Plain Sailing And Soaring Smoothly: Emissions Reduction Strategies In Shipping And Aviation

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The Abdullah Bin Hamad Al-Attiyah International Foundation for
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INTRODUCTION

PLAIN SAILING AND SOARING SMOOTHLY: EMISSIONS REDUCTION STRATEGIES IN SHIPPING AND AVIATION

The Paris Agreement has generated momentum to reduce greenhouse gases (GHG) emissions within national borders. However, international transport is also responding to the imperative to cut its carbon footprint. The International Maritime Organisation (IMO) and International Civil Aviation Organisation (ICAO) have both set policies to align their industries with the Paris goals. While the two sectors are not significant emitters today, they are an essential part of future forecast growth. These two transport industries face a complex mix of options, including efficiency, mode shifts, and alternative propulsion, with varying technological and commercial readiness. But, a broad set of actors across the value chain have to be aligned to deliver low-carbon options with the right timing, performance, and costs.

Sustainability Report

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EXECUTIVE SUMMARY

- Aviation and shipping are not large emitting sectors in the global total. They are, however, forecast to grow relatively rapidly, and abatement options are more limited than in sectors such as power and ground transport.
- The IMO and the ICAO have therefore put forward emissions reduction plans intended to be compatible with the Paris Agreement. However, these fall well short of carbon neutrality by 2050.
- Both sectors' governing bodies have similar targets of reducing emissions by 50% by 2050, but their medium-term targets vary significantly.
- Efficiency measures can mostly achieve the IMO's target for improving shipping carbon intensity by 40% by 2030 on 2008 levels. However, improvements beyond that will likely require lower-carbon fuels or propulsion.
- The ICAO's objective of cutting aviation emissions 50% by 2050 can probably be met with a mix of efficiency measures and alternative fuels. However, low-carbon aviation fuels are relatively technically immature, limited in volume, and costly.
- Depending on the forecast, combined oil use in maritime and aviation could be from 4.3-14 Mbbl/day in 2050, compared to 12.9 Mbbl/day in 2019. The relative balance of offsets, efficiency, and alternative fuels is, therefore, crucial for future oil demand.
- Climate policy in these sectors is likely to be driven by a mix of carbon pricing/trading, mandates, corporate and consumer demands, and subsidies for new technologies and alternative fuels.
- As the experience of IMO 2020 sulphur regulations shows, carbon policies will have to be integrated between fuel suppliers, port/airport operators, airlines, and shipping lines.

EMISSIONS FROM SHIPPING AND AVIATION: CURRENT STATUS AND OUTLOOK

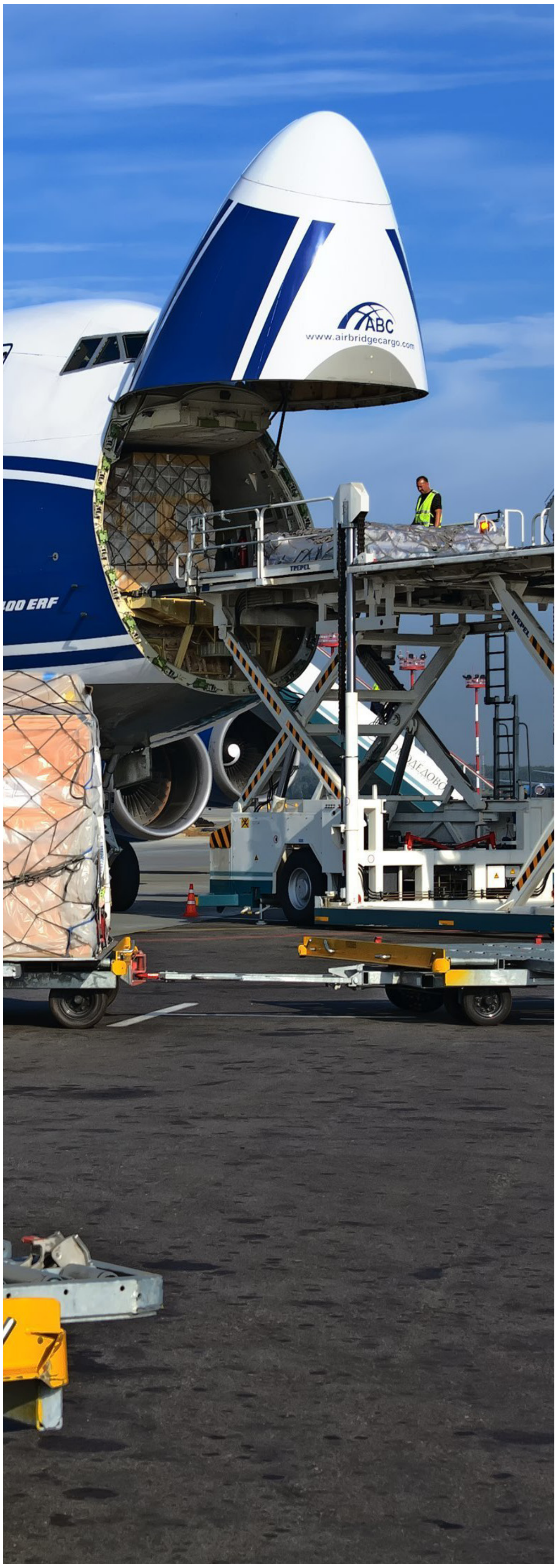
Shipping and aviation are currently relatively small emitting sectors. In 2018, out of 33.8 gigatonnes (Gt) of carbon dioxide emissions from energy use worldwide, 0.9 Gt came from aviation (2.7%) and 0.8 Gt from shipping (2.4%). These small emissions contrast to the power sector, which contributes 38.5%, or ground transport, which represents about 12%. Ships carry about 90% of world trade with a much smaller carbon footprint than ground transport.

