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Pathways

Global transport sector: Investment opportunities and challenges on the flight path to net zero

Part 2 | June 2024

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Executive summary

The aviation sector accounts for around 10% of transport sector CO_2 emissions (which in turn are around 22% of total global emissions). Efficiency gains have helped to mitigate emission growth relative to the growth in air travel volumes, but they are likely to slow going forward.

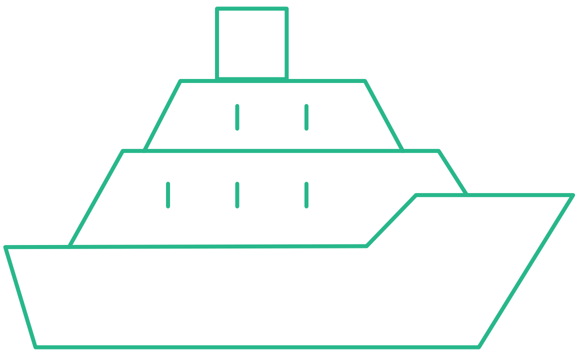
Sustainable aviation fuel (SAF) will be a key part of the solution for this hard to decarbonise sector, with forecasters estimating that SAF could account for 65-80% of sector fuel consumption in 2050. This would require the production of around 350 million tonnes (Mt) of SAF per annum. In 2023 total SAF production was 0.5 Mt.

The price of SAF has been coming down, but it is still a multiple of the jet fuel price. Greater use of SAF will likely add to airline cost bases and ticket prices, although we don't think this will have a significant impact on air travel volumes.

The transport sector may require as much as $US25 trillion in capital expenditures (capex) to decarbonise. Most of this is for charging infrastructure, with $US6-8 trillion required for a public charging network, and as much as $US10-13 trillion of capex needed for charging depots for heavy-duty vehicles (HDVs).

For aviation, around $US2.5 trillion is likely to be needed for SAF. For shipping, the path ahead remains unclear, but in most plausible scenarios around $US3 trillion of capex will be needed for alternative fuels and direct air capture.

Introduction: The global transport sector in context



The transport sector is a huge sector globally and one of the biggest emitters of CO_2, producing around 8 gigatonnes (Gt) in 2022[1] or 21.7% of total energy-related carbon emissions[2] (Figure 1). Road transport accounts for the bulk of transport sector emissions (around 75%), with shipping (10.9%) and aviation (10.1%) the other two sector main contributors (Figure 2). Moreover, growth in transport volumes is closely linked to gross domestic product (GDP) growth, so by 2050 CO_2 emissions could reach 12.6 Gt[3] if efficiency gains are not accelerated or CO_2-producing energy use is not curtailed.

Figure 1:
Global energy-related CO_2 emissions by major sector (% of total)

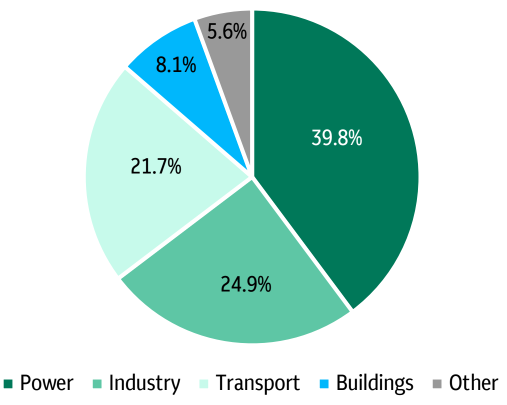
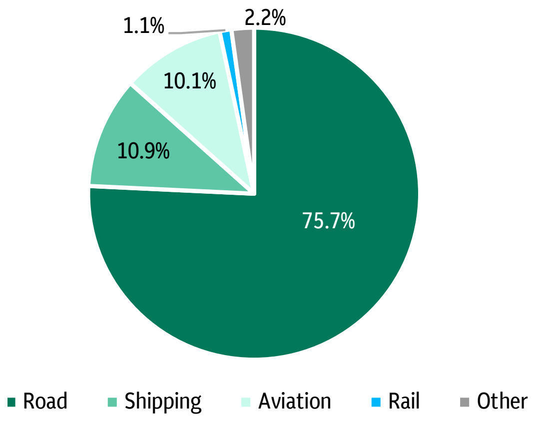


Figure 2:
Transport sector emissions by sub-sector (%)



Source: International Energy Agency (IEA), "Global CO_2 emissions from transport by sub-sector in the Net Zero Scenario 2000-2030," June 2023. Charts are for illustrative purposes only.

1. IEA, "CO_2 emissions in 2022," 2022
2. IEA, "CO_2 emissions in 2022," 2022. According to Our World in Data, a further 4.31 Gt coming from land use change to give a total of around 41.11 Gt of CO_2 emissions. Note that Our World in Data estimates CO_2 from fossil fuels to be 37.15 Gt for a global total of 41.46 Gt.
3. Based on a regression of the relationship between global GDP growth (measured in purchasing power parity terms) and transport sector emissions from 1990 to 2019 and forward estimates of GDP based on International Monetary Fund (IMF) and Macquarie Asset Management projections.

For aviation, the altitude at which the CO_2 is released means that, from a warming perspective, these emissions are disproportionately important. In this sense, aviation "plays above its weight" as represented in Figure 2. It is also the case that travel, and particularly air travel, is a middle-class consumption option of choice – people love to travel, and spending on it comprises a relatively large share of marginal disposable income.

This has meant that flight volumes have grown strongly in recent decades as real incomes have continued to increase, low-cost carriers have made air travel accessible to segments of the population that previously were infrequent users, and emerging market countries have reached levels of GDP per capita at which air travel has become affordable.[4] Globally, this growth is likely to continue for decades to come. In short, aviation is popular and growing rapidly, but it is technically difficult to decarbonise. In this sense it presents very real challenges for the energy transition and a range of solutions will probably be needed, although SAF is, in our view, set to play an important role.

The investor implications of the global transport sector moving to a net zero world are profound. The capex needed to effect the transition is huge – we estimate it could be as much as $US25 trillion in total. Most of this is the charging network and facilities required for road vehicles (both light and heavy). For aviation, SAF has to be a major part of a net zero scenario for this sector and building out the capacity for the ~350 Mt of annual production forecasters think will be needed is likely to require $US2.3-2.9 trillion in investment. Shipping is more uncertain and there are a range of possible paths ahead, meaning one cannot be too precise about the required capex. But in most plausible scenarios we believe it is in the ballpark of $US3 trillion for the alternative fuels and direct air capture that will likely be needed.

4. For those interested in more detail on the drivers of air travel volumes, please see our paper, "Pathways: The post COVID-19 recovery in air travel," April 2022.

Aviation: The flight path to net zero

The global airline industry completed 36.8 million flights in 2023,[5] and August 11 was the busiest day with a global capacity of more than 18 million seats. Measured by available seat kilometres the busiest route was London Heathrow to New York's JFK Airport, and the largest airline was Southwest, followed by American Airlines.[6] In short, the aviation sector has grown to be a major global sector and Figures 3 and 4 below show a breakdown by revenue passenger kilometres (RPKs) and CO_2 emissions.

There are two key points:

- Passenger flights account for 85% of volumes and emissions, with the remaining 15% coming from cargo flights.
- While short-haul flights account for only 11% of RPKs, they account for 16% of emissions. This is because for short-haul flights a greater percentage of total fuel burn is used for non-cruising activities such as taxi, takeoff, and climb, increasing the amount of fuel burned per kilometre travelled.

Figure 3:
Aviation sector volumes (in RPKs)

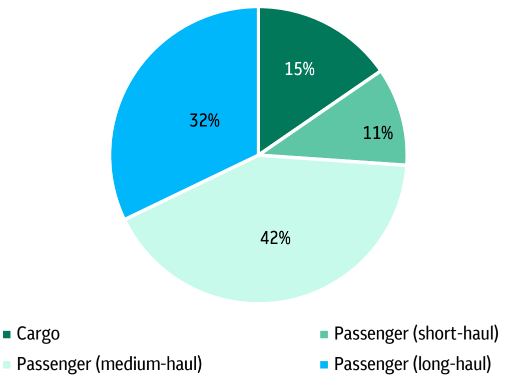
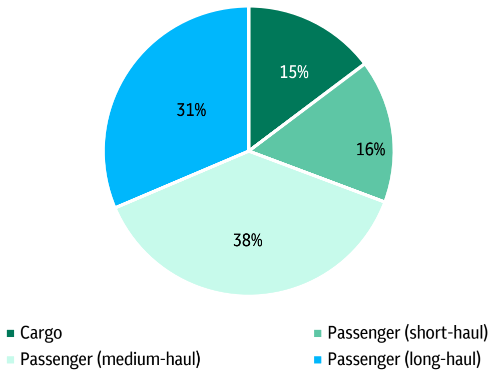


Figure 4:
Aviation sector CO_2 emissions (Mt)



Source: Shell, "Decarbonising Aviation: cleared for take-off," May 2024. Short-haul refers to flight distance of within 1,000 km, medium-haul refers to flight distance of between 1,001 and 4,000 km, and long-haul refers to flight distance of more than 4,000 km.

