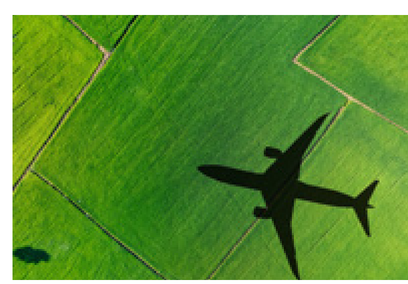
Decarbonising Aviation
Exploring the Consequences



Corporate Partnership Board Report

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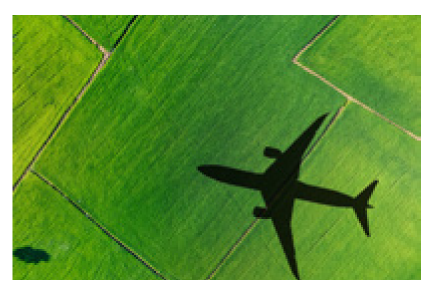

Corporate Partnership Board Report

The International Transport Forum

The International Transport Forum is an intergovernmental organisation with 69 member countries. It acts as a think tank for transport policy and organises the Annual Summit of transport ministers. ITF is the only global body that covers all transport modes. The ITF is politically autonomous and administratively integrated with the OECD.

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

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This report draws on contributions gathered in a hybrid (online and onsite in Paris) workshop, organised on 13 March 2024 with members of the CPB and external experts. See Annex B for a full list of workshop participants.

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Decarbonisation will increase air ticket prices

Ticket prices are expected to be, on average, 25-30% higher by 2060 under the ITF's Net Zero Emissions scenario compared to the Baseline scenario due to increased costs associated with emission-reduction measures, however these costs will be largely progressively distributed and will not necessarily affect airline profits.

Sustainable Aviation Fuels (SAFs) are crucial to reduce emissions while safeguarding connectivity

Governments have a key role to play in establishing policy frameworks which create the market conditions necessary to facilitate a massive and rapid uptake in SAF production and use.

The broader consequences of decarbonising aviation are multifaceted

Policymakers need to consider the consequences of decarbonising aviation on connectivity, tourism, equity, and the labour market.

Main findings

Historically, demand for global air travel has doubled every 15 years. The projected continuous growth in GDP per capita and population, particularly in developing economies, suggests that, under the current paradigm, demand for air travel is set to keep growing steadily as access to travel and tourism continues to increase. Global aviation has generated significant benefits for society; however, this increased mobility also comes with significant environmental costs, currently accounting for around 2.5% of global energy-related carbon dioxide (CO_2) emissions. In 2022, governments signed up to the International Civil Aviation Organization's (ICAO) long-term global aspirational goal (LTAG) for international aviation of net-zero CO_2 emissions by 2050. While there are notable discrepancies among industry stakeholders, researchers, and policymakers regarding their assessment of the likelihood of achieving this goal, there is broader consensus on the policy measures and technological developments necessary to facilitate the transition to decarbonised aviation.

This report sets out the current implementation status of the main policies for decarbonising aviation and projects their impacts on aviation demand and CO_2 emissions from 2019 to 2060 for three scenarios developed by the ITF – a "Baseline scenario" (continuation of the status quo, where only policies that are already adopted are reflected), a "High Ambition scenario" (co-ordinated efforts of governments, international regulators and the industry to heavily reduce aviation's CO_2 emissions), and a "Net Zero Emissions scenario (NZE)" (further policy interventions that lead to a widespread adoption of SAFs and allow the aviation sector to reach net-zero emissions by 2060). The scope of this analysis is limited to tank-to-wake (TTW) CO_2 emissions and does not account for non-CO_2 effects generated by air transport that also contribute to global warming. The extension of the timeframe of analysis from 2050 to 2060 allows for the potential significant adoption of new liquid fuels and technologies – which, even if deployed at an unprecedent speed, are currently unlikely to show sufficient scale to decarbonise the sector by 2050.

The adoption of cleaner fuels, the development of new zero-emission aircraft (electric and hydrogen propelled) and the regulatory measures necessary to make aviation carbon-neutral will, however, lead to higher costs. Technological and operational efficiency improvements will not be enough to offset these expected cost increases, and these will likely be transferred to ticket prices. As a result, by 2060, air ticket prices under the High Ambition and NZE scenarios are expected to be, on average, 25-30% higher than in the Baseline scenario. This, together with the increased availability of cleaner alternative modes (such as high-speed rail in some world regions) and shifts in traveller behaviour, means that air passenger-kilometres in 2060 under the NZE scenario are expected to be around 30% lower than they would otherwise be in the Baseline scenario. This could lead to broader consequences on transport connectivity, tourism, equity and the labour market.