However, both transport modes have attracted growing environmental and policy attention to their specific decarbonisation challenge, for seven main reasons:

1. Their emissions are forecast to grow relatively rapidly, in comparison to other sectors such as power generation where emissions are dropping in many countries. In BP's 'Business-as-Usual' (BAU) scenario, for instance, aviation emissions would grow at about 0.85% annually to 2050 (this includes an allowance for the recent effects of the Covid-19 pandemic) and maritime emissions about 0.3% annually. These rates may appear low, but they are still incompatible with a low-carbon economy around mid-century. Forecast BAU emissions would be 44% greater than the entire emissions of BP's 'Net Zero' scenario in 2050, and 22% of its 'Rapid Transition' scenario;

2. Aviation's climate impact exceeds its direct CO_2 emissions, because of emissions of other GHG, particularly nitrous oxides; and the release of water and cloud nuclei, forming contrails (high-altitude cirrus clouds) that cause warming. These other factors multiply the climate effect of aeroplane-emitted CO_2 by a factor 1.9-4.7 (likely around two overall);

3. They are important economic sectors with already a high degree of energy efficiency, within current technical limits, and without easy options for substitution or reduction. Aviation, in particular, has demanding technical and safety requirements. Both are highly competitive commercial businesses operating on thin margins. They compete with each other, and with other industries, such as road and rail passenger and freight haulage;



4. They are international businesses, which makes it hard to allocate their emissions to a single country. They have some flexibility to vary routes and registration locations to avoid GHG restrictions or taxes. For instance, airlines flying from North America to Asia can use intermediate hubs in Morocco, Turkey or the Gulf instead of the EU. The shipping industry's use of 'flags of convenience' in locations such as Liberia, Panama, and the Marshall Islands is well-known [i];

5. Ships and planes and associated infrastructure are long-lived and expensive capital assets. A typical commercial airliner has a lifetime of 27-30 years; major cargo ships have a 25-30-year lifespan. For aircraft, especially the path to design and certify new models, it is at least 15 years [ii]. The list price of a Boeing-787 Dreamliner is more than $200 million, while a new-build huge crude carrier (VLCC) would cost about $120 million and a large cruise ship $555 million;

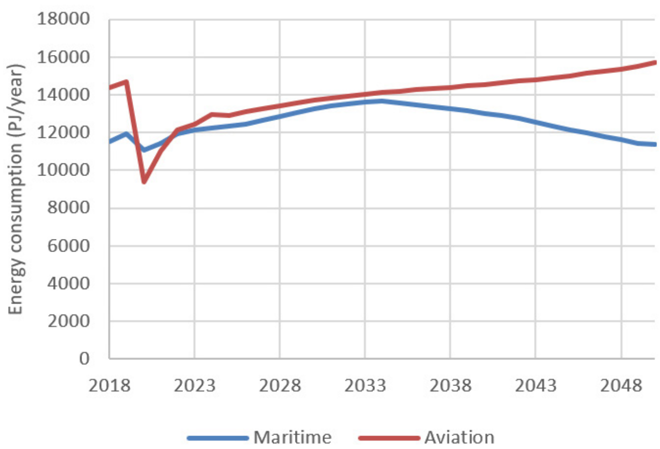
6. Decarbonisation options today appear relatively technically challenging and costly. Aeroplanes and ships are typically used in long-distance routes where intermediate refuelling is not convenient or even possible. These technical challenges are in contrast to, for example, ground transport, where electric vehicles are already commercially available with good performance and starting to achieve significant sales; and

7. Current infrastructure at airports and ports, and indeed the choice of port locations and routes, is geared to supplying and using oil-based fuels. Alternative fuels, particularly those that gave a shorter range, would require new fuelling infrastructure.

Virtually all energy for shipping and flight currently is supplied by oil (jet kerosene in aviation, heavy fuel oil and marine gasoil in shipping), with a little use of liquefied natural gas in shipping (mostly for LNG carriers themselves) and a minor quantity of biofuels and electricity. Oil-based fuels are well-understood, affordable, and have acceptable performance. Most importantly, they have a high energy density, which permits long-distance travel without refuelling while retaining plenty of capacity for cargo and passengers.

Primary energy use in aviation is set to continue growing to 2050, while primary energy use in maritime transport may fall after the mid-2030s (Figure 1). Nevertheless, continuing high consumption in both sectors demands decarbonisation.

FIGURE 1 PRIMARY ENERGY CONSUMPTION IN SHIPPING AND AVIATION [iii]



THE POLICY CHALLENGE

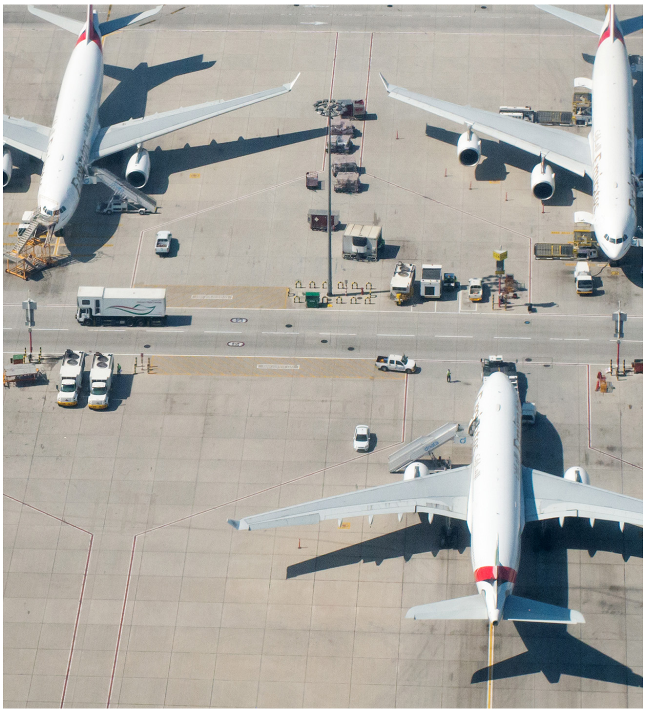
The aviation and shipping industries are under pressure to reduce emissions. The Paris Agreement of 2015 covered only domestic aviation and shipping, not international. This decision was a significant omission, given that international aviation produces 62% of the sector's CO_2 emissions. Nevertheless, several countries and regions have set zero-carbon/carbon-neutral goals:

- EU 40% cuts in emissions (on 1990 levels) by 2030, and 'carbon-neutral' by 2050;
- UK net-zero emissions by 2050;
- China 'carbon-neutral' (including all GHGs) by 2060;
- South Korea 'carbon-neutral' by 2050 (non-binding target);
- Japan 'carbon-neutral' after 2050 [iv];
- US 'carbon-neutral' no later than 2050 (under presidential candidate Joe Biden's plan); and
- New Zealand 'carbon-neutral' by 2050 [v].