5. Statista, June 2024.
6. OAG, "Air Travel Statistics 2023," December 2023.

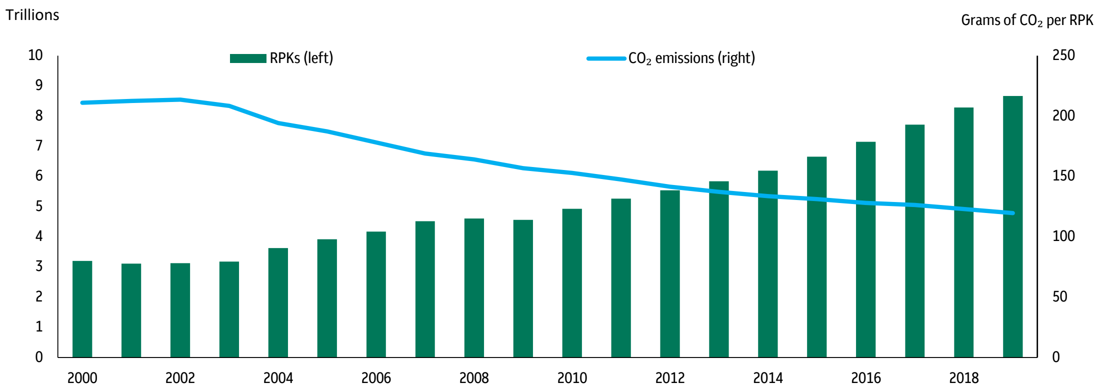
In 2023 RPKs globally grew by 36.9%[7] to reach, by our estimate, 8 trillion passenger kilometres. If RPKs grow at a GDP multiplier of 1.41x,[8] global RPKs are likely to reach around 21 trillion by 2050.[9] If CO_2 emissions grow in line with this (assuming efficiency remains at 2019 levels) then emissions from air travel would reach 2.5 Gt.

There are a range of options for the decarbonisation of the sector, including efficiency gains, electric engines coupled with batteries or fuel cells, hydrogen jets, direct air capture, and SAF. We consider each option in turn.

Efficiency gains: Only a mitigant

Like other transport sectors, the aviation sector has produced meaningful efficiency gains over time. Aviation volumes – as measured by RPKs – grew from 3.2 trillion in 2000 to 8.7 trillion by 2019, an increase of 170.6%. CO_2 emissions increased from 675.6 Mt to 1,036.5 Mt over the same period (or 53.4%), meaning there was an efficiency gain in terms of the quantity of CO_2 emitted per RPK of 43.3%, or 2.9% per annum (Figure 5).

Figure 5:
Aviation volumes and CO_2 emissions



Sources: IEA, "CO_2 emissions in aviation in the Net Zero Scenario 2000-2030," May 2024; Our World in Data, "Global airline passenger capacity and traffic," July 2023.

7. International Air Transport Association (IATA), "Air Passenger Market Analysis," December 2023.
8. As estimated in our Pathways paper from April 2022 – see Figure 26. IMF, IATA Air Passenger Market Analysis (December 2021), Boeing Commercial Market Outlook (2009, 2014, 2021).
9. This is within the range of other major forecasters where estimates range from 15.6 trillion to 25.7 trillion.

These improvements are the result of better process design and improved aircraft technology, as well as delivering more passengers per flight. The latter is achieved via larger aircraft sizes, higher seat density, and improved load factors. McKinsey[10] has estimated that about half of the fuel efficiency gains between 2005 and 2019 came from fleet upgrades (43%) and fuel-efficiency programs such as reduced engine taxi and optimised routes (7%), while the other half of the efficiency improvement came from higher seat density and load factors. The global load factor improved from 71.1% in 2000 to 82.4% in 2019,[11] and the seat density – defined as percentage of seats in an aircraft compared with the maximum potential number of seats the aircraft is certified for – reached 88% in 2019, mainly driven by the increased market shares of low-cost carriers. This means that at least half of the efficiency improvement levers are approaching their limits, making additional efficiency gains more challenging.

Historically, each new generation of aircraft is around 15-20%[12] more fuel-efficient than the previous generation. While new developments are expected to continue this trajectory with more fuel-efficient engines, lightweight materials and improved aerodynamics, less can be assumed going forward from load factors. Overall, further gains in efficiency are likely in the years and decades ahead as aircraft design and materials continue to evolve, although the rate of improvement will probably be slower than it was over the past couple of decades.

If we assume the gains are roughly half the historical average that occurred between 2000 and 2019, this translates into the sector producing around 1.6 Gt of CO_2 in 2050. Like for road transport, efficiency gains matter, but they do not get you close to net zero.

Sustainable aviation fuel (SAF): Key to emissions reduction

There is no single definition of SAF[13] and there are a multitude of different methods and feedstocks to produce it. What they have in common is a significant lowering of net CO_2 emissions compared with fossil fuel use.

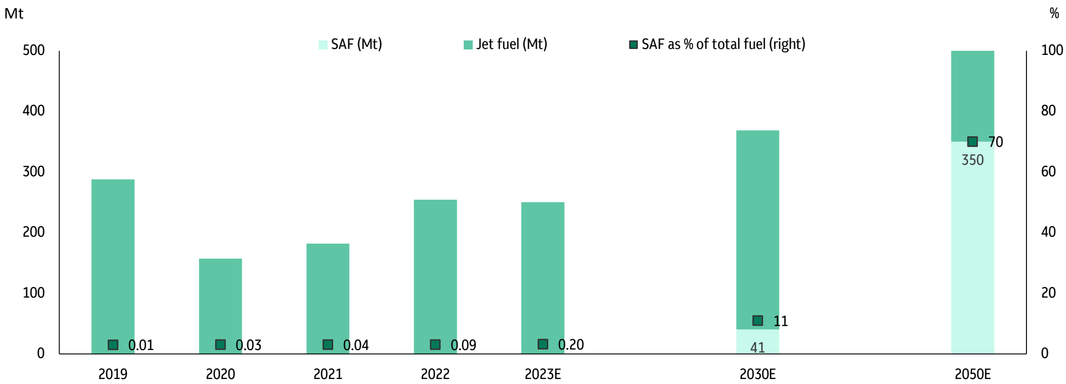
Most SAF types (with the main exception being hydrogen) are partial or full drop-in replacements for conventional aviation fuels. They are, therefore, carbon based and when burned produce CO_2 emissions that are comparable to fossil fuels. However, SAF aims to achieve carbon neutrality through its life cycle by virtue of the carbon emissions from burning SAF roughly matching the CO_2 consumed during the production of the SAF, either in the form of biomass growth or captured CO_2 in the case of e-fuels, which synthesise jet fuel from CO_2 and hydrogen. In the case of SAF produced from municipal waste, the reduction of emissions comes from avoiding the counterfactual use of fossil fuels, as well as avoidance of landfill CO_2 and methane emissions. The different production methods result in different net emission reductions.

10. McKinsey "Fuel efficiency: why airlines need to switch to more ambitious measures," March 2022.
11. Our World in Data, "Global airline passenger capacity and traffic," July 2023.
12. IATA, "Net zero 2050: new aircraft," June 2024.
13. IATA, "What is SAF?" May 2024.

Although airlines were approved to use SAF to fly commercial passengers in 2011 following years of safety tests and scrutiny, the first regular supply of SAF only started being delivered in 2015.[14] SAF can be blended at a ratio of up to 50% with conventional jet fuel to be used in today's aircraft, as per the guidance from ASTM International.[15] The 50% limit is primarily due to a lack of aromatics in SAF, which help prevent leakage by enabling seals to swell inside older engines. Newer engines do not have this concern and the SAF blend limit will eventually increase to 100%. Aircraft manufacturers have declared that all new aircraft will be capable of flying with 100% SAF by 2030.[16]

To reach net zero emissions, the International Energy Agency (IEA) estimates SAF should account for 11% of total energy demand in aviation in 2030 and 70% in 2050 (Figure 6), with the remaining hard-to-abate emissions addressed through either new technology (electric, hydrogen aircraft) or market-based measures such as carbon offsets and carbon capture and storage.

Figure 6:
SAF and jet fuel out to 2050



Source: IATA, "Sustainable aviation fuel output increases, but volumes still low," September 2023; Waypoint 2050, "Balancing growth in connectivity with a comprehensive global air transport response to the climate emergency: a vision of net zero aviation by mid-century," September 2021; IATA, "Net zero carbon 2050 resolution," 2021.

14. Waypoint 2050, "Balancing growth in connectivity with a comprehensive global air transport response to the climate emergency: a vision of net zero aviation by mid-century," September 2021, page 74.
15. IATA, "Fact Sheet 2 Sustainable Aviation Fuel: Technical Certification," May 2024.
16. IATA Air Passenger Market Analysis, December 2021; Boeing Commercial Market Outlook, 2009, 2014, 2021; Airbus, "Global Market Forecast 2023-2042," May 2024.

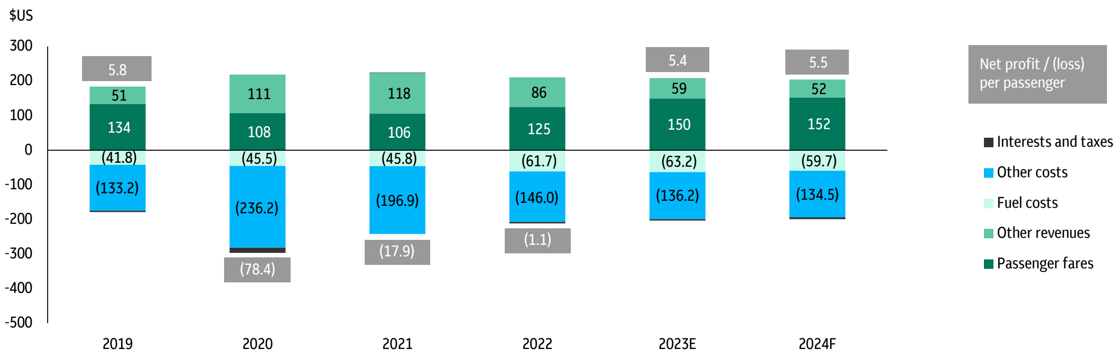
Reaching these targets translates to demand for about 350 Mt of SAF per annum by 2050. With the capacity of an average facility expected to be around 100,000 tonnes, but producing about 65,000 tonnes of SAF per annum,[17] more than 5,000 facilities would be required by 2050. The scale-up of SAF is still in its infancy, with global SAF production accounting for less than 0.1% of commercial airlines' jet fuel consumption during 2019 to 2022, even though off-take agreements for SAF almost tripled in volume between 2021 and 2022, from 0.08 Mt to 0.24 Mt.[18] SAF production is estimated to have been around 0.5 Mt in 2023.[19]

The World Economic Forum has estimated that currently announced SAF production capacity should reach 15 Mt/year by 2030[20] (of which SkyNRG estimated 6.2 Mt in the US and 3.3 Mt in Europe and the UK[21]), which represents about 37% of what we should be delivering to hit the net zero target by 2030 (according to IEA estimates). Key barriers to the ramp-up of SAF include its high price, the availability of cheap and sustainable stockfeed to produce it, and the maturity of the technology to produce alternative forms of SAF.