Top recommendations

Implement policies that support adoption of SAFs to safeguard benefits from aviation connectivity

To safeguard the varied and many benefits that connectivity via aviation generates, it is essential that the sector further decouples demand growth from carbon emissions growth. The ITF's NZE scenario expects major emissions reduction from SAFs, which implies an equivalent annual demand of around 500 billion litres by 2060, more than 1 000 times current production levels. The energy sector and in particular fuel producers, airlines, airports, investors, and governments must make coordinated and sustained efforts to achieve this objective. Governments have a key role to play in establishing policy frameworks which create the market conditions necessary to facilitate a massive and rapid uptake in SAF production and use. Taking both a "carrot" and "stick" approach, where financial incentives are coupled with strong regulatory requirements, works best to scale up production while avoiding sharp price increases in the short-to-medium term. Given the amount of investment required to bring SAF production facilities online, governments should ensure that any support measures are sufficiently robust and stable over time to generate adequate confidence in future demand for offtake agreements. Specific policies which should be considered as part of a portfolio approach include carbon pricing (emission trading schemes and carbon taxes), low-carbon fuel standards and fuel-blending mandates (accompanied by non-compliance penalties), financial incentives (including via public finance to de-risk private investment, e.g. grants, concessional loans, guarantees, and revenue certainty mechanisms like "contracts for difference"), research and development funds, and compliance with evidence-based international fuel certification schemes which take into account effects from indirect land-use change.

Preserve connectivity in remote, aviation-dependent areas

Aviation plays an important role in maintaining connectivity for remote, aviation-dependent areas, where it facilitates economic integration, trade, employment, and access to critical services like healthcare. However, not all air transport routes are commercially viable without government support, and increased costs due to decarbonisation may result in the proliferation of such circumstances. To preserve connectivity in this context, supporting policy measures may need to be strengthened. However, the positive impacts of these policies must be weighed against their costs. Such policies may require significant public subsidies - which put pressure on government funding, may distort the decision-making of airlines and provide them with weak incentives to be efficient, and may unintentionally restrict competition if routes are overprotected. Governments must therefore be clear about the public policy objectives they are seeking to achieve through these measures and rationalise their support accordingly in light of potential increasing demands from remote aviation-dependent regions. The use of public service obligations may be preferable to other measures because any distortion is restricted to the specific routes affected and conditions are well defined in a competitively tendered contract. Governments should also consider promoting the deployment of alternative propulsion technologies, such as electric and hydrogen aircraft, which are well-suited for the short, lower-capacity flights typically serving these areas.

Promote more sustainable forms of tourism - shorter distances, cleaner modes and longer stays

Around 75% of the tourism sector's CO_2 emissions stem from transport, with air travel alone contributing 40%. However, the impacts of climate change and consequences of decarbonisation aviation are not evenly spread among countries. For example, in small island developing states, tourism often accounts for a relatively high proportion of national GDP, there is a high reliance on air connectivity, and higher risk from the impacts of climate change. Furthermore, given expected increases in ticket prices as aviation decarbonises, the distance of travel is likely to carry more weight in the traveller's destination choice. This demonstrates differing vulnerability stemming from decarbonising aviation for tourism destinations located in different world regions. For destinations where alternative modes of transport are feasible, government and industry should work together to shift the pattern of tourism-based trips to achieve more sustainable outcomes. This involves promoting more near-by tourism (whether domestic or arrivals from more proximate inbound international markets) where alternatives to aviation, like high-speed rail, are available. Increasing the cost and quality competitiveness of rail in comparison to air travel should be the focus, however, softer measures, like providing information to consumers on the carbon intensity of different travel options, can also help generate mode shift. For some destinations, alternative modes to aviation are not feasible due to geographic constraints, be that inaccessible land, sea, or very long distances. For countries in this position, it is important for governments to work closely with the aviation and tourism industries to do two key things 1) accelerate efforts to bring SAF use and alternative propulsion aircraft online and 2) incentivise longer stays from international inbound tourism.

Recognise that the costs of policies to decarbonise aviation are progressively distributed

The wealthiest 25% of the world's population is responsible for over 90% of aviation-related travel activity and resultant CO_2 emissions. The wealthiest 5% alone accounts for more than 55% of aviation activity and emissions, and tends to take longer trips. Globally, individuals under the median income barely participate in air travel. Policies designed to reduce aviation emissions, which typically put upward pressures on air ticket prices, inherently affect wealthier frequent flyers more than the average population, in absolute terms. The strong link between income and air travel means that the costs of such policies are progressively distributed, with higher-income groups bearing a larger share of the cost. This makes economic measures, such as carbon pricing or air taxes, potentially progressive tools in tackling emissions without unduly burdening low-income populations. This insight is corroborated by ITF modelling which indicates that when assessing the NZE scenario against the Baseline scenario for 2060, access to air travel is only marginally reduced for low-income cohorts in comparison to high-income cohorts. The issue of equity extends beyond commercial aviation to private jets, which account for around 4% of global aviation emissions but are responsible for disproportionately high environmental impacts per passenger. To address this disproportionate impact, taxes on private jet fuel and tickets (based on flight distance and aircraft weight) as well as stricter requirements to use higher shares of SAFs and, in time, transition to zero-emission aircraft (electric or hydrogen propelled), should be considered.

