suit the required steady state operation mode of the Haber Bosch (HB) process..., given its non-flexible nature and risk of operation interruption (mainly due to the damage of the catalyst)." [Bouaboula, H. et al \(2023\)](#)

⁹⁸ "MSRs may provide several advantages over other renewables: the base power output of MSRs is continuous instead of intermittent, the infrastructure occupies small footprints; and implementation is much less constrained by the natural resources of [sic] in a given geographical location..." [Mærsk Mc-Kinney Møller Center for Zero Carbon Shipping \(2022\)](#)

⁹⁹ "Ammonia as an energy storage medium is a promising set of technologies for peak shaving due to its carbon-free nature and mature mass production and distribution technologies." [Tawalbeh et al \(2022\)](#)



Adverse Effects

Because ammonia is corrosive and toxic, there are public health and environmental risks associated with scaling up its production, transport, and storage.¹⁰⁰ Although complete combustion of ammonia produces hydrogen and water, some applications also produce nitrogen oxides (NOx), which are toxic and can react to form ozone.¹⁰¹

E-SAFs

Overview

Most jet fuels are kerosene-based. Kerosene is a hydrocarbon that is considered suitable for aviation, given that it remains in a liquid state within a relatively large temperature range. However, synthetically producing such fuels is difficult, given their long hydrocarbon chains. Direct production involves hydrogen and carbon dioxide as feedstocks and a variety of reactions and processes.¹⁰²

Synthetically produced jet fuels—also referred to as e-jet fuels, power-to-liquid (PtL) fuels, or e-SAFs—are considered by definition to be drop-in ready and don't require engine retrofits.¹⁰³

Challenges and limitations

E-SAF production is expensive, energy-intensive, and requires a supply of hydrogen and CO₂. Like e-methanol, scaling e-SAFs while reducing climate impact will rely on scaling green hydrogen and carbon removal technologies like direct air capture (DAC); our understanding is that biomass alone cannot provide the amount of CO₂ required to produce e-fuels at scale.¹⁰⁴ We also think further R&D is needed to develop efficient and cost-effective catalysts for the necessary reactions.¹⁰⁵

¹⁰⁰ "In considering expanded roles for ammonia in energy storage, the health risks from ammonia exposure and the environmental risks arising from leaks must be closely scrutinised and all systems must be designed to minimise, and effectively eliminate, these risks." [The Royal Society \(2020\)](#)

¹⁰¹ "Short-term exposure to concentrations of NO₂ can cause inflammation of the airways and increase susceptibility to respiratory infections and to allergens...Nitrogen oxides are also precursors for the formation of ozone." [UK Department for Environment, Food, & Rural Affairs](#)

¹⁰² "...direct CO₂ hydrogenation route, which is usually described as a combination of the reduction of CO₂ to CO via the reverse water gas shift (RWGS) reaction and the subsequent hydrogenation of CO to long-chain hydrocarbons via Fischer-Tropsch synthesis (FTS)." [Yao, B. et al \(2020\)](#)

¹⁰³ "E-Jet fuel is a drop-in synthetic fuel that works seamlessly with existing aircraft." [Smart Energy Decisions \(2023\)](#)

¹⁰⁴ "The study shows that fossil sources (industry and power) and biomass will not be enough to fulfil the demand for CO₂." [Transport & Environment \(2022\)](#)

¹⁰⁵ "The key to advancing this process is to search for a highly efficient inexpensive catalyst, that can preferentially synthesise the target hydrocarbon range of interest." [Yao, B. et al \(2020\)](#)



Co-Benefits

Early-stage carbon removal technologies like DAC are very expensive, and more deployment is needed to bring down costs. In the absence of broad demand, the production of e-SAFs provides an end-use for captured CO₂ and could potentially serve as a niche market for technologies like DAC as they scale.¹⁰⁶

Adverse Effects

Our understanding is that certain catalysts, especially when production is scaled, may pose potential risks or adverse effects. For example, iron-based catalysts may require large amounts of water consumption.¹⁰⁷

Cost-competitiveness

The cost trajectories of e-fuels are inextricably linked to the cost of green hydrogen. In turn, the cost of green hydrogen will depend on the cost of clean energy and electrolysis technology. Our impression is that renewables are already cost-competitive but that there may be significant capital costs in building out the necessary renewable energy capacity.¹⁰⁸ In addition, more innovation is needed to bring down the cost of electrolyzers. Research suggests that costs could fall significantly if installed capacity increases but that this will depend largely on the ambition level of policies and investments.¹⁰⁹

According to a 2019 study (Figure 3), while e-methanol and e-ammonia are more expensive than their fossil fuel counterparts at present, they could become cost-competitive by 2040 and even cheaper by 2050.