High price of SAF

Fuel costs account for around 30% of airfares,[22] or around one-third of airlines' total operating costs,[23] and are the single largest overhead expense for airlines (Figure 7). This is the case for recent years, even with the elevated fare prices against the backdrop of high fuel prices.

Figure 7:
Global commercial airlines revenues and costs breakdown, $US per passenger



Source: IATA, "Industry Statistics Fact Sheet"; Macquarie Asset Management calculations, December 2023.

17. Waypoint 2050, "Balancing growth in connectivity with a comprehensive global air transport response to the climate emergency: a vision of net zero aviation by mid-century," September 2021, page 85.
18. IATA, "Chart of the Week: Sustainable aviation fuel output increases, but volumes still low," September 2023.
19. IATA, "SAF Volumes Growing but Still Missing Opportunities," December 2023.
20. World Economic Forum, "Scaling Up Sustainable Aviation Fuel Supply: Overcoming Barriers in Europe, the US and the Middle East Insight Report," March 2024.
21. SkyNRG, "Sustainable aviation fuel market outlook 2023," May 2023.
22. S&P Global, "Decarbonizing aviation: Passengers likely to shoulder price of SAF," November 2023.
23. Shell, "Decarbonising Aviation: cleared for take-off," May 2024.

Over the past three years the average SAF price was 2.2-3.9x the price of conventional jet fuel (Figure 8). Taking as a given the profitability structure of global commercial airlines between 2019 and 2022, this means the fare on a per-passenger basis would need to increase by 30-71% today if all airlines had to blend in 50% SAF, while a 15% SAF blend would translate to a 9-21% ticket price increase (Figure 9).

Figure 8:
Price of SAF relative to jet fuel

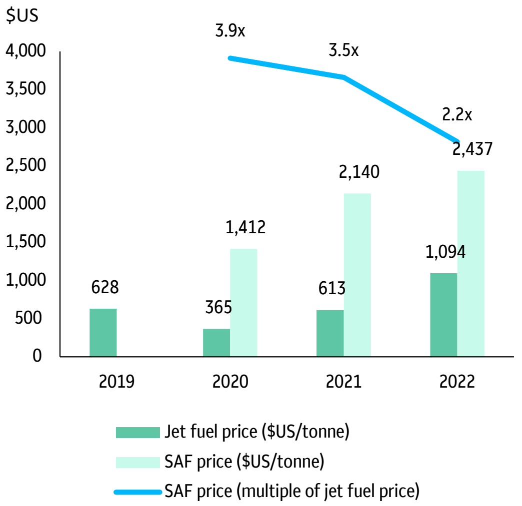
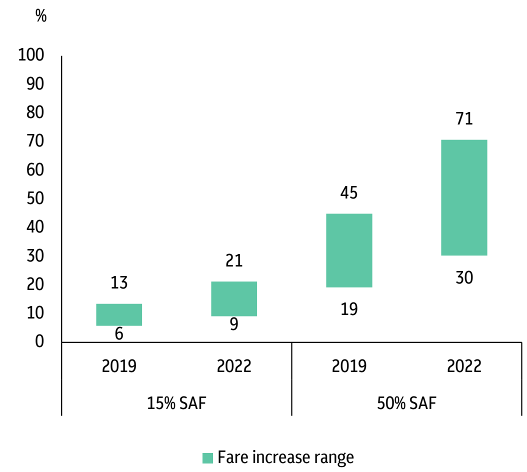


Figure 9:
SAF's potential impact on air fares



Source: IATA, "Sustainable aviation fuel output increases, but volumes still low," September 2023.

Today SAF production costs vary depending on the feedstock and pathway, but there is an overall expectation in the market that the SAF production cost will come down to the range of ~$US1,000-1,500 per tonne for hydrotreated esters and fatty acids (HEFA) and eSAF (SAF derived from renewable energy) produced from hydrogen by 2050.[24] With the cost of carbon estimated to be $US100-200 per tonne from 2030 to 2050, this is likely to be within an acceptable margin of fossil jet fuel prices at the time. Excluding government subsidies, the SAF production cost reductions are likely to come from economies of scale, the maturing of the technology, and reduced feedstock costs.

24. World Economic Forum, "Clean Skies for Tomorrow," November 2020, page 34; PwC, "The real cost of green aviation," 2022, page 28; Waypoint 2050, "Balancing growth in connectivity with a comprehensive global air transport response to the climate emergency: a vision of net zero aviation by mid-century," September 2021.

SAF technology and availability of feedstock

The cost of SAF varies depending on the feedstock (raw materials from which fuels are produced) and the technology used. As of July 2023, there are 11 approved pathways that can be used to generate SAF for commercial flights, with a further 11 in the pipeline for testing and approval over the coming years.[25] The approved pathways include feedstocks sourced from biomass, used cooking oil, agricultural residues, and industrial waste gases. In the case of eSAF produced from renewable energy, hydrogen, and CO_2 through a synthetic process, there is no theoretical limit to its scalability.[26] However, this technology is still in its infancy and has a high production cost.[27]

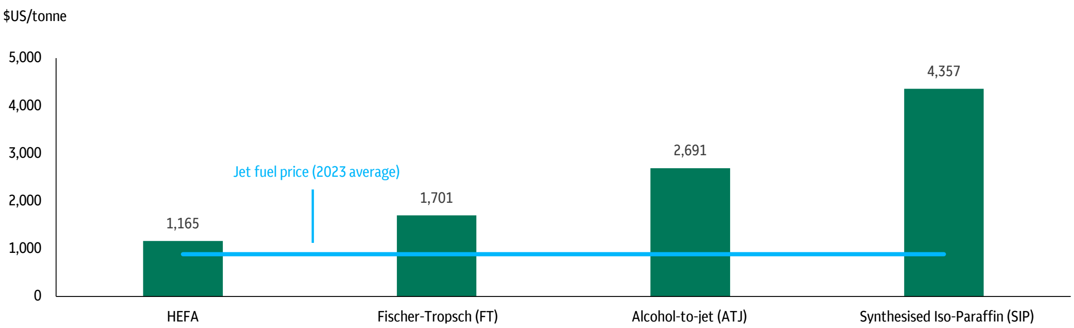
HEFA refines vegetable oils, waste oils, or fats into SAF through a process that uses hydrogen. This is one of the most mature[28] and cheapest ways to produce SAF today[29] (Figure 10).

ING estimates that around 98% of currently announced SAF[30] is produced through the HEFA pathway and it is expected to represent the vast majority of the global SAF supply this decade. However, HEFA faces the challenge of feedstock limitation, and the Air Transport Action Group (ATAG) estimates that HEFA will account for only 27 Mt[31] of SAF production by 2050, representing less than 7% of the SAF needed by that time. Alternative pathways and/or the upscaling of synthetic SAF is clearly going to be required in the longer term.

Assessing the four ASTM-approved processes – HEFA, Fischer-Tropsch, Alcohol-to-Jet, and Synthesised Iso Paraffin (SIP) – with a focus on feedstocks that are already used by these technologies, the SAF price premium to jet fuel (as of 2023) ranges from $US278/tonne (HEFA) to $US3,470/tonne (SIP).

25. IACO Environment, “Conversion processes,” May 2024.
26. ICF, “Roadmap for the development of the UK SAF industry,” April 2023.
27. BP, “How all sustainable aviation fuel (SAF) feedstocks and production technologies can play a role in decarbonizing aviation,” April 2023.
28. Capgemini, “Identifying sustainable pathways for SAF production,” 2023 ; IATA, “Jet Fuel Price Monitor,” 2023.
29. Base on average jet fuel price in 2023.
30. ING, “Stronger supply of sustainable aviation fuels crucial to securing uptake,” May 2023.
31. Waypoint 2050, “Balancing growth in connectivity with a comprehensive global air transport response to the climate emergency: a vision of net zero aviation by mid-century,” September 2021.