Ensure a just transition for the labour force as aviation decarbonises

While air passenger-kilometres are expected to grow strongly between 2024 and 2060 along with associated jobs, the demand suppression and substitution effect of decarbonisation may mean fewer direct jobs in the aviation sector than might otherwise be the case. However, this may be offset by additional job creation to scale-up SAF production which could stimulate economies around the world given the diversity of potential feedstocks. Indeed, large-scale SAF production could provide livelihoods for groups that previously did not participate in the global energy market, including rural inhabitants of middle- and low-income countries. Beyond emissions savings, countries may also see benefits of investing in SAF production to improve domestic fuel-supply resilience and national balance-of-payments positions as they move from fuel importers to exporters. However, to make decarbonisation a reality, the skills profile of jobs in the aviation sector will need to evolve. To ensure a just transition, collaboration between governments, the private sector, labour organisations, and educational institutions is essential. Skills forecasting and developing targeted re-skilling and up-skilling programmes will be required. At the global level, the aviation sector should follow a similar approach to the maritime sector by establishing an international “Aviation Just Transition Task Force”, initially focusing on developing a better understanding of the scale and nature of challenges and opportunities ahead for workers in aviation and wider supply chain. At the regional or national level, governments could consider creating “just transition” committees comprised of all key aviation sector stakeholders to undertake collective long-term workforce planning, similar to the European Commission’s “Pact for Skills” initiative.

Decarbonising aviation policies: current status

The aviation sector acknowledges that it needs to decarbonise, with industry groups and governments having pledged to reach net-zero by 2050. Representatives of the world's major aviation industry associations and largest aircraft and engine makers have done so via the 2021 "Commitment to Fly Net Zero 2050" declaration (IATA, 2021b). Meanwhile, governments have signed up to the 2022 International Civil Aviation Organization's (ICAO) long-term global aspirational goal for international aviation (ICAO, 2022). This net-zero carbon emissions goal is ambitious; reaching it will require several emission-reduction measures, including adoption of low-carbon fuels, more efficient aircraft and operations, novel propulsion technologies, carbon pricing and offsets for residual emissions (ITF, 2021b).

The sector expects most emission cuts to come from sustainable aviation fuels (SAFs). Indeed, in 2023 during the Third ICAO Conference on Aviation and Alternative Fuels (CAAF/3), ICAO and its member states agreed to a collective global aspirational vision to reduce carbon dioxide (CO_2) emissions in international aviation by 5% by 2030 through the adoption of a global framework to facilitate the scale-up of SAFs, lower carbon aviation fuels (LCAFs) and other aviation cleaner energies through harmonised regulatory foundations, supporting implementation initiatives, and improved access to financing (ICAO, 2023b). However, the cost of SAFs is much higher than that of conventional kerosene and supply remains very limited, despite growing strongly from 0.01-0.015% of global jet fuel use in 2022 to a projected 0.53% in 2024 (IATA, 2024b; ITF, 2023d). A multi-pronged approach that draws on all available decarbonisation measures and supporting policies is therefore necessary to feasibly reach ICAO's long-term global aspirational goal for international aviation of net-zero carbon emissions.

This section of the report briefly sets out the key policy options to support aviation decarbonisation and the development of technologies on the path to net-zero by 2050, as well as a non-exhaustive review of their current implementation status at both the national and international level. The scope of this report does not include non-CO_2 emissions.

Carbon pricing and market-based carbon offsetting

Carbon taxes and emissions trading schemes (ETSs), also known as cap-and-trade systems, place a price on CO_2 emissions. In theory, carbon taxes are based on marginal damage-cost estimates of emitting an additional tonne of CO_2. Based on these estimates, optimal carbon prices maximise the net benefits of CO_2 emission reductions to society. However, given the uncertainties in estimating damage costs, a wide range of values of the social cost of carbon exists, and this approach is of limited assistance to policy makers in defining actual carbon prices (Wang et al., 2019). In practice, carbon prices are often based on the abatement costs of current mitigation policies, i.e. the estimated abatement costs of the measures that should be introduced to meet a given emissions target or the near-term carbon price needed to reach climate goals (ITF, 2015; Kaufman et al., 2020). Under an ETS, carbon is priced indirectly by setting an overall emissions target for a given period of time and permitting emission trading. A corresponding number of permits or allowances is issued and auctioned. Entities reducing their emissions below their allowance level are able to sell surplus allowances to entities facing mitigation costs that are higher than the traded price of allowances. An ETS thus creates a market for carbon credits (ITF, 2021b). A carbon tax can also be implemented in parallel to an ETS to act as a price floor. Carbon taxation and ETS use different mechanisms to price carbon emissions, but both are cost-effective decarbonisation instruments (OECD, 2018). Carbon pricing incentivises emitters to introduce the abatement measures that can be implemented at a cost below the carbon price.

In the aviation sector, on the supply side, a carbon price incentivises accelerated technological innovation, fleet renewal, the use of alternative and less carbon-intensive fuels, and operational improvements including flight re-routing. However, the price signal needs to be sufficiently high to be effective. Carbon pricing also manages demand by pricing carbon externalities into airline ticket or freight costs, and it limits the "rebound effect"[1] of efficiency improvements. The design of carbon pricing instruments for aviation should be based on a life cycle accounting for CO_2 emissions. It should factor in combustion-related but also production-related CO_2 emissions for the different jet fuel options (unless they are covered already by another carbon pricing mechanism, in which case double carbon taxation should be avoided).

Both carbon taxation and ETSs can be applied globally, regionally, or domestically. A single international approach is better suited to avoid economic distortions and potentially facilitate financial flows to middle- and low-income countries for scaling key technologies like SAFs, but it would also require a sufficiently strong international agreement, which is challenging and takes time to negotiate.

Carbon offsetting is a mechanism allowing one entity to reduce its carbon footprint by paying for emissions reduction projects carried out by other entities. It is argued that offsets are a valuable interim measure in hard-to-abate sectors, such as aviation, by allowing for emission reductions at a lower cost. Under effective programme design rules and robust sustainability criteria, carbon-offsetting projects can also generate co-benefits that contribute to several UN Sustainable Development Goals, like alleviating poverty and preserving biodiversity (Cames, 2016; ITF, 2021b).