Given this policy challenge, the governing bodies for the sectors – the IMO and the ICAO – have given growing attention to decarbonisation. Both are specialist agencies of the United Nations. Other governing bodies have also addressed the issue.

Shipping Policy

The IMO's initial GHG strategy, announced in April 2018, was to reduce carbon intensity (CO_2 emissions per unit of transport, e.g. per tonne-mile) by at least 40% by 2030 and 70% by 2050 on 2008 levels. Moreover, to reduce emissions from international shipping by 50% by 2050 (again on 2008 levels), and to phase them out entirely by 2100. It also stated that these GHG



reductions should be compatible with the Paris Agreement's 1.5°C target [vi]. The IMO will release a revised strategy in 2023.

The IMO sets two efficiency standards: The Energy Efficiency Design Index (EEDI), which applies to new-build vessels, and the Ship Energy Efficiency Management Plan (SEEMP), governing ship operations.

Starting on 19 October 2020, the IMO began hosting virtual meetings to agree on standards for measuring the carbon intensity of large ships [vii]. Its Data Collection System regulation, introduced in January 2019, requires all ships of 5,000 gross tonnes or larger to report annually on fuel consumption.

Among regional bodies, since 2015, the EU has required all ships calling at European ports to report their fuel consumption, transport work, energy efficiency, and CO_2 emissions. This requirement is an essential first step to achieving the IMO's goals as well as to making the Poseidon Principles and Sea Cargo

Charter workable (see below). Monitoring is particularly challenging for ships, because of the possibility to switch fuels in mid-ocean. However, compliance so far to the IMO's sulphur regulations has been high, which is encouraging for the success of potential measures on CO_2.

These data-gathering activities are intended as initial steps to understand shipping emissions, reconcile discrepancies between different sources, and outline areas for improvement.

The EU's plans as regards international shipping are the most specific and stringent. The European Commission has committed to extending its Emissions Trading System (ETS) to shipping. This proposal could enter into force by 2022. The EU has pushed for the most polluting vessels to be scrapped by 2029.

The American Bureau of Shipping released its first low-carbon outlook in June 2019, charting a path intended to be IMO-compatible [viii]. The International Chamber of Shipping is also supportive of the IMO goals [ix].

The Poseidon Principles were announced in June 2019 and intend to align shipping investors and financiers with the IMO timeline. They were developed by three prominent banks serving the shipping industry – Citigroup, Société Générale, and DNB – along with major shipping and certification firms, including A.P. Møller Mærsk, Cargill, Euronav, Gram Car Carriers, and Lloyds Register. Now, 17 leading banks with 30% of global ship finance have joined. However, the Poseidon Principles still awaits a signature from major Chinese lenders, who are a large part of the market.

The Sea Cargo Charter is similar and is intended to align all parties along the shipping charter value chain with the IMO goals, as well as promoting monitoring, verification, and transparency of GHG emissions [xi]. Signatories including influential oil and commodity trading firms, including Shell, Equinor, Total, Occidental Petroleum, Trafigura, Bunge, Cargill, Gunvor, and Louis Dreyfus.

"Despite all the noise and confusion about IMO 2020, the disruption from the global sulphur cap is likely to be dwarfed by what comes after it. The greatest challenge of our generation - and the next - will be the decarbonisation of the shipping industry."

Christopher J. Wiernicki, chairman of American Bureau of Shipping

Ports such as Helsinki, Stockholm, Milford Haven, Antwerp, Rotterdam, Jebel Ali, Singapore, and Guayaquil are moving towards being 'carbon-neutral' in their operations, by 2035 in the case of Helsinki.

Aviation Policy

The ICAO has put forward GHG reduction goals since 2004. In 2010, it affirmed the aims of improving fuel efficiency by 2% annually, and not increasing net carbon emissions after 2020, targets that were reaffirmed in 2013 and 2016. The ICAO also worked on a long-term aspiration that would be consistent with the Paris Agreement's 1.5°C target. A number of industry bodies, including the International Air Transport Association (IATA), collectively declared the aim of improving CO_2 efficiency 1.5% per year between 2009-20 and reducing CO_2 emissions by 50% from 2005 to 2050 [xii]. The ICAO's declaration also contained provisions on market-based measures (MBMs), e.g. carbon taxation or trading, on thoroughly assessing the climate impact of flying, on implementing carbon offsets, and on sustainable aviation fuels (such as biofuels).

The Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA), set up by the ICAO [xiii], sets global rules for emissions reductions and offsets. A pilot phase will operate from 2021-23 on a voluntary basis, and additional states may join the first phase from 2024-26. From 2027, all states with 0.5% or more of worldwide revenue tonne-kilometres (RTK), or in the top 90% of aviation emitters, are supposed to join the second phase. Least-developed countries, small island developing states, and landlocked developing countries are exempt from the second phase unless they voluntarily decide to participate.

The EU's ETS currently covers all flights operating within the European Economic Area (the EEA is EU plus Iceland, Liechtenstein, and Norway). Post-Brexit, the UK is expected to introduce an ETS linked to the EU and Swiss ETSs that is at least as stringent [xiv]. For now, the EU ETS does not cover flights between the EEA and other countries. Such extra-area flights are intended to be covered by CORSIA [xv]. However, since CORSIA is currently not compatible with the EU's goal of carbon neutrality by 2050, and the EU is uncomfortable with relying heavily on offsets, additional measures will likely have to be introduced [xvi].