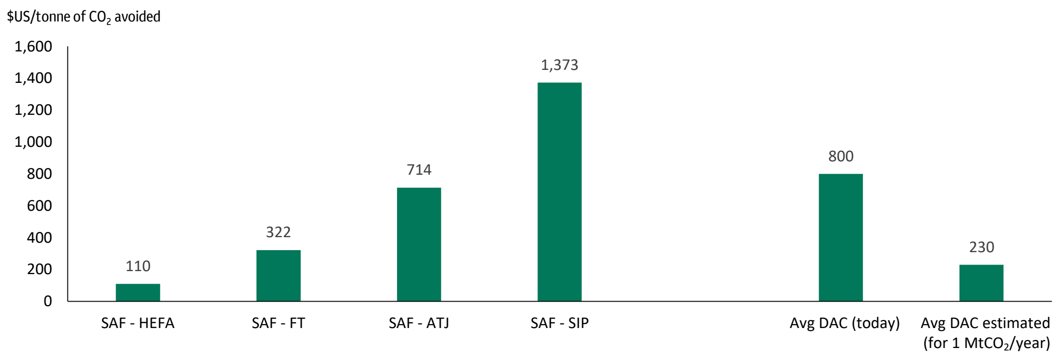
Figure 10:
SAF production cost by process (2023)



Sources: Capgemini, "Identifying sustainable pathways for SAF production," 2023; IATA, "Jet Fuel Price Monitor," 2023.

Compared with direct air capture (DAC), which extracts CO_2 out of the air and currently costs an average of $US800 to remove one tonne of CO_2, SAF produced from the cheapest HEFA process is more economical at a cost of $110 per tonne. However, given the limitation of HEFA feedstock, combined with the estimated cost reductions of DAC due to scaling effects, DAC may become a more cost-effective alternative to the more expensive SAF produced from other processes (Figure 11).

Figure 11:
Comparison of net CO_2 removal cost by pathway (2023)



Sources: World Economic Forum, "Achieving net zero: Why costs of direct air capture need to drop for large-scale adoption," August 2023; IEA, "Direct Air Capture: A key technology for net zero," April 2022; Macquarie Asset Management calculations. Assume jet fuel combustion CO_2 emission factor of 3.16 kg/kg burned, SAF CO_2 emissions reduction factor of 80% expected for HEFA (although processes like FT and ATJ are expected to have a higher rate), SAF premium to jet fuel per Figure A7.

Implications for the sector

To build the estimated 5,000-7,000 facilities needed to produce sufficient levels of SAF (350 Mt) to reach net zero, it is estimated that $US1,100-1,450 billion will be required ($US41-54 billion annualised)[32], implying an average cost of $US207-220 million per facility. The Asia-Pacific region is expected to have the largest number of SAF facilities (39%), followed by Europe (21%) and North America (17%), with the total investments required split in similar percentages by region (Figure 13). To put the amount of investment required in perspective, global upstream oil and gas investment amounted to $US555 billion in 2019,[33] with ~$US318 billion[34] in subsidies provided in the same year (subsidies averaged $US423 billion per annum over the past decade).

Figure 12:
SAF – Estimated number of facilities by region

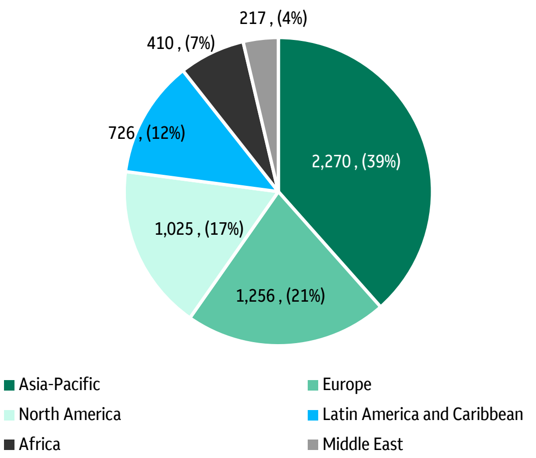
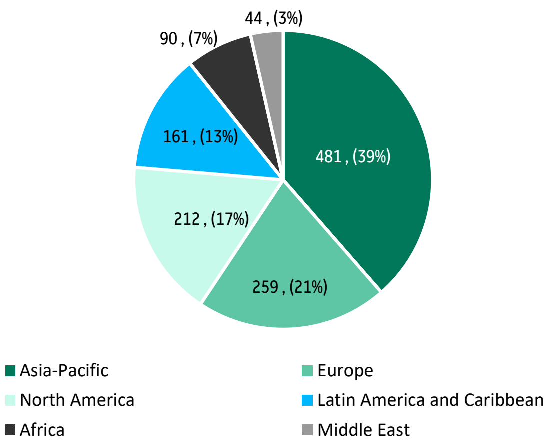


Figure 13:
SAF – Estimated investment required ($US billions) by region



Source: ATAG, Waypoint 2050, "Balancing growth in connectivity with a comprehensive global air transport response to the climate emergency: a vision of net-zero aviation by mid-century," September 2021.

Because the aviation industry is highly concentrated, a small number of manufacturers, airlines, and airports could meaningfully influence the pace of the transition towards net zero. Governments are also increasing fiscal support for the ramp-up of SAF production and mandating SAF use. In Europe, the revised EU Emissions Trading System rules will phase out free allowances for the aviation sector until 2026, which currently cover 85% of emissions in the sector. In addition, the European Parliament Plenary approved the Regulation "ReFuelEU aviation" (ReFuelEU) in September 2023,[35] which mandates that at least 2% of aviation fuels delivered to EU airports need to be SAF by 2025, with the share increasing to 6% by 2030, 20% by 2035, and 70% by 2050.

32. Air Transport Action Group (ATAG) estimates.
33. IEA, "World Energy Outlook 2023," October 2023.
34. IEA, "Low fuel prices provide a historic opportunity to phase out fossil fuel consumption subsidies," June 2020.
35. EBAA, "Refuel EU sets ambitious SAF mandate but open book & claim dilemma for business aviation," September 2023.

The ReFuelEU also mandates 1.2% synthetic aviation fuel by 2030, which gradually increases to 5% by 2035, and 35% by 2050.[36] Current SAF production capacity in Europe is estimated to be 0.24 million tonnes.[37] As of 2023, about 45 e-fuel projects were identified in the European Economic Area with a potential production capacity of 1.7 Mt in 2030. Although this is above the 0.6 Mt mandated by ReFuelEU, it should be noted that none of the major projects have reached final investment decision yet.[38]

In the US, the Inflation Reduction Act of 2022 provides tax credits for SAF, and this is expected to incentivise production to reach 3 billion gallons in 2030 and 35 billion gallons by 2050, which would be enough to fuel all US flights.[39] The UK has dedicated £165 million to support SAF projects as part of its 2022 Jet Zero pledge, and recently announced SAF mandates of 10% by 2030 and 22% by 2040.[40] In 2022, Japan proposed legislation mandating that SAF must account for 10% of total aviation fuel by 2030. These countries together account for almost half (46%) of global jet fuel consumption in 2019, led by the US (24%) and EU (15%).[41]

Direct air capture: An interesting alternative

DAC is a process that removes CO_2 from the air through a filter. Today's leading system uses chemical reactions (either liquid solvents or solid sorbents) to capture CO_2 from the air, and heat is then applied to release CO_2 for permanent storage or use. Globally, there are three companies with 18 plants of varying capacity of 1-4,000 tonnes of CO_2 (tCO_2)/year in Canada, Europe, and the US, capturing a total of just under 8,000 tCO_2/year today. This compares with the 70 metric tonnes of CO_2 ($MtCO_2$)/year in 2030 and 600 $MtCO_2$/year in 2050 that the IEA estimates is needed to meet the net zero target.[42] The three companies have received combined investments of $US788 million[43] to date. Since 2020, governments have spent almost $US4 billion in funding specifically for DAC development and deployment.[44]

The first large-scale DAC plant of up to 1 $MtCO_2$/year capacity is under development in the US and is expected to be operational in late 2024.[45] In November 2022, the company also announced plans to deploy 100 plants by 2035,[46] each with a capture capacity of up to 1 $MtCO_2$/year. More policy support is required to scale up DAC production, and the expected cost reduction is also subject to availability of a low-carbon energy source and CO_2 storage.

36. IATA, "Statement on refuel EO proposals," April 2023.
37. Bird & Bird, "Why REFuel EU may not work," February 2024
38. Transport & Environment, "The challenges of scaling up e-kerosene production in Europe," January 2024.
39. IEA, "World Energy Outlook 2023," October 2023, page 118.
40. Department for Transport, "Supporting the transition to jet zero: Creating the UK SAF mandate," April 2024.
41. Independent Statistics and Analysis, "U.S. Energy Information Administration Petroleum and other liquids," accessed May 2024.
42. IEA, "Unlocking the potential of direct air capture: Is scaling up through carbon markets possible?" May 2023.
43. World Resources Institute, "6 things to know about direct air capture," May 2022.
44. IEA, "Direct air capture a key technology for net zero," April 2022. See Page 8.
45. 1PointFive, "1PointFive and Carbon Engineering announce direct air capture deployment approach to enable global build-out of plants," June 2022.
46. IEA, "Direct air capture," April 2024.