Current implementation status

At the global level, in 2016 ICAO agreed a resolution to establish a global market-based measure to address CO_2 emissions from international aviation – the Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA). CORSIA aims to stabilise CO_2 emissions at 85% of 2019 levels by requiring airlines to offset growth above this level by purchasing "eligible emissions units" generated by projects that reduce emissions in other sectors. CORSIA allows aircraft operators to reduce their offsetting requirements through the use of "CORSIA eligible fuels", which include SAFs and lower carbon aviation fuels, with emissions reductions calculated on a lifecycle basis. To aid implementation, CORSIA requires airlines to monitor, report and verify emissions on international routes. Domestic flights are out of scope and exemptions apply for least developed countries, small island states, landlocked developing countries, small operators and aircraft, and flights with a public purpose. CORSIA is being implemented in three phases: a pilot phase (2021-2023), a first phase (2024-2026), and a second phase (2027-2035). Participation is voluntary for the first two phases (2021-2026). From 2027 onwards, participation will be determined based on 2018 Revenue Tonne Kilometre (RKT)[2] data, and to be enforced will require countries to pass national legislation to ratify CORSIA. CORSIA will cover all states with an individual share of 2018 RTKs higher than 0.5% of total RTKs or whose cumulative share in the list of states from the highest to the lowest amount of RTKs reaches 90 per cent of total RTKs. As of 2024, 126 states are participating in CORSIA, with two more having announced their intention to participate from 2025, bringing the total number to 128 (ICAO, 2024). CORSIA currently would allow for relatively affordable carbon offsets (~3-15 USD/tCO_2), raising uncertainties regarding real-world carbon abatement potential of the framework.

[1] For a definition of "rebound effect", see under "Operational improvements" later in this section.
[2] One RTK is generated when a metric tonne of revenue load is carried one kilometre.

At the regional level, the EU ETS is currently the only international carbon pricing mechanism for international air transport. The EU ETS is a cap-and-trade mechanism that sets an annual decreasing emissions target and issues emission allowances to regulated entities. Entities receive or buy credits through auctions and trade allowances with one another to comply with the target. Companies emitting below their allowance level trade surplus allowances with companies emitting above their allowance level. Direct CO_2 (tank-to-wake) emissions from intra-European Economic Area (EEA) flights have been included in the EU ETS since 2012. This accounts for flights between the EU member states, Iceland, Norway, and Liechtenstein (departing flights to Switzerland and the United Kingdom are also included). Under the EU ETS, aviation contributed to reducing 160 million tonnes of carbon in other sectors during the third trading period (2013-2020), with over 99.5% of aviation emissions covered by the trade of allowances (European Union Aviation Safety Agency, 2022). The original legislation adopted in 2008 was designed to apply to all flights arriving at and departing from EEA airports; however, in 2012, the EU agreed to exclude extra-EEA flights to facilitate CORSIA negotiations. Following the launch of CORSIA, in 2021 the exclusion of extra-EEA flights, known as the “stop the clock” measure, was extended until the start of 2027, with the European Commission set to carry out an assessment by mid-2026 on whether further carbon mitigation action is required that could extend the scope of the EU ETS to flights departing the EEA, exempting incoming flights. Alternatively, if CORSIA participation and implementation are strengthened, the EU ETS aviation scope could remain focused on intra-EEA flights only, with CORSIA applying to flights departing or arriving at EEA airports (European Commission, 2024c). 2021 also saw other revisions to the EU ETS Directive on aviation with the gradual phase-out of free emissions allowances by 2026 - with a decrease of 25% in 2024 followed by a 50% reduction in 2025. Furthermore, the funds obtained via 20 million allowances (EUR 1.6 bn at an allowance price of EUR 80) have been reserved to cover some, or all, of the price gap between conventional fossil fuels and eligible alternative aviation fuels used from January 2024. The value of 5 million allowances will also be added to the EU Innovation Fund, which airlines and airports can access to support the decarbonisation of the sector, including through electrification of aviation.

At the national level, most governments currently exempt jet fuel used on international routes from tax. Taxing jet fuel for international flights would require the amendment of Air Service Agreements between countries, which often raises concerns of carbon leakage or reduced competitiveness for firms operating in jurisdictions subject to the tax (International Carbon Action Partnership, 2020). While there are fewer obstacles to taxing jet fuel used on domestic routes, few countries apply either a carbon or fuel excise tax. Countries which do include Argentina, Armenia, Australia, Canada, India, Ireland, Japan, Norway, Myanmar, Saudi Arabia, Switzerland, Philippines, Thailand, Vietnam and the United States (OECD, 2019). Tax rates vary by country and also – namely for the United States – by State. Domestic aviation is included in the ETSs of New Zealand and South Korea, while Shanghai’s ETS is the first among eight Chinese ETS pilots to include aviation (Asian Development Bank, 2018; Ministry for the Environment New Zealand, 2019; World Bank Group, 2024).