Some airlines have gone beyond the ICAO's policy to declare ambitions to be carbon neutral. JetBlue announced in January 2020 that it would make all its domestic US flights carbon neutral, while Delta will reduce or offset all its emissions (about 40 million tonnes of CO_2) by 2030 [xvii]. The UK's aviation sector has pledged carbon neutrality by 2050, in line with the British government's overall aim.

A growing number of airports are aiming at carbon neutrality. For instance, Heathrow has become carbon neutral, including offsets, and aims to operate zero-carbon infrastructure by 2035 [xviii]. However, this applies to their operations and not to the flights served from these airports.

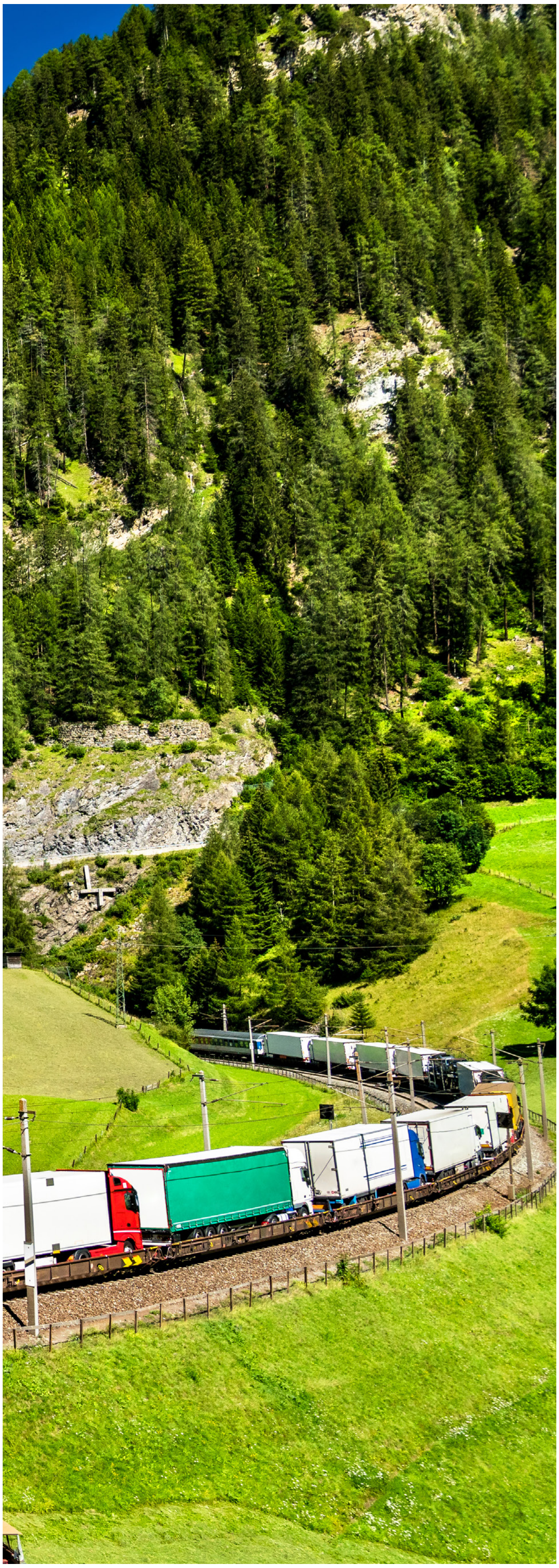
OPTIONS FOR DECARBONISING THE AVIATION AND SHIPPING SECTORS

As discussed above, aviation and maritime transport have specific technical challenges, mainly related to the advantages and familiarity of oil-based fuels over alternatives.

The primary options for decarbonisation fall into three categories:

- Improved efficiency: this reduces emissions but will not eliminate them on its own;
- Modal changes, e.g. shifting from aviation and shipping to electric rail, or travel to videoconferencing. However, many uses of air and sea travel will not be substitutable; and
- Use of non-carbon fuels/propulsion systems, or those with zero lifecycle emissions such as biofuels.

For emissions that cannot be eliminated, carbon offsets are an option. Companies or travellers can pay for bio-sequestration (e.g. reforestation) or possibly for direct air capture (DAC) – removing CO_2 directly from the atmosphere. For instance, from January 2020, Air France has offset 100% of the emissions on its domestic flights, mostly via forestry projects [xix]. However, offsets from bio-sequestration at least may compete with a lot of other hard-to-eliminate emissions.



LOW-CARBON SHIPPING

The shipping industry already concentrates heavily on efficiency, as fuel makes up 50-70% of a vessel's operating costs [xx]. However, substantial room for gains remains. The IMO requires ships constructed from 2025 to be 30% more efficient than those built in the 2000s[xxi]. Efficiency improved 1.6% annually from 2000 to 2017, compared to the EEDI's requirement of 1.5% per year from 2015 to 2025. Therefore, there is some criticism that the IMO should tighten the EEDI standards.

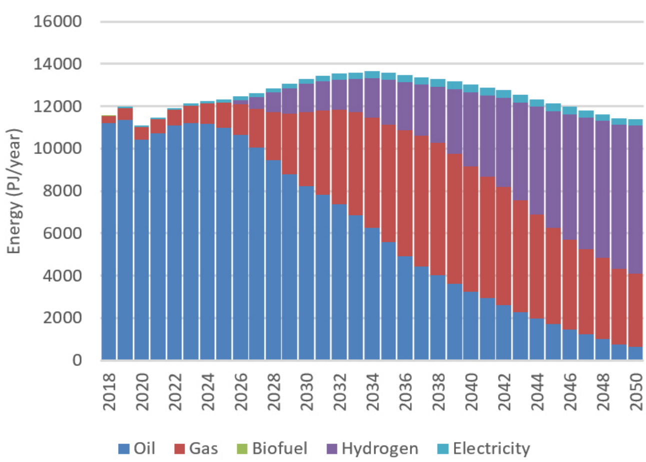
Overall, it appears that up to 35% of fuel could be saved with conventional measures with a payback of 15 years or less. More speculative technologies such as contra-rotating propellers (saving of 13%) and air lubrication (9%) could extend this further [xxii]. This suggests that the EU target for new ships can be achieved with some margin to spare. The IMO target for carbon intensity of a 40% reduction by 2030 could be largely achieved by improved ship design. However, some additional contribution from operations or lower-carbon fuels is likely required.