Production cost of synthetic fuels like e-methanol and e-SAFs will also rely on the price of CO₂. The most climate-beneficial sources of CO₂ may either be through carbon removal technologies like DAC, which are currently quite expensive, or sustainable biomass, for which feedstocks are limited.¹¹⁰ E-SAFs are among the most costly fuels given the price of feedstocks as well as the various reactions that are involved in the

¹⁰⁶ “DAC developers are working on scale up, reduced energy use, and demonstrated operation with proven reliability, whilst exploring early markets for the CO₂ captured to bring revenue that can be reinvested in RD&D and further scale up and roll out. These include production of e-fuels...” [E4Tech \(2021\)](#)

¹⁰⁷ “Iron-based catalysts, widely used in both the RWGS and FTS reactions, are typically prepared by chemical co-precipitation routes, which unfortunately consumes significant amounts of water.” [Yao, B. et al \(2020\)](#)

¹⁰⁸ “If we were to use solar power alone to generate 550 MT of green hydrogen a year, that would require around 13 terawatts of PV, according to a rough calculation by Palacios. That assumes an optimistic 24 percent capacity factor for solar, along with an electrolyzer efficiency of almost 79 percent. That’s around 18 times the almost 714 gigawatts of solar power that the International Renewable Energy Agency estimates had been installed worldwide as of the end of 2020.” [Canary Media \(2021\)](#)

¹⁰⁹ “Policy support in recently unveiled hydrogen strategies in many countries is mostly in the form of explicit electrolyser capacity targets and, to a more limited extent, cost targets. These have yet to translate into specific regulatory instruments. So far, these explicit targets are not enough to be in line with 1.5°C decarbonisation pathways.” [IRENA \(2021\)](#)

¹¹⁰ “The sustainability of biomass-based feedstocks and fuels is largely contingent on the impact of biomass production on land and soils. These impacts are summarized in “direct land use change” (dLUC, emissions from the land onto which crop production is expanded) and “indirect land use change” (iLUC, emissions from land onto which other agriculture activities are displaced by bio-energy applications on primary lands) metrics associated with each feedstock.” Carbon Direct (2023)



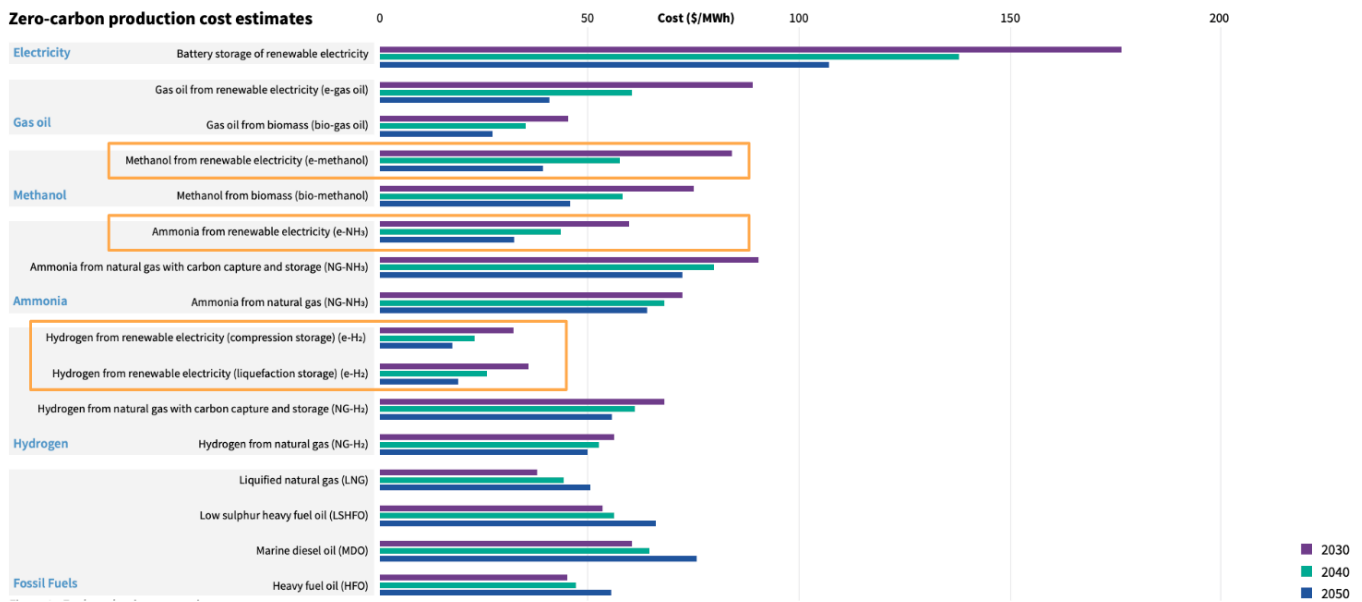


Figure 3: Zero-carbon production cost estimates - Adapted from *Lloyd's Register, UMAS (2019)*