Ticket taxes

Ticket taxes are levied on origin-destination passengers departing from an airport on the levying jurisdiction’s territory, as a percentage of the airfare or at a flat rate. The rate tends to be distance- or region-based. Other potential differentiation factors include age, class of travel, and for specific airports. Exemptions can apply to remote territories, children under a certain age, and domestic or connecting flights. As with fuel taxes, carbon leakage and competitiveness risks are possible depending on the circumstance. While ticket taxes may or may not be intended as environmental measures, they affect the cost of travel and hence can influence demand for air travel.

Current implementation status

Many countries levy ticket taxes for revenue-raising or emissions mitigation purposes. The UK's Air Passenger Duty, levied on all UK-departing flights since 1994, raises revenue from aviation with rates varying depending on distance and class of travel (Seely, 2019; UK Government, 2020). The French government started levying an "ecotax" on all flights departing its territory in 2019, in an attempt to address a rising sentiment of fiscal injustice among citizens regarding air transport and to finance sustainable infrastructure projects, notably in the rail sector (Public Sénat, 2019). Switzerland has also introduced a ticket tax on all flights (excluding transit) departing its territory. A share of the revenue from Swiss environmental taxes, including those from the air ticket tax, will go to a national climate fund financing emissions abatement initiatives (Ambassade de France en Suisse, 2020). Singapore has introduced a SAF levy paid by passengers based on class and distance with funds raised used to purchase SAF for distribution at Changi airport (Civil Aviation Authority of Singapore, 2024). Other countries, including Australia, Austria, Germany, Italy, Japan, Norway, Sweden and the United States, have similar revenue-raising taxes in place (CE Delft, 2019; Faber, 2018).

Low-carbon fuel standards and fuel-blending mandates for SAF

Low-carbon fuel standards (LCFSs) support the deployment of alternative fuels. They decrease the carbon intensity of fuel by setting a decreasing lifecycle-based carbon intensity target for fuel sold in the jurisdiction and allow fuel suppliers or companies producing, importing, distributing or selling fuel to trade credits to achieve the target. Fuel-blending mandates are an alternative policy instrument to reduce the carbon intensity of fuel and work by requiring blending by volume or energy content.

Current implementation status

LCFSs originated in California (USA) and are now also in place in Oregon (USA), Washington (USA) and British Columbia (Canada). In 2023 British Columbia amended its LCFS to include a SAFs fuel-blending volume sub-target of 1% in 2028, 2% in 2029, and 3% in 2030 and subsequent compliance periods (Government of British Colombia, 2024). Brazil's RenovaBio policy and Canada's proposed nationwide Clean Fuel Standard both draw from a LCFS approach (Agência Nacional do Petróleo Gás Natural e Biocombustíveis, 2020; Murphy, 2020). The US Congress has also expressed interest in a nationwide LCFS (Select Committee on the Climate Crisis, 2020).

An increasing number of jurisdictions have either implemented or are considering implementing fuel-blending mandates. In 2021, as part of the "Fit for 55" package of emissions reduction targets, the EU set out the aforementioned "ReFuelEU Aviation" regulation, which replaces any national member state mandates and requires a gradual increase of the share of SAFs blended into conventional jet fuel supplied at EU airports, with financial penalties for non-compliance equal to twice the cost of fossil kerosene. The definition of SAFs is set out in Article 3(7) of the regulation and includes synthetic aviation fuels, advanced and other aviation biofuels, as well as recycled-carbon aviation fuels. The measure requires (regardless of the carrier and destination of the flights) a 2% share of SAFs at EU airports from 2025, 6% in 2030, 20% in 2035, 34% in 2040, 42% in 2045, and 70% by 2050. It also includes a sub-mandate for synthetic aviation fuels, increasing from 1.2% in 2030 to 35% by 2050. Furthermore, aircraft operators departing from EU airports are required to take on fuel necessary to operate the flight to mitigate carbon leakage by avoiding so-called "tankering"[3] practices (European Commission, 2024d). Norway has a 2% mandate from 2023, with an ambition of 30% by 2030, although it may yet align with ReFuelEU targets.

In 2024, the UK announced plans to set a SAFs mandate starting in 2025 at 2% of total UK jet fuel demand, increasing to 10% by 2030, then 22% in 2040. The mandate also puts a cap on SAFs from the hydroprocessed esters and fatty acids (HEFA) process at 71% in 2030, and 35% in 2040, as well as a separate obligation on power-to-liquid fuels from 2028 that reaches 3.5% of total jet fuel demand in 2040. In addition, the mandate will include a buy-out mechanism for both the main and power-to-liquid obligations to incentivise supply while protecting consumers where suppliers are unable to secure a supply of SAFs (UK Department for Transport, 2024).

Also in 2024, South Korea announced it will introduce a 1% SAFs blend mandate for all departing international flights from 2027, accompanied by regulatory reform to make it easier for local fuel refiners to use waste plastic pyrolysis oil, waste lubricants and biomass in the refining process as well as waste cooking oil and food waste as feedstock for biofuel production (S&P Global, 2024). Similarly, Singapore introduced a SAF fuel blending target for departing flights in 2024, starting at 1% SAF from 2026, with a goal to increase this to 3-5% by 2030, subject to global developments and the wider availability and adoption of SAFs (Civil Aviation Authority of Singapore, 2024).