Within operations, gains can be achieved from optimising speeds and voyage plans, better weather prediction, and maintaining a ship's condition. Energy consumption is lower at slower speeds; reducing speed 10% saves 20% of fuel. The industry has widely adopted slow steaming at times of high oil prices or low charter rates. However, this effectively requires a larger shipping fleet (with greater consumption of steel and other materials) and is not suitable for time-sensitive cargoes.

Modal changes would primarily apply to shifting from sea to electrified rail for cargo. This change only applies where there is a suitable alternative land route. Rail is somewhat quicker than shipping. For instance, the China Railway Express line to Germany takes about 15 days; the equivalent marine route is 30-45 days. However, as of 2018, only 7% of China-Europe container trade was by land, while 62% went by sea [xxiii]. Rail transport still costs about three times as much as sea transport per container, even with Chinese rail subsidies, and has limited capacity. Crossing borders, with the issues of documentation, tariffs, and inspections has improved but remains problematic [xxiv]. Still, rail could potentially gain market share in inland areas of Eurasia as networks improve. To have climate-friendly electric rails, zero-carbon electricity is needed, but Chinese electricity is still coal-dominated.

For alternative fuels, one forecast is shown in Figure 2. In this view, oil use does not quite recover to pre-Covid-19 levels by 2023, before going into decline, and is minor by 2050. Gas becomes the leading fuel in the 2030s, while hydrogen gradually grows and is the primary fuel in the 2040s. The higher efficiency of hydrogen used in fuel cells results in an overall drop in shipping energy consumption after 2034. Biofuels do not feature in this view,

FIGURE 2 FORECAST OF SHIPPING ENERGY CARRIERS [xxv]



probably because they are preferred for use in aviation. Electricity has a small share, likely for short-range vessels and in-port operations.

Shipping has a broader range of potential alternative fuels than aviation. The IMO regulation reducing the allowable content of sulphur in fuel from 3.5% to 0.5%, or requiring the use of scrubbers, came into force from January 2020 and was intended to cut maritime air pollution. It inspired growing interest in alternative fuels. However, for now, it appears the most popular replacement for high-sulphur fuel oil (HSFO) is low-sulphur fuel oil (LSFO), which does not have an advantage in reducing GHG emissions.

Alongside heavy fuel oil and marine gasoil (equivalent to diesel), LNG is already quite widely used (mostly for LNG carriers). Liquefied petroleum gas (LPG, composed of propane and butane) and ethane are also used in a few vessels. The first ethane-powered vessels were introduced in 2016 [xxvi].

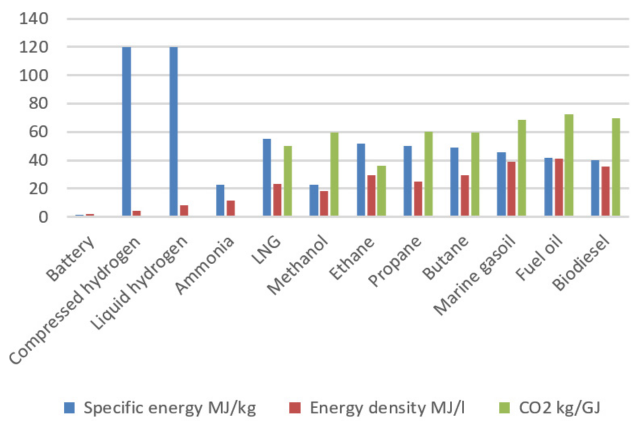
For alternative marine fuels, batteries, hydrogen (compressed or liquid), and ammonia are zero-carbon (Figure 3). Hydrogen could be burnt in engines or used in fuel cells to generate electricity for power – fuel cells are expensive but more efficient. However, current fuel cells of up to six megawatts (MW) would have to be scaled up to the 28 MW of engine power required for large vessels [xxvii].

Biodiesel can be low-carbon over its lifecycle, depending on the source. LNG is 32% lower in CO_2 emissions than fuel oil. However, leakage and methane slip in engines can be significant, increasing the GHG footprint. Ethane has half the carbon footprint of fuel oil and the global warming potential of leaked ethane is less than a third of that of methane. The other marine fuels do not offer much advantage in carbon dioxide emissions; methanol is about 20% lower than fuel oil, but this excludes lifecycle emissions in its manufacture.

Synthetic fuels, including close analogies of jet fuel, can be made from atmospheric CO_2, with low lifecycle emissions. Prometheus Fuels has signed an agreement to supply such fuel for a planned supersonic aircraft made by Boom [xxviii].

Apart from biofuels or synthetic hydrocarbons, alternative fuels are inferior in energy density to fuel oil and gasoil. This inferiority is particularly so for batteries, hydrogen, and ammonia. The large storage space they require would leave less room for cargo or require more frequent refuelling. The weight of alternative fuels is less critical for shipping purposes than energy density.

FIGURE 3 COMPARISON OF ALTERNATIVE MARINE FUELS [xxix]



Clean fuels also have a substantial cost disadvantage. Low-carbon hydrogen would cost about six times as much as current marine fuels.

The widespread introduction of alternatives would create complications in fuelling ships. Bunkering ports would need to make available a range of different fuels. This issue has already arisen with IMO 2020, but HSFO, LSFO, and marine gasoil are relatively similar. It would be a much more significant challenge to deal with a mix of LNG, methanol, hydrogen, ammonia, biodiesel, and battery charging.

Another option is to use traditional fuels but with on-board carbon capture and storage (CCS). Captured CO_2 would then be offloaded at the destination for eventual use or safe underground disposal. Tanker company Stena Bulk is conducting a feasibility study together with the Oil and Gas Climate Initiative (OGCI), a consortium of major international oil companies [xxx]. Japanese shipper K'Line plans to test on-board CCS with Mitsubishi Shipbuilding. This CCS use would be comparable to the use of on-board scrubbers to catch sulphur dioxide emissions, but more energy-intensive and bulky. The captured CO_2 would have a higher volume than the fuel combusted to make it, and the capture process consumes energy. The size of the equipment would also reduce cargo capacity.