Electric aviation and hydrogen aircraft: Not anytime soon

According to the International Council on Clean Transportation (ICCT),[47] current battery technology with a pack-level specific energy of 250 watt-hours/kilogram (Wh/kg) could allow a fully electric plane carrying nine passengers to fly for up to 140 km, after accounting for reserves. Aviation developed battery-powered aircraft Alice was the first passenger electric plane, completing its maiden voyage in September 2022.[48] Alice can carry up to nine passengers, with an expected travel range of 445 km.[49]

To enable such a journey with 90 passengers and fly up to 280 km would require the battery specific energy to nearly double to 500 Wh/kg, according to the ICCT analysis. While this is the consensus among market experts, startup company Elysian announced in January 2024 a newly designed electric aircraft called E9X that is able to hold 90 people and fly up to 800 km without having to stop to recharge,[50] which is partially enabled by a battery pack with an energy density of 360 Wh/kg.[51]

While these are impressive improvements, the examples make clear that, for aviation, battery technology is a long way away from meaningful commercial usage. There are currently three main challenges that fully electric aircraft face: (1) the weight of battery; (2) the highly regulated nature of the aerospace industry, which means that all new electric aircraft must be type certified for air worthiness by regulatory bodies, such as the Federal Aviation Administration and the European Union Aviation Safety Agency (EASA); and (3) the readiness of the ecosystem and infrastructure for enabling and facilitating electric aircraft operations. More on each below:

- As of 2022, the state-of-the-art commercial lithium batteries are ~50 times heavier than aviation fuel.[52] Even accounting for the much lower energy losses through an electric engine leaves a ~25 times net energy weight disadvantage. This means current electric planes are only feasible on short-haul flights. However, the latest development announced by Elysian means there is hope that more advanced technology may enable longer flights. The timeline over which this is likely to be feasible makes it challenging, however, for electric planes to meaningfully contribute to a reduction in carbon emissions by 2050.
- The two-seater Pipistrel Velis Electro is the first full electric aircraft in the world to be certified by the EASA (June 2020) and approved for pilot training purposes, and it is the only EASA type certified electric aircraft to date (as of January 2024).[53]
- Changes are required from all stakeholders, such as airports, airlines, and the energy industry, to support the supply, storage, and distribution of electricity for charging electric planes.

Electric aviation could represent a good opportunity for airports to serve as "energy hubs" that provide clean energy and charging abilities to local communities (e.g. charging buses overnight), and grid storage plus backup for power outage to critical infrastructure.[54]

47. ICCT, "Performance analysis of regional electric aircraft," July 2022.
48. Popular Mechanics, "Alice, the world's first all-electric passenger jet, just aced her maiden flight," October 2022.
49. DW, "Are electric planes ready for takeoff?" January 2023.
50. ABC News, "How passenger electric planes could become a reality within the next decade," January 2024.
51. Institution of Mechanical Engineers, "Elysian start-up sets ambitious electric flight targets thanks to new research," January 2024.
52. International Civil Aviation Organization (ICAO), "ICAO Environmental Report 2022," 2022, page 120.
53. POLITICO, "Why electric aircraft may never be the next big thing," January 2024.
54. ICAO, "ICAO Environmental Report 2022," 2022, page 122.

Hydrogen is another feasible and promising technology to decarbonise aviation, as it allows the elimination of inflight CO_2[55] emissions. Hydrogen can be used either through combustion in modified gas-turbine engines or via hydrogen fuel cells that convert hydrogen into electricity.[56]

In 2020, Airbus set its ambition to bring to market the world's first hydrogen-powered commercial aircraft by 2035.[57] This concept was a 100-seat aircraft capable of travelling about 1,850 km with six engines. A total of 1.2 megawatts (MW) of power is required for each engine at takeoff.[58] In late 2023, Airbus's first ZEROe engine fuel cell successfully powered on at 1.2 MW,[59] a pivotal step towards its ambition. On a smaller scale, ZeroAvia is targeting a 480 km range with 9-19 seat aircraft by 2025, and up to 1,126 km in a 40-80 seat aircraft by 2027, after successfully flying the largest aircraft powered by a hydrogen-electric engine in January 2023.[60]

While liquid hydrogen has a high gravimetric energy density (about three times that of jet fuel), it has a lower volumetric density, which means liquid hydrogen produces about a quarter of the energy from the same volume of jet fuel.[61] The first-generation hydrogen aircraft could operate within a limited range of up to 3,700 km,[62] due to the requirement to carry four times the volume of fuel. This range represents 74% of the intra-European air traffic today.[63]

Aside from the limitation on range, hydrogen aircraft face the same challenge of requiring regulatory body certification for the new aircraft technology, as well as support for infrastructure and the value chain. For example, major changes to airport infrastructure are required to support hydrogen aircraft because hydrogen cannot be combined with existing jet fuel, so separate transport, storage, and distribution facilities are needed. It should also be noted that the airports need a sufficient storage, distribution, and refuelling system to be able to handle four times the equivalent of jet fuel volumes.

In short, while both electric and hydrogen-powered planes are interesting technologies and real progress is being made, they are both unlikely to become commercial and scale fast enough to have a meaningful impact on carbon emissions by 2050.

55. Clean Aviation, "H2 powered aircraft," accessed May 2024.
56. EIA, "Hydrogen explained, use of hydrogen," June 2023.
57. Airbus, "ZEROe, towards the world's first hydrogen-powered commercial aircraft," 2023.
58. Airbus, "At Airbus, hydrogen power gathers pace," June 2023.
59. Airbus, "First ZEROe engine fuel cell successfully powers on," January 2024.
60. ZeroAvia, "ZeroAvia makes aviation history, flying world's largest aircraft powered with a hydrogen-electric engine," January 2023.
61. The gravimetric energy density of hydrogen is 120 megajoules per kilogram (MJ/kg) (versus 43 MJ/kg for Aviation Jet A-1 kerosene), while liquid hydrogen has a volumetric density of only 71 kilograms per cubic metre (kg/m3) (versus 804 kg/m3 for jet fuel), so the energy stored on a volumetric basis is 8.5 MJ/L (= 120 x 0.071) for liquid hydrogen versus 34.7 MJ/L for jet fuel (=43 x 0.804). This means that the energy density per litre of liquid hydrogen is only 24.5% (=8.5/34.7) of that of kerosene.
62. Transport & Environment, Analysing the costs of hydrogen aircraft," April 2023. See page 5.
63. Transport & Environment, Analysing the costs of hydrogen aircraft," April 2023. See page 6.

Implications for investors: Opportunities and threats as the transport sector transitions to net zero

Reaching net zero will require seismic changes in the global transport sector (road, shipping, and aviation) and these changes are both a once-in-a-generation sized opportunity for capital deployment and a threat to the productive lifespans of some existing assets. In this section, we explore these opportunities and challenges in more detail.

Overall, while there are a lot of uncertainties, we estimate that as much as $US25 trillion in investment will be needed by 2050 for the transport sector to transition to a net zero world. Most of this is in road transport, which will require a large public charging network and facilities to enable the electrification of both light-duty vehicles (LDVs) and heavy-duty vehicles (HDVs).

Estimates of the amount of capex required for the public charging network vary, ranging between $US3 trillion and $US9 trillion (Figure 14). Our own calculations based on the expected size of the fleet in 2050 (Figure 15) produce similar estimates, depending on the capacity requirement assumption – based on EU standards (one charger per 10 vehicles) around $US2 trillion is required, while if the aim is to replicate the capacity of the existing gasoline refuelling network, then $US6-8 trillion may be needed.

Figure 14:
Charging network capex estimates by forecaster

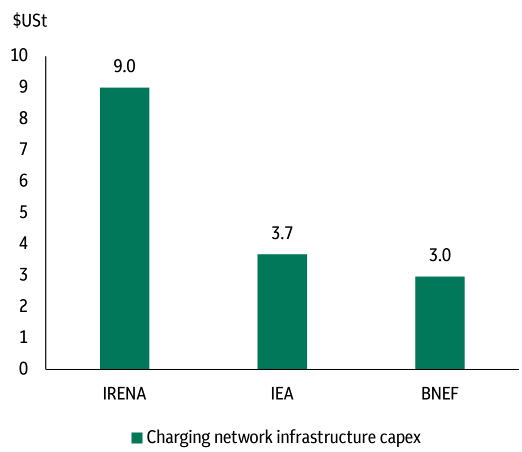
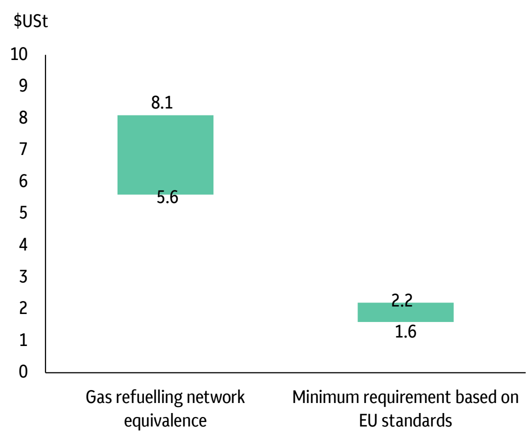


Figure 15:
Charging network capex estimates by standard



Source: International Renewable Energy Agency (IRENA), "World Energy Transitions Outlook 2023," 2023; IEA, "Net Zero by 2050: A Roadmap for the Global Energy Sector," May 2021; BNEF, "New Energy Outlook 2024," 2024; Macquarie Asset Management calculations.

Shipping and aviation are technically much harder to decarbonise and hence the range of potential options is wider and the path ahead more uncertain. The aviation sector would require $US2.3-2.9 trillion in investment to decarbonise the sector by 2050, assuming a 65-80% SAF penetration rate[64] by 2050 (Figure 16). It is difficult to estimate shipping investment requirements given the uncertainty over which fuel option will prevail, but in the hypothetical scenario where green ammonia – the option with the highest new infrastructure requirement – becomes the only fuel option, as much as $US3.2 trillion will be required (Figure 17).