Several other countries are considering introducing SAFs fuel-blending mandates with various targets including China (10% in 2035), India (1% in 2027, 2% in 2028, and 5% in 2030), Indonesia (1% from 2027, 2.5% by 2030, 12.5% by 2040, 30% by 2050, and 50% by 2060), Japan (10% by 2030), Malaysia (1% from 2027), Thailand (1% from 2027), Türkiye (1% in 2025/26 increasing to 5% by 2030), the UAE (1% by 2031), and Australia (TBC) (ATAG, 2024). While not a fuel-blending mandate, in 2024 Brazil introduced a SAFs use mandate starting in 2027 which aims to reduce GHG emissions from domestic flights by 1% initially, scaling to a 10% reduction by 2037 (Brazilian Government, 2024).

Financial incentives to scale SAF production

In addition to carbon pricing and setting fuel standards or mandates for SAF uptake, governments can implement several measures to help incentivise the scale-up of SAF production. These include creating tax incentives, using public finance (for example via loans, guarantees, credit enhancement, or equity investments), and steering private finance flows (via bonds or other financial instruments and inclusion of SAF in green investment taxonomies).

Current implementation status

In the USA, the Inflation Reduction Act of 2022 includes a two-year tax credit for those who blend SAF, a subsequent three-year tax credit for SAF producers, and a grant program of USD 290 million over four years to carry out projects that produce, transport, blend or store SAF, or that develop, demonstrate, or apply low-emission aviation technologies. To be eligible, the SAF must achieve at least a 50% improvement in greenhouse gas (GHG) emissions performance on a life-cycle basis as compared with conventional jet fuel. The tax credit starts at USD 1.25 per gallon and increases with every percentage point of improvement in life-cycle emissions performance up to a cap of USD 1.75 per gallon (U.S. Department of Energy, 2022).

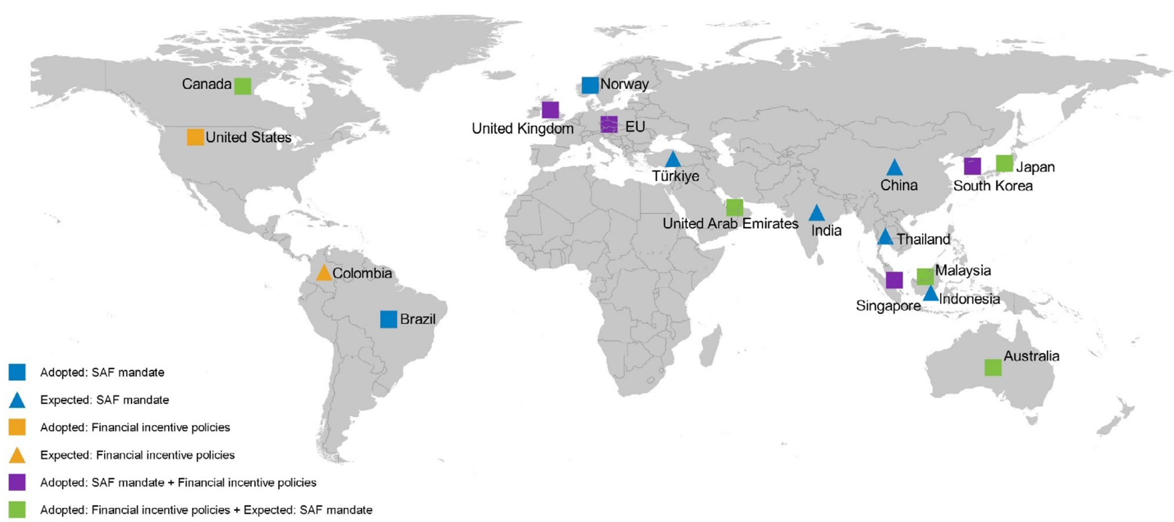
[3] *Tankering* refers to a practice whereby an aircraft carries more fuel than required in order to reduce or avoid refuelling at the destination airport for subsequent flight(s), for operation reasons or to save money when the cost of fuel at the departure airport is significantly lower than at the destination airport.

In the EU, ReFuelEU Aviation sets out flanking measures including financing to de-risk SAF production at all stages of technology maturity, particularly through various instruments like "Horizon Europe", the "Innovation Fund" and "InvestEU", as well as individual member country support provided it complies with EU guidelines on state aid for climate, environmental protection and energy. The Taxonomy Regulation of 2020 includes aviation as a sustainable investment class to facilitate access to private investment for SAF production and uptake, including through EU green bonds, and the EU's Net Zero Act facilitates investment through removing administrative barriers for construction of new SAF plants (European Commission, 2024d).

Elsewhere, the United Kingdom (UK) has rolled out an "Advanced Fuel Fund" of GBP 135 million for the development of SAF production facilities and is considering implementing a revenue certainty mechanism (Department for Transport, 2024a, 2024b). As part of its 2024 "SAF Expansion Strategy", South Korea will introduce tax breaks and other incentives for domestic refiners to invest in SAFs and lower production costs (S&P Global, 2024). Japan's Green Transformation for the Environment and Technology (GTET) Act offers USD 2.2 billion over five years from 2024 and Australia has established an innovation fund worth AUD 1.7 billion over 10 years, both to support SAF production. Malaysia and the United Arab Emirates (UAE) have some support measures in place and are considering going further, while other countries, like Colombia, are considering introducing SAF specific incentives.

Figure 1 summarises the current state of both fuel mandates and financial incentive policies designed to scale the production and use of SAFs around the world in 2024.