production process, and analysis indicates that costs may be unlikely to drop below that of fossil-based jet-fuel or biomass-based sustainable aviation fuels without adequate policy support. This is demonstrated in the International Council on Clean Transportation's model in Figure 4, using California's Low Carbon Fuel Standard (LCFS).

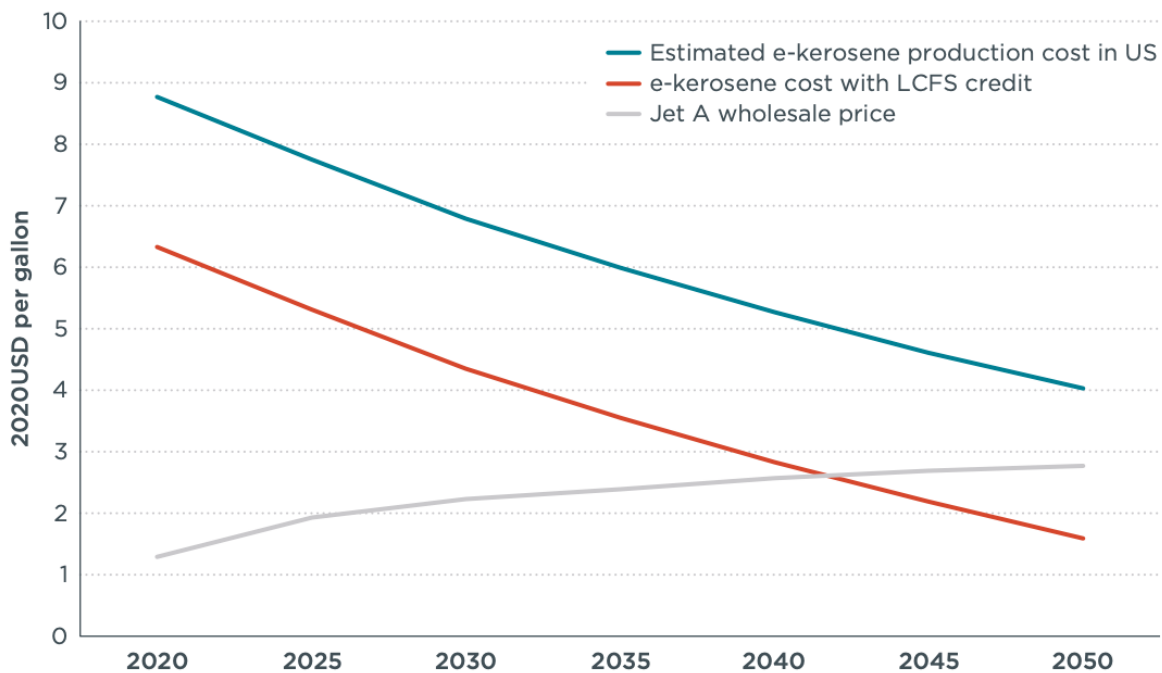


Figure 4: The impact of California's LCFS credit on the cost of e-kerosene production in the United States
ICCT (2022)



Maturity

Inspired by the [Fuel Pathway Maturity Map \(Figure 3\) in a 2022 Mærsk Mc-Kinney Møller Center for Zero-carbon Shipping report](#), we provide a summary of our impression of current maturity levels based on the information included above for each fuel type. *High* corresponds to ready or almost ready at commercial scale. *Medium* indicates that a few barriers to deployment at scale exist but that there are clear pathways to addressing these barriers. *Low* means that significant progress must still be made before commercial readiness.

Fuel	Sector Applicability	Availability of feedstock for fuel production	Production	Storage & Transport	Safety	Engine readiness	Cost-competitiveness
green hydrogen	Aviation Maritime Shipping Industry Power	high	medium	low	medium	medium	medium
e-methanol	Maritime Shipping	low	low	medium	medium	medium	low
e-ammonia	Maritime Shipping Industry Power	medium	low	medium	low	low	low
e-SAFs	Aviation	low	low	high	high	high	low

Table 2: Maturity assessment of alternative fuels