Figure 16:
Aviation capex requirements

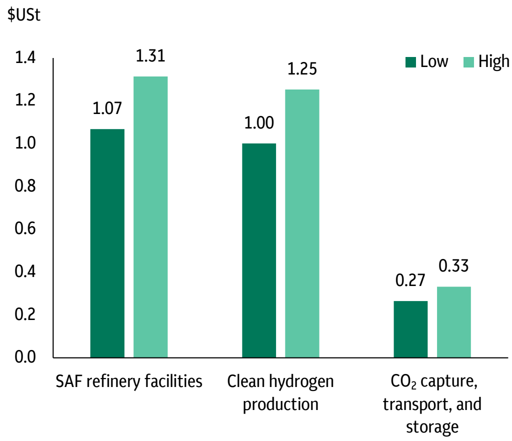
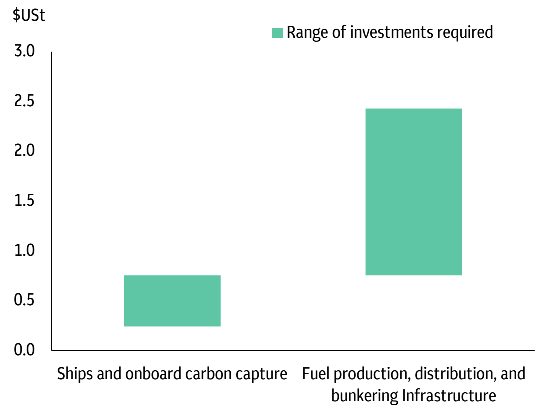


Figure 17:
Shipping capex requirements



Source: United Nations Conference on Trade and Development, "Review of Maritime Transport 2023: Towards a green and just transition," October 2023; World Economic Forum, "Aviation industry net zero tracker," 2023; ATAG, Waypoint 2050, "Balancing growth in connectivity with a comprehensive global air transport response to the climate emergency: a vision of net zero aviation by mid-century," September 2021; World Economic Forum, United Arab Emirates Ministry of Energy & Infrastructure, "Power-to-Liquids Roadmap: Fuelling the Aviation Energy Transition in the United Arab Emirates," July 2022; Macquarie Asset Management calculations.

Charging infrastructure

For the electrification of the road sector, significant amounts of electric vehicle (EV) charging infrastructure will be needed for both LDVs (e.g. passenger vehicles) and HDVs (mostly trucks). Indeed, the infrastructure should "front run" the EV fleet because of the positive impact it is likely to have on EV sales and, therefore, the pace the transition.

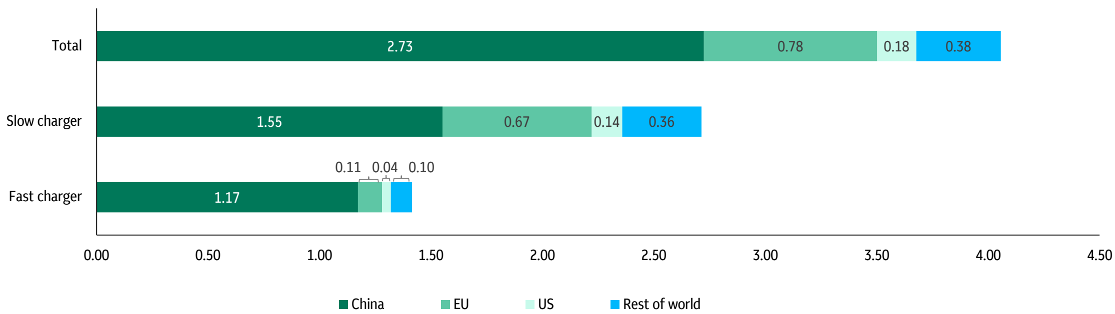
These two categories of vehicles have somewhat different infrastructure requirements – their respective vehicle numbers, energy consumption, and charging schedule mean that different solutions will be required for different types of vehicles.

64. This estimates of the major forecasters in this area are as follows: Sustainable aero lab (65%), IEA (75%), ATAG (76%), ICAO and BP (78%), IRENA (82%).

Light-duty vehicles

In 2023 there were approximately 4.1 million public charging points globally, with most located in a handful of markets. About 66% were installed in China (Figure 18).[65] The rest were mostly located in Europe or the US, which accounted for 19% and 4%, respectively, of public chargers globally. About 35% of the global total are fast chargers (chargers with power ratings of at least 43 kilowatts (kW)). Again, the overwhelming majority (83%) of these were located in China, with Europe and the US accounting for 8% and 3%, respectively, of the total.

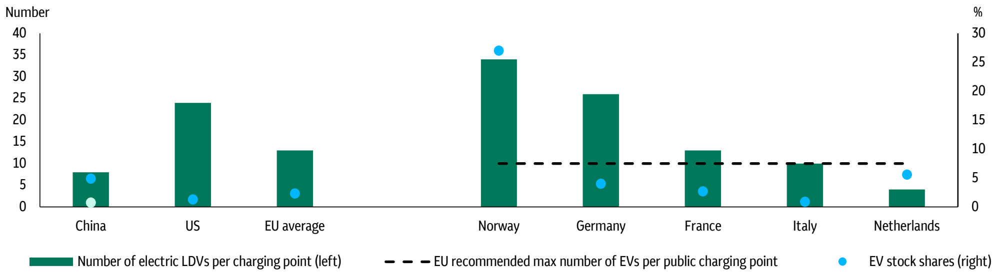
Figure 18:
Number of public chargers (millions)



Sources: Source: BNEF, “EV Outlook 2023,” accessed May 2024.

In terms of the density of the existing charging network, there are roughly 10 LDVs per public charging point (PCP) worldwide (IEA, 2022).[66] However, figures vary widely across countries and regions (Figure 19). In general, as initial infrastructure deployment tends to precede EV sales, countries with relatively small EV stocks often have relatively high charger-to-EV ratios (low EV-to-charger ratios).

Figure 19:
Number of EVs per public charging point in selected countries



Sources: IEA, “Global EV Outlook 2023: Trends in charging infrastructure,” 2023.

65. https://www.bnef.com/interactive-datasets/2d5d59acd9000017?data-hub=2e600dd97f00010a
66. IEA, "Global EV Outlook 2023," 2023.

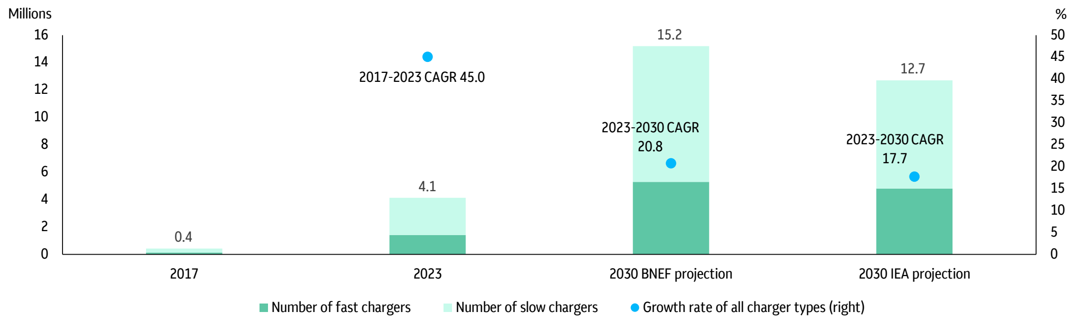
In addition to the PCPs, there were roughly 16.7 million home chargers in 2023. Among the global total, 5.9 million (or 35%) were in China, 6.3 million (38%) were in Europe, and 3.0 million (18%) were in the US.[67] The split between public and private charging points is largely determined by the availability of home charging, which today correlates with the share of dwellings that are single-family homes. Going forward, consumer demand and/or regulatory pressures may mean that apartment buildings are likely to increasingly provide charging, so this relationship may weaken over time.

Charging infrastructure projections

Despite this progress, the existing charging infrastructure is still insufficient to provide the same refuelling convenience to drivers as gas stations. Based on the cars -per -gas -pump ratio and typical car fuel consumption today, we estimate that the current gas refuelling network roughly supports a distance of 47 km per hour per LDV.[68] That is, there is enough capacity in the gasoline refuelling network for every LDV to be driven 47 km every hour of every day. This is comparable to a public charging network with a capacity of 4.71 kW per LDV,[69] but the current global charging capacity is only about 2.4 kW per LDV.[70]

BNEF and IEA projections for public chargers in 2030 (Figure 20) imply growth between 2023 and 2030 of 21% and 18%, respectively, per annum. While slower than the 45% compound annual growth rate (CAGR) of the 2017-2023 period, this is still a very rapid rate of growth and highlights the scale of the capital deployment opportunity. The number of public chargers required globally by 2030 is estimated at 15.2 million (BNEF, 2023) and 12.7 million (IEA, 2023), estimates which are respectively about four times and three times the number we have in 2023.

Figure 20:
Projections for public chargers in 2023

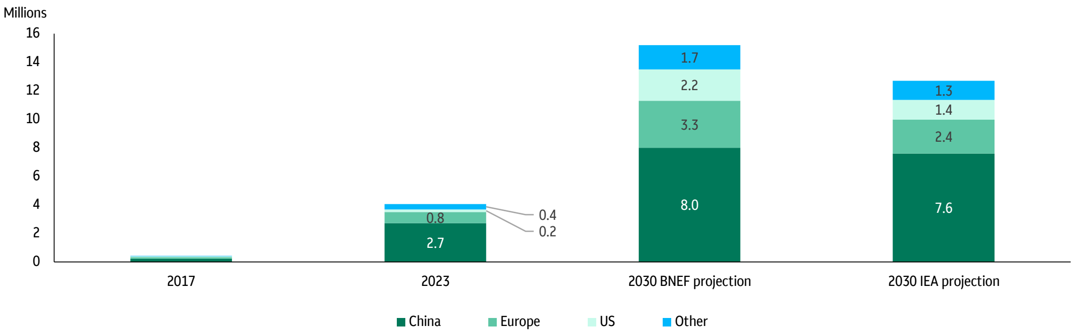


Sources: BNEF, "EV Outlook 2023," accessed May 2024; IEA, "Global EV Outlook 2023: Trends in charging infrastructure," 2023.