Figure 1. SAF specific policies around the world, 2024



Source: Author's own elaboration building on data from (ATAG, 2024; IATA, 2024a)

Research and Development funds

Multiple governments around the world have established research and development funds aimed at accelerating the deployment of alternative propulsion technologies for aviation. Several manufacturers are working on both hydrogen- and electric-powered aircraft; however, due to current technological and cost limitations, they are only likely to be viable for short- to medium-haul, rather than long-haul, flights before 2050 (ITF, 2023b).

Current implementation status

In the USA, USD 33 million in funding has been provided for two Advanced Research Projects Agency-Energy (ARPA-E) programmes: Aviation class Synergistically Cooled Electric-motors with iNtegrated Drives (ASCEND) and Range Extenders for Electric Aviation with Low Carbon and High Efficiency (REEACH). These programmes aim to reduce energy use and CO_2 emissions from commercial aircraft through electrification (Department of Energy, 2020). In the EU, funding can be channelled to alternative propulsion system research through the "Horizon Europe" and "Innovation Fund", including via the reallocation of EU ETS allowances. There are also prominent public-private research initiatives, including the SESAR 3 Joint Undertaking which was set up to accelerate up-take of cutting-edge digital air traffic management technologies, and the Clean Aviation Joint Undertaking focused on reducing aircraft emissions and noise. Individual member states have also taken action. For example, France allocated EUR 1.5 billion over a three-year period (2020-2023) to support research and development in the aviation sector as part of a broader support package following the Covid-19 pandemic (Gouvernement Francais, 2020). The German Federal Ministry for Economic Affairs and Energy (BMWi) sponsors research within the framework of the Aviation Research Programme of the Federal Government (LuFo), with aims including maintaining and improving public acceptance of aviation by reducing pollutant and noise emissions (German Federal Ministry for Economic Affairs and Energy, 2018). Other jurisdictions have set ambitious goals for uptake of alternative propulsion systems, including Norway, whose state-owned airport operator Avinor, supported by government and industry partners, has set a target of all domestic flights being electric by 2040. The first fully battery-electric domestic flights in Norway are expected to operate by 2030 (Avinor and Luftfartstilsynet, 2020).

Operational improvements

Improving the efficiency of airspace management and airport operations can reduce CO_2 emissions for flights. Due to a wide array of different factors, routes flown by aircraft are never a perfect fit with the shortest path possible, and inefficiencies on the ground can cause delays in take-off and landing, leading to excess fuel burn. Airports, air navigation service providers, airlines and other aviation stakeholders are already taking co-ordinated action to make air transport operations as efficient as possible and to mitigate indirect emissions linked to airport operations and surface access. Airlines are undertaking similar optimisation efforts, primarily due to economic drivers, to maximise the share of available seats in use on board each aircraft. However, reducing operating costs can also stimulate demand if savings are passed through to ticket prices, resulting in potentially lower overall energy-efficiency savings - a phenomenon known as the rebound effect. This effect may be less pronounced in the future as a result of additional costs associated with decarbonisation.

Current implementation status

Global average load factors rose from 75% in 2005 to 82% in 2019, which resulted in non-negligible reductions in the direct CO_2 emissions per unit of air transport activity (ICAO, 2019; Statista, 2023). Better operational efficiencies also contributed to lower CO_2 emission intensity of air travel. The scale of the reductions in direct CO_2 emissions per unit of activity imputable to air traffic management improvements may be similar. The IPCC had projected a 6% to 12% fuel burn reduction by 2020, with an expectation that the full potential available would have been exploited in this timeframe; however, further efficiency improvements continued after 2020 (IPCC, 1999). On the ground, emissions under airport control account for around 5% of total aviation CO_2 (ACI, 2017). Pooling responsibility for air traffic control between countries can support more direct flight paths – an approach currently being explored in the EU, where doing so could reduce fuel use by 9-11% (Eurocontrol, 2020).

Substituting high-speed rail for aviation and enhancing multimodality

Decarbonising transport requires a global shift towards the most energy-efficient transport modes. Shifting short-haul air transport to rail and high-speed rail (HSR), where rail alternatives exist, can significantly reduce transport sector emissions on routes with high demand. HSR operational energy use per passenger kilometre is around 10% that of air transport at high load factors, and low-carbon electricity from renewables and nuclear energy can be used to power HSR, if available (ITF, 2021b). However, to offset the CO_2 emissions from the construction of HSR infrastructure, significant traffic volumes of around 10 million annual passengers per route are needed, and most of the traffic diverted to HSR must come from air transport (Westin & Kågeson, 2012). The overall net impact on CO2 emissions over time of building an HSR line needs to be considered before the investment is made (Kortazar et al., 2021). In markets with rail infrastructure supporting high-load factors, HSR is considered a competitive substitute for air transport on routes with comparable travel time, generally for distances under 700-1000 kilometres.

Current implementation status

The opening of an HSR corridor on some routes of a length of 700-1000 kilometres has more than halved air transport’s modal share (e.g. Paris-Lyon, Madrid-Seville, Brussels-London and Wuhan-Guangzhou (IEA and UIC, 2017). To spur further mode shift, in 2023 France introduced a short-haul flight ban between cities linked by a train journey of less than 2.5 hours, with Spain considering a similar policy, while Germany increased taxes on domestic and intra-European flights by 75% in 2020. In Japan, the Shinkansen’s market share is always higher than that of air transport on routes under 965 kilometres (Albalate, 2012). In China, the immediate years following introduction of HSR led to a reduction of 28% in air travel demand between 2010 and 2013 and a 10% decrease in monthly departures over the longer term, 2011-2016 (Zhang et al., 2017; Zhu et al., 2020).