Given batteries' low energy density, electric ships are really viable on short routes, such as ferries and offshore supply vessels. They are heavily promoted in such applications in Scandinavia. Practically, electric ships are likely to be limited to routes under 75 km [xxxi]. This limitation would be acceptable for UK-France, UK-Ireland, Strait of Gibraltar or Bosphorus ferries, but popular journeys between Helsinki-Tallinn or the two main New Zealand islands would be at the outer limit. However, hybrid electric vessels can achieve some efficiency savings. Ships can be supplied at port with electricity by cable, reducing the need to run their engines, also having a positive effect on local air quality.

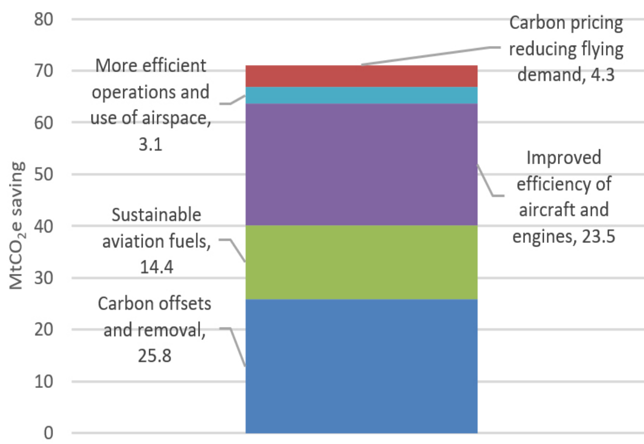
Nuclear power is a long-standing and effective zero-carbon means of propulsion for military vessels (submarines and aircraft carriers). However, it appears unlikely to be adopted for commercial vessels because of concerns over cost, safety, and non-proliferation.

In addition to alternative fuels, other forms of propulsion are being considered. Various versions of auxiliary sails seem promising, including soft and rigid sails, wing-sails, towing kites, and rotating cylinders. For instance, Wallenius Marine's OceanBird has designed a cargo ship that can carry 7,000 cars (comparable to the larger car carriers operating today), using five sails that resemble aeroplane wings. It would reach about two-thirds the speed of conventional vessels and could be delivered by 2024 [xxxii]. While running almost entirely on wind, it has an auxiliary engine for manoeuvring and entering port. These various wind-powered designs still need operational validation. They have disadvantages such as only assisting in certain wind conditions, increasing drag, and taking up deck space.

On-board solar photovoltaics (PV) could provide 0.2-12%, and wind-solar systems up to 40% of required energy.

The UK aviation sector's carbon-neutral pledge would require saving a forecast 71.1 $MtCO_2e$ of emissions by 2050 (Figure 4). If we take this as typical, it can be seen that only a small part of the reduction comes from less flying (in this case, incentivised by carbon pricing). Of the remaining emissions, about 61% can be eliminated by improved efficiency and sustainable fuels, leaving 39% to be offset. This, therefore, goes further than the IATA-led group's aspiration of a 50% cut by 2050, mentioned above.

FIGURE 4 UK AVIATION SECTOR'S CARBON-NEUTRAL PLAN [xxxiii]



The airline industry has concentrated heavily on efficiency for decades, as fuel is a large share of operating costs: 23.7% in 2019 [xxxiv]. Pressure for improvement has been incredibly heavy at times of high oil prices. Between 1990 and 2018, CO_2 emissions per revenue-tonne-kilometre fell 53%. This was achieved by improvements in engine and plane design, reductions in weight, denser passenger configurations, higher passenger loads, and better air traffic operations. However, some of these levers are likely approaching saturation.

The UK plan above implies efficiency improvements of about 1.7% annually to 2050, a slower rate than the 2.7% gains achieved from 1990-2018, but a bit faster than the 1.5% aspiration of the IATA-led group referenced above.

Modal changes for aviation have mainly related to the use of high-speed rail. If electrified with low-carbon electricity, this offers significant carbon reductions and avoids the problem of contrails. Over short distances, it also can save passengers' time. However, high-speed rail networks take time to build and are expensive to develop. They cannot serve small or infrequent destinations, are costly to construct through rugged terrain such as mountains, and obviously cannot cross substantial stretches of water without bridges or tunnels.

Other, more speculative, options include the 'Hyperloop' for high-speed, medium-distance travel as an alternative to rail, or possibly autonomous electric road vehicles over shorter distances. Airships could replace some flights and shipping for cargo, particularly for heavy loads, to remote locations at moderate speeds. Their lifting capability could be favourable for powering them with hydrogen or batteries [xxxiv]. Nevertheless, the development of modern airships has been slow.

Otherwise, air travel could be reduced absolutely. The Swedish phenomenon of 'flygskam' or 'flight shame' refers to the social unacceptability of flight because of climate change. The Covid-19 pandemic has shown that virtual working and videoconferences are a time-saving and acceptable replacement for much – but far from all – long-distance travel. It seems likely such factors will slow air travel's growth, but not eliminate it, due to rising demand from developing Asian countries in particular.

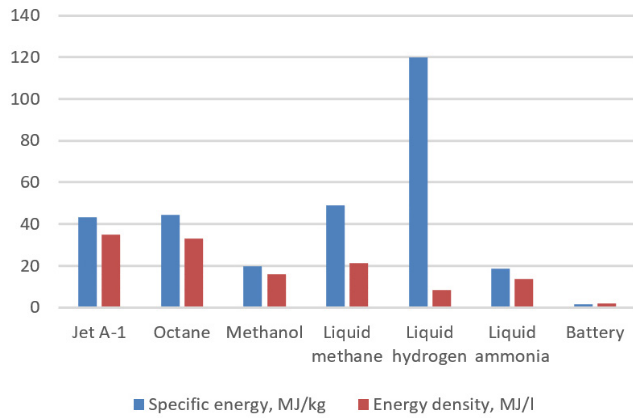
Several alternative fuels have been proposed for use in aviation. However, the range of fuel options is narrower than for shipping because of the technical challenges of performance requirements, lower specific energy (energy per unit mass), and energy density (energy per unit volume) as shown in Figure 5.