67. IEA, "Global EV Outlook 2023," 2023; BBC, "How China's buses shaped the world's EV revolution," December 2023.
68. It is calculated based on a ratio of 357 LDVs per pump and the assumption that LDVs have a 45% road fuel share. The per LDV figure is calculated by dividing the total public charging demand (of both LDV and commercial vehicles) with the total number of LDVs. Our calculation assumes that the ratio between LDV and commercial vehicles is stable.
69. We assume that an EV typical electricity consumption today is 0.16 kWh/km, and home charging accounts for 60% of LDVs' charging demand while depot charging accounts for 80% of commercial vehicles' charging demand.
70. IEA, "Global EV Outlook 2023," 2023.

Diving into the breakdown by market (Figure 21), BNEF and IEA expect a substantial increase in growth in public chargers in the US, from an annualised pace of 24% between 2017 and 2023 to anticipated CAGRs of 44% and 34% (BNEF and IEA, respectively) between 2023 and 2030. This is because historically the US has lagged Europe and China in terms of EV adoption and charging infrastructure rollout, but with increased government support such as the National Electric Vehicle Infrastructure Formula Program, which allocated $US7.5 billion in public financing for charging infrastructure, this trend is expected to soon reverse.

Figure 21:
Charging network requirements by market



Sources: BNEF, "EV Outlook 2023", accessed May 2024; IEA, "Global EV Outlook 2023: Trends in charging infrastructure," 2023.

In the EU, the 2014 Alternative Fuel Infrastructure Directive (AFID) recommended that EU member states reach a ratio of 10 electric LDVs per PCP by 2020, and the Alternative Fuelling Infrastructure Regulation (AFIR) proposed an average kW per EV of 1.3kW for battery EVs (BEVs) and 0.66 kW for plug-in hybrid EVs (PHEVs) for 2030. Based on the IEA's projection of 37 million BEVs and 19 million PHEVs in Europe by 2030,[71] the EU will need to have 5.6 million public chargers to meet the AFID target and almost 61 gigawatts (GW) of charging capacity – equivalent to about 173,000 350-kW fast chargers – to meet the AFIR targets.

Considerations for capital deployment in this space

There are substantial investment opportunities within the charging infrastructure space. On the assumption that there will be around 1.8 billion electric LDVs globally by 2050, to provide the same level of convenience as gas refuelling stations today the global charging network needs to have a total public charging capacity of 8.49 terawatts (TW) by 2050. This is equivalent to about 8.5 million of 1-MW fast chargers or 1.2 billion of 7-kW slow chargers (or some combination thereof) and implies a total capital investment requirement range of $US5.6-8.1 trillion based on the capital cost of chargers today.[72]

71. IEA, "Global EV Data Explorer," April 2024.
72. Our estimate considered public chargers with power ratings of 7 kW, 50 kW, 150 kW, 350 kW, and 1 MW.

Another way to consider the capital deployment requirement is by looking at the PCP-to-car ratio. Within the EU, AFID recommended a LDV-to-charger ratio of 10-to-1.[73] AFID did not specify the type of charger used, but taking into account EU's AFIR requirement of at least 1.3 kW of public charging per LDV,[74] on average each charger needs to have a charging capacity of at least 13 kW. Applying these standards at a global scale, our 1.8 billion electric LDV would imply 180 million chargers and, in turn, a minimum total charging capacity of 2.34 TW by 2050. This translates into a minimum capital requirement of $US1.6 trillion if a mix of 7-kW slow chargers and 50-kW-and-above fast chargers are installed, and $US2.2 trillion if only 50-kW-and-above fast chargers are installed.

Overall, our calculations suggest that $US1.6-2.2 trillion is the minimum capex requirement to support 2050 EV demand, but a total investment of $US5.6-8.1 trillion would be required to make the charging network as convenient as the gas refuelling network today. Our estimates are roughly in line with the figures put out by other forecasters, which have a range of $US3-9 trillion[75] (Figure 14).

Several issues and challenges remain for investors to consider when investing in this space.

- **Strategic importance of location.** Existing gas stations along major highways and urban centres present attractive opportunities due to their high visibility and footfall. A prime location promises high utilisation and can significantly enhance the profitability of charging stations. Many of these well-located assets are owned and operated by a handful of companies, so it may be difficult for new entrants to establish a foothold in the market. For investors looking to invest in motor service areas, the shift to EV charging can be a growth and value accretion opportunity.
- **Upfront capex.** McKinsey estimates that the upfront capital costs and installation costs of one 150-350 kW fast charging unit can be anywhere from $US85,000 to $US250,000.[76] Furthermore, upgrading the electrical connections and other infrastructure to support fast charging can add substantially to the total investment requirement.
- **Grid connection.** Grid connectivity can be a major bottleneck to charging infrastructure deployment, and many European countries currently have a long queue for grid[77] connection. In the UK, the wait time can be up to 13 years for renewable and battery site projects to connect to the grid. In Spain, Reuters recently reported that nearly half of Repsol's 1,600 charging stations were dormant due to a lack of power connection in December 2023.[78] Regulators have attempted to cut the wait time by various means. For example, the UK Office of Gas and Electricity Markets (Ofgem) has recently changed the rules governing connections to the UK national transmission grid to enable slow-moving or unviable projects to be ejected from the connection queue.[79] While these new policies should help to shorten the wait time, it is important for investors to keep the connection wait time in mind

73. IEA, "Global EV Outlook 2022," 2022.
74. European Commission, "European Alternative Fuels Observatory Finland AFIR fleet-based target," accessed May 2024.
75. While they don't provide details, we think large difference in estimates from the forecasters may be driven by their different assumptions on home and depot charging. We assume home and depot charging respectively account for 60% of LDVs' charging demand and 80% of commercial EVs' charging demand. However, if we change the assumption to 80% of LDV's charging demands fulfilled by home charging, then only $US 3.9-5.6 trillion of capital deployment will be required.
76. McKinsey & Company, "Can public EV fast-charging stations be profitable in the United States?" October 2023.
77. Financial Times, "Renewables groups sound alarm over UK grid connection delays," 2024
78. Reuters, "EV charging growth plans slowed by EU's power grid problems," December 2023.
79. Clifford Chance, "UK national grid connection queue management reforms and the use of arbitration," March 2024.

when planning for a charging project. It is also an area where efficiency improvements by approval agencies could make a big difference in the rate of charging network buildout and therefore EV adoption

- **Longevity of charging standard.** The fast evolution of commercially available chargers has led to concerns about whether chargers installed today will quickly become obsolete. In recent years, the maximum charging speed of fast chargers has increased greatly from 7-22 kW to 50-350 kW (rapid and ultra-rapid chargers). MW chargers have also come to market this year: Finnish charger maker Kempower started taking orders for its MW charging system, which has a peak power of 1.2 MW, in April and delivered the first order on May 31.[80] However, investors can, to a certain extent, futureproof their charging station project today by planning for excess grid capacity and laying more powerful cable that can cope with higher charging standards in the future, even though this will require additional capex.
- **Legal and permitting challenges.** The legal landscape for establishing charging infrastructure can involve navigating a maze of local and national regulations. In the EU, the "Fit for 55" legislative package aims to simplify this process, but investors still face considerable variability in permitting procedures across member states. In the US, the situation is similarly complex, with the permitting process varying from one jurisdiction to another, often extending project timelines. Unexpected delays could directly impact investor returns, so understanding and assessing this accurately will be important from an investor standpoint.

Heavy-duty vehicles

HDVs, such as trucks and buses, have different charging infrastructure needs due to different usage patterns, larger battery sizes, and the physical size of the vehicles. HDVs are primarily used for commercial purposes and have larger batteries to accommodate longer distances and heavier loads. Their charging needs can be divided into "off-shift" downtime, usually overnight, and "mid-shift", i.e. during the mandatory resting period required by law.

Electric trucks and buses will rely on off-shift charging for the majority of their energy, achieved mainly at private or semi-private charging depots or at public stations on highways. Depots to service growing demand for heavy-duty electrification will need to be developed, and in many cases may require distribution and transmission grid upgrades. Depending on vehicle range requirements, depot charging will be sufficient to cover most urban bus operations, as well as urban and regional truck operations.

Opportunities and challenges for capital deployment

BNEF estimates that a typical truck charging station will have a power capacity of 25 MW, fulfilled by a combination of 1-MW, 350-kW, and 150-kW fast chargers.[81] While the e-truck market is still at an early stage, we already have examples of companies building depot charging stations of this size. For example, in May 2024, US e-truck charging solution provider WattEV opened an e-truck charging depot in Bakersfield, California, which features three 1.2-MW chargers, 16 360-kW chargers, and 15 240-kW chargers.[82]

80. Kempower, "Kempower's megawatt charging system for electric trucks arrives in Europe," April 2023; Kempower, "Kempower and Virta to deliver megawatt charging system for electric cars and trucks to Hedin Supercharge's public charging in Linkoping, Sweden," May 2024.
81. BNEF, "E-trucks need a revved-up grid to get rolling," accessed May 2024
82. WattEV, "WattEV opens world's largest solar-powered truck charging depot boasting megawatt charging, fourth station to open this year," May 2024

The hardware, installation and operations and management (O&M) costs to build a truck charging station with this configuration today will run about $US17-18 million, and grid connection could cost an extra $US3.75-7.5 million, meaning that the total capital cost could be in the range of $US20.75-25.5 million. In the scenario where the global public charging network in 2050 is as convenient as the gas refuelling network today (we assume a depot charging ratio of 80%), this translates into a charging capacity of 12.9 TW, which is equivalent to about 515,000 25-MW charging stations. Multiplying these numbers out results in a needed capex range of $US10.7-13.1 trillion.