Projecting aviation demand and CO_2 emissions under different policy scenarios

Air transport has experienced remarkable traffic growth over the more than 100 years it has provided commercial services. Historically, global air travel has doubled every 15 years (ATAG, 2020). While this metric offers insight into past trends, it is not necessarily directly linked to air travel future growth. However, the projected continuous growth in GDP per capita and population, particularly in developing economies, suggests that, under the current paradigm, demand for air travel is set to keep growing steadily as access to travel and tourism continues to increase.

In 2022 ICAO, which governs global civil aviation, agreed to a long-term aspirational goal of achieving net-zero CO_2 emissions from international aviation by 2050 (ICAO, 2021). Significant uncertainty remains about the feasibility of achieving this goal. Challenges such as regulatory complexity in a global industry, the lack of available solutions at scale, and the substantial investment required may hinder the ability of aviation to reach ICAO's goal by 2050. While there are notable discrepancies among industry stakeholders, researchers, and policymakers regarding their assessment of the likelihood of achieving net-zero emissions in aviation, there is broader consensus on the policy measures and technological developments necessary to facilitate the transition to decarbonised aviation. A combination of policy incentives and mandates will be essential to improve operational efficiency, support aircraft technological advancements, and promote the production of SAFs. Effective governance and enforcement of regulatory policies will play a key role in determining the outcome of the decarbonisation efforts and the ability to achieve the net-zero aviation goal.

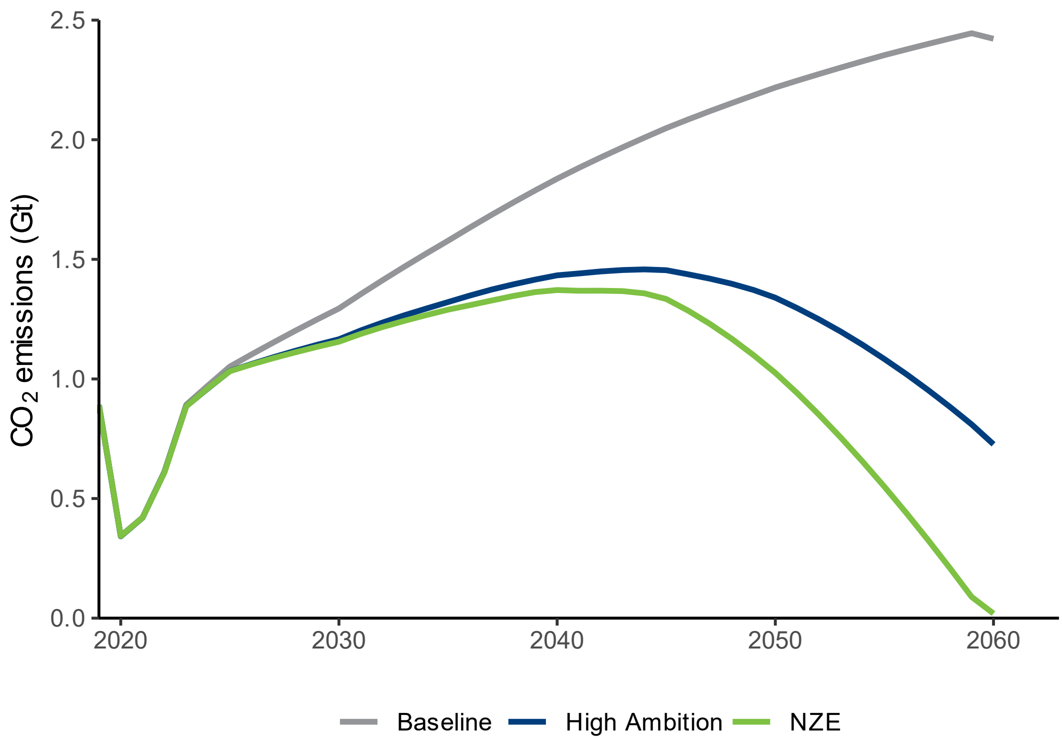
This section of the report lays out the projected impacts of the main policy measures discussed in the previous section on aviation demand and CO_2 emissions through to 2060. The scope of this analysis is limited to tank-to-wake (TTW) CO_2 emissions and does not account for non-CO_2 effects generated by air transport that also contribute to global warming. It presents air transport activity and CO_2 emissions projections from 2019 to 2060 for three scenarios developed by the ITF and aligned with the scenario design included in the forthcoming *ITF Transport Outlook 2025* (ITF, 2025). The extension of the timeframe of analysis from 2050 to 2060 allows for the potential significant adoption of new liquid fuels and technologies – which, even if deployed at an unprecedent speed, are currently unlikely to show sufficient scale to decarbonise the sector by 2050. Three scenarios are examined:

- Baseline scenario: A continuation of the status quo, where only policies that are already adopted are reflected.
- High Ambition scenario: Co-ordinated efforts of governments, international regulators and the industry to heavily reduce aviation's CO_2 emissions.
- Net Zero Emissions scenario (NZE): Further policy interventions