Biofuels are the most mature option and have been proven technically adequate, but still had only 0.1% of the market in 2018. Only five airports distribute biofuel regularly today (Bergen, Oslo, Stockholm, Brisbane, and Los Angeles). Fossil fuel jet kerosene costs about $0.3 per litre to produce (at $50/bbl crude oil price); current jet biofuels cost $0.7-1.6 per litre and advanced fuels, with more sustainable feedstocks, cost $1-2.5 per litre [xxxvi]. Therefore, a combination of significant technology improvement and cost reduction, along with carbon pricing or sustainable fuel mandates, is required.

Liquid hydrogen has a very high specific energy, but this is offset by its low density and need for a heavy and highly refrigerated tank. Octane, methanol, and liquid methane still contain carbon, so they could only be a low-carbon solution if made synthetically using atmospheric carbon dioxide. Ammonia's combustion properties are not very favourable for flight, nor fully understood or optimised.

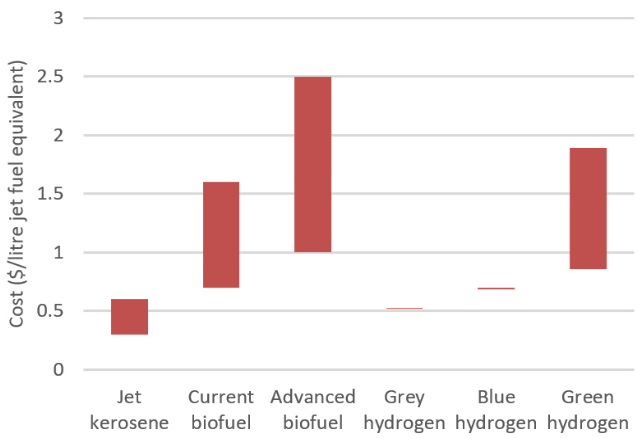
Batteries have by far the lowest energy density and specific energy, even with significant anticipated technical improvements. This lower energy density is partly offset by higher efficiency, but electric propulsion systems have a lower power-weight ratio than turbofans—a further disadvantage. Unlike combustion fuels, batteries do not lose weight during flight and weigh the same even if only partly charged, and so increase the average load that has to be carried. Practical ranges may be about 800 km or up to 1,600 km with major battery improvements [xxxvii].

FIGURE 5 ENERGY DENSITY AND SPECIFIC ENERGY OF ALTERNATIVE AVIATION FUELS [xxxviii]



However, any hydrogen-containing fuel has the potential for contrail formation from water droplets. This potential can be reduced by cutting the content of sulphur and emissions of black carbon (unburnt particles). Contrail formation can be tackled to some extent by re-routing, to avoid weather conditions that favour it.

FIGURE 6 PRODUCTION COST OF DIFFERENT AVIATION FUELS [xxxix]



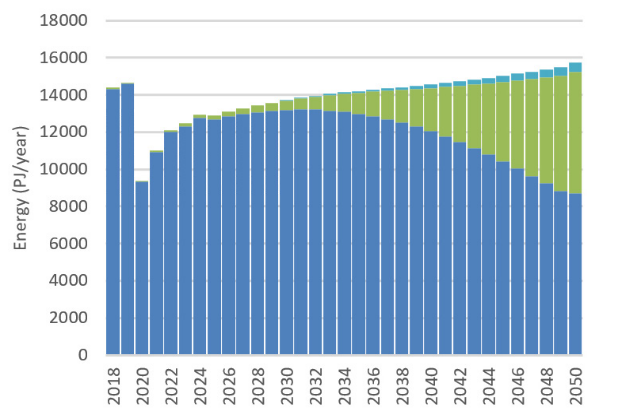
The cost of different aviation fuel options is shown in Figure 6. Jet fuel is shown for a range of crude oil prices from $50-100/bbl. 'Blue' hydrogen is more costly than jet fuel even with crude at $100/bbl. 'Green' hydrogen and advanced biofuels are even more expensive. This does not account for the additional costs of new refuelling infrastructure and, for hydrogen, new engines and plane designs.

Nevertheless, Airbus has developed three hydrogen-fuelled designs, which it targets to come into service by 2035:

- Turbofan with 120-200 passengers' capacity, 2,000 nautical mile range;
- Turboprop with up to 100 passengers' capacity, 1,000 nautical mile range; and
- Flying wing with 200 passengers' capacity, 2,000 nautical mile range xl.

One forecast of worldwide aviation energy use is shown in Figure 7. In this view, oil use in aviation never recovers to 2019, pre-Covid-19 level, but grows from 2020 up to 2031, before declining. Nevertheless, it remains the leading fuel even by 2050. The main low-carbon option is biofuels (41% by 2050), while electricity takes a small share - 3% by 2050 - likely for short-range flights. In this forecast, there is no use of hydrogen.

FIGURE 7 FORECAST OF AVIATION ENERGY CARRIERS [xli]



THE WAY FORWARD

Some measures to reduce shipping and aviation carbon footprints, and eventually reach zero-carbon levels, are similar between the two sectors (for instance, coverage by the EU ETS). Some are complementary or at least related, such as the development of hydrogen as a fuel. Others are unrelated, such as R&D into more efficient designs of ships and aeroplanes.

Policies can address the 'supply' or 'demand' side for zero-carbon transport. These have to be coordinated so that low-carbon options become available with realistic prices and performance as and when users require them.

On the supply side are subsidies for research and development (R&D), and deployment of low-carbon propulsion systems, and into the production and distribution of zero-carbon fuels such as hydrogen and ammonia.

Some mechanism is required to fund R&D for low-emission fuels and systems in aviation and shipping. This mechanism would ideally be global to avoid distorting international competition. Many shipowners have suggested a $2/tonne levy on bunker fuels (about 1% of the current price), to raise $500 million annually for research into zero-emission fuels[xlii].