Because stations with such high power needs will incur significant costs in both installation and grid upgrades, policy incentives may be required to encourage development of this type of charging infrastructure. For instance, the EU's AFIR aims to enable mid-shift charging across the EU's core TEN-T network, which covers 88% of total long-haul freight activity, and along other key freight corridors.

The provisional agreement reached by the European Council and Parliament includes a gradual process of infrastructure deployment for electric HDVs starting in 2025.[83]

In addition to fast charging, other options to provide power to electric HDVs include battery swapping and electric road systems. Electric road systems can transfer power to a truck either via inductive coils in a road, or through conductive connections between the vehicle and road, or via catenary (overhead) lines. Battery demand can be further reduced, and utilisation further improved, if electric road systems are designed to be compatible not only with trucks but also electric cars. However, such approaches would require inductive or in-road designs that come with greater hurdles in terms of technology development and design and are more capital intensive.

Shipping: A range of potential scenarios

The extent of the infrastructure investment opportunities for shipping decarbonisation varies depending on the eventual decarbonisation path chosen. For example, biofuel and renewable methanol are compatible with existing bunkering infrastructure, so switching to these alternative fuels would require relatively little investment in fuel logistics infrastructure but substantial investments in biofuel refining capacity and related infrastructure. Ammonia is not compatible with existing bunkering infrastructure and thus entails significant port and fuel logistics investments on top of the ammonia plants. In addition, for all alternative fuels, distribution pipelines will need to be added as demand for these fuels grows.

83. EC Council of the European Union, "Alternative fuel infrastructure: Provisional agreement for more recharging and refuelling stations across Europe," March 2023.

To the extent that onboard carbon capture is part of the solution for this sector, additional port infrastructure for the handling and temporary storage of CO_2, plus the sequestration infrastructure and logistics assets (whether shipborne or by pipeline) for connecting the port to the sequestration site, will be required.

In our view, clean ammonia and DAC will be the primary shipping decarbonisation solutions in the long run. In a hypothetical scenario where 100% of international shipping uses green ammonia there would be demand for 426 million tonnes of clean ammonia annually.[84,85] This implies a significant capex requirement: the Global Maritime Forum estimates that 20 million tonnes of green ammonia will be required per year to fully decarbonise the Asia-Europe route, a major trade route that accounts for 2.1% of global trade volume.[86] The corresponding capex requirement is about $US150 billion, comprising $US98 billion for fuel production (wind/solar production capacity, electrolyser, hydrogen storage and ammonia plant), $US0.2 billion for bunkering vessels and ammonia storage tanks, and $US52 billion for new vessels that can be fuelled with ammonia.[87] Based on this, a total capex of about $US3.2 trillion will be required if 100% of international shipping uses green ammonia.

Co-location, i.e. fuel production near the ports, is assumed in this estimate, meaning that minimal fuel transmission pipeline is required. However, it is likely that co-location is not possible for all routes and some routes will inevitably require distribution pipelines, resulting in even higher capex requirements.

Meanwhile, it is estimated that when DAC is eventually performed at industrial scale, a one million tonne per annum DAC plant would cost about $US1.25 billion.[88] Therefore, if 100 million tonnes of CO_2 (about 10% of global shipping emissions) is decarbonised by DAC, then a capex of $US125 billion would be required.

In an alternative scenario where clean ammonia is 50% of the 2050 fuel mix, DAC accounts for 20% and biofuel and renewable methanol each account for 15%, we estimate that a capex of about $US2.8-3.1 trillion would be required.[89] Given the lead time of clean ammonia and DAC projects, which can take as much as a decade from planning to operation, the required capital will need to be deployed well ahead of 2050.

84. Based on IRENA estimate that 183 Mt of clean ammonia will be required if it accounts for 43% of the fuel mix by 2050.
85. IRENA, “A pathways to decarbonise the shipping sector by 2050,” 2021.
86. Global Maritime Forum, “The Next Wave Green Corridors,” 2021.
87. Global Maritime Forum, “The Next Wave Green Corridors,” 2021.
88. GLG Insights, “Direct Air Capture Industry Implementation and Key Challenges”, January 2024.
89. We assume that for renewable methanol, the fuel production capex requirement is about three times that of clean ammonia, but minimal capex would be required for bunkering and new vessels. We also assume that the capex required for biofuel on a per unit of energy basis is no more than clean ammonia.

Aviation: SAF will be key

In our view, SAF is the only viable option for the aviation sector in the near to medium term, as it remains the most economical and technologically mature choice. While hydrogen and electric aviation could, in time, become potential solutions to short-haul and some medium-haul flights, long-haul flights would still be highly reliant on SAF to decarbonise. With the support of various government mandates on SAF usage, industry forecasters estimate about 65-80%[90] of total fuel required in 2050 would need to be SAF, which translates to 325-400 Mt of SAF per annum.[91]

With SAF production being 0.5 Mt per annum in 2023, this projection implies a CAGR of ~28% for the next 27 years. Although SAF is compatible with today's aircraft and the current fuel storage and delivery infrastructure, the escalating demand for SAF still entails a range of new investment opportunities. Specifically, new infrastructure is required upstream of the airport, spanning the gathering of the feedstock to production at refineries.[92]

- **Refineries and fuel blending.** Up to $US1.1-1.3 trillion will be required to build renewable fuel refineries to keep up with the escalating SAF demand. In addition, SAF derived from HEFA requires infrastructure to transform the fat oils and greases into a liquid blend that can be mixed with jet fuel.
- **Feedstock production and carbon capture.** Existing pathways of SAF feedstocks include those sourced from biomass, used cooking oil, agricultural residues, and industrial waste gases. The infrastructure requirement of each pathway varies – for instance, carbon capture facilities are needed for the Power-to-Liquid (PtL) pathway, where CO_2 captured from the atmosphere or industrial emissions is combined with hydrogen from the electrolysis of water to produce SAF. DAC capacity may also need to exceed 640 Mt per annum in our estimates.[93] However, as of 2023, there was only 4,000 tonnes of DAC commercial capacity and the largest DAC projects in the pipeline today have removal capacity of only 0.5-1.0 Mt. Furthermore, infrastructure for CO_2 storage and transport are also needed for this pathway, which could require $US100-150 billion in investment for the 640-800 $MtCO_2$ for eSAF production. An additional $US1.0-1.3 trillion capex is likely to be required to produce the 85-110 Mt[94] of clean hydrogen needed for eSAF production.
- **Distribution pipeline.** As SAF production volumes grow, and with many domestic fuel pipeline systems already at capacity, the sector will likely need new transportation capacity including distribution pipelines to accommodate the supply integration of the additional SAF.

90. Per researches done by IEA, ATAG, ICAO, IATA, IRENA, BP, Sustainable aero lab.
91. With estimated global jet fuel of 500 Mt required by 2050, per ATAG estimate.
92. IATA, "Energy and New Fuels Infrastructure Net Zero Roadmap," 2023.
93. We estimate at least 325 Mt of SAF is required by 2050, of which only 27 Mt are produced from HEFA, assume half of the remaining SAF is produced from PtL with CO_2 from DAC. The World Economic Forum estimated that 4.3 tonnes of CO_2 is required to produce 1 tonne of PtL jet fuel. See page 52 of World Economic Forum, "Power-to-Liquids Roadmap: Fuelling the Aviation Energy Transition in the United Arab Emirates," July 2022.
94. About 0.58 tonnes of hydrogen is required to produce 1 tonne of eSAF through PtL pathway. See page 52 of World Economic Forum, "Power-to-Liquids Roadmap: Fuelling the Aviation Energy Transition in the United Arab Emirates," July 2022.

In short, total capital investments of \$US2.3-2.9 trillion could be needed for the aviation sector to land at the net zero destination by 2050, of which 45% would be used to build the SAF refinery facilities, with similar amounts needed for the production of clean hydrogen for eSAF. As discussed earlier in this paper, the average SAF price is currently more than double that of jet fuel, and an increase in the SAF blend percentage will result in increasing ticket prices. However, the CO_2 tax introduced for aviation as well as shipping in some markets, such as the EU Emissions Trading System in Europe, will help to reduce the price premium associated with SAF. We also expect the impact on travel volumes to be minimal overall as we think the sensitivity to prices is low at the national level and GDP is a far more powerful driver of growth in air travel volumes.[95]

Finally, other means to decarbonise the aviation sector, if they materialise, also require new infrastructure. For instance, if electric aviation becomes available for commercial use, airports will need to add charging infrastructure for aircraft. In addition, hydrogen is another potential route to decarbonise the aviation industry. The combustion process of hydrogen primarily produces water vapor and can eliminate carbon emissions of aircraft (though they can only reduce the global warming effect of aviation). That said, this technology is still under development and there is currently no commercial operation of hydrogen aircraft. The market outlook also remains unclear due to the high cost of producing hydrogen and safety concerns. If hydrogen is adopted as an aviation fuel, its low density and cryogenic storage requirements mean that significant modification to aircraft design and fuel storage in aircraft will be required. Fuel handling at airports would also be needed. Airports would likely need bespoke supply pipelines. Consequently, while hydrogen aircraft see potential adoption by some market segments in the long run, far more likely in the near and medium term are solutions that allow aviation to continue with minimal logistic changes, such as through the use of hydrocarbon SAF. This could be complemented by DAC drawdowns, particularly if the regulator comes to recognise continued fossil fuel use with DAC drawdown for its net zero compliance.

95. See our Pathways paper "The post-COVID-19 recovery in air travel," April 2022.

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