On the demand side are policies that raise the cost of carbon emissions, such as the EU ETS and fuel levies, that mandate lower emissions, such as efficiency standards, or that outright ban emissions in certain situations.

For instance, the EU or other countries could, at some point, ban the use of carbon-emitting fuels for journeys where viable alternatives exist, such as short-range ferries. This targetted banning would be comparable to existing plans to prevent internal combustion engine cars from entering cities such as Paris and London.

As part of the Covid-19 related bailout of Air France, the French government has required the airline to stop competing with high-speed rail routes and to cut emissions 50% by 2030 [xliii].

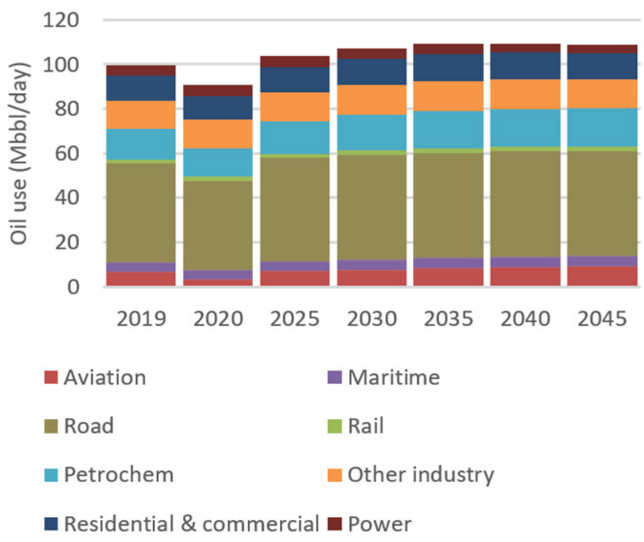
The European ETS and CORSIA are important in setting a price on international transport emissions. As additional countries, including China, Japan, and perhaps the US, adopt carbon-neutrality goals, carbon prices would be likely to align internationally or via carbon border tariffs. Carbon prices could also be applied to journeys beginning, passing through, or ending in a given country or bloc. However, carbon prices at politically-tolerable levels are probably not sufficient to reach these sectors' emissions reduction goals. At the moment, low-carbon fuels or alternative propulsion, particularly for aeroplanes, seem to require very high carbon prices. Therefore, carbon prices, for now, will tend more to encourage efficiency measures and offsets and some demand reduction. Eventually, biofuels for long-range flights, and perhaps batteries for short-range, may be viable as costs fall. Carbon pricing may be more effective in the medium term in shipping, where LNG offers a relatively cheap alternative with moderate GHG reductions. Moreover, where 'green' ammonia or methanol could be viable long-term options, possibly combined with wind power (sails).

Ports have a vital role to play in supporting carbon neutrality from their users. This role includes supplying biofuels and electric charging [xliv], ensuring on-time departure [xlv], linking to multi-modal transport through rail links, and powering their operations with renewables and electric vehicles. Similarly, airports and air traffic control need to align with airlines on the goals of cutting their emissions, improving efficiency, interfacing with other transport modes, and making alternative fuels widely available.

IMPLICATIONS FOR MAJOR OIL AND GAS PRODUCERS

The path of decarbonisation in aviation and maritime use is important for oil demand. In OPEC's view (Figure 8), which is overall bullish for long-term oil demand compared to most other forecasts, the current share of aviation and maritime in oil demand, 11% in 2010, rises a little to 13% in 2045 at a total 14 Mbbl/day. In the DNV view, much more negative on oil demand, the combined share falls from 17% to 14% over that period, at 4.3 Mbbl/day, as oil is virtually phased out of the maritime sector.

FIGURE 8 OIL USE BY SECTOR, 2019-2045 [xlvi]



The impact on gas will be less significant. Gas use (as LNG) in the maritime sector could be moderately important: in DNV's view, it peaks at 6,250 PJ/year in 2038, about 160 billion cubic metres (BCM), equivalent to about 4% of 2019 gas consumption for all uses (3,929 BCM). Otherwise, the main issue for gas will be how widely hydrogen or a hydrogen-derived fuel such as ammonia is used in aviation and shipping, and how much of this is 'blue' hydrogen (made from fossil fuels with CCS).

Beyond these macro-scale effects, there are numerous industry-specific issues for oil and gas producers to consider. For example, many have invested in airlines and shipping fleets for economic diversification; these will have at least to follow global trends of decarbonisation. Vessels such as ammonia carriers (similar to current LPG carriers) or hydrogen carriers will be required, while oil tankers may be in lower demand; new infrastructure will be required to supply and store alternative fuels.

CONCLUSIONS

The maritime and aviation sectors are becoming more proactive in reducing their carbon footprints and contributing to meeting the goals of the Paris Agreement. In the case of the shipping sector, the successful introduction of IMO 2020 rules on the sulphur content of fuels, though a modest change in comparison to decarbonisation, do give some confidence the industry can adjust to a clear goal over a few years.

Realistic assumptions on energy efficiency in the shipping sector can achieve most of the required carbon intensity cuts to 2030, before more use of low-carbon propulsion will be required. The aviation sector, however, will probably have to rely on efficiency and offsets, and a small but growing number of biofuels. There is some synergy between the two sectors in the development of hydrogen as a fuel, but they will likely compete for a limited biofuel pool. Since aviation's choice is more constrained, it may opt for biofuels or other carbon-neutral synthetic hydrocarbons, leaving the maritime sector to use a mix of LNG, hydrogen-based fuels such as ammonia, and perhaps on-board CCS.

Moderate progress towards emissions reduction goals is already enshrined in policy from the IMO and ICAO, but these are relatively followers rather than leaders so far. National and corporate carbon-neutrality goals are more aggressive and growing in scope and will soon have to be reflected in IMO and ICAO regulations. Shipping costs may not rise much because improving efficiency balances carbon costs and more expensive alternative fuels. Aviation, though, is likely to see much sharper cost increases, helping to constrain demand, unless there are technical breakthroughs.

APPENDIX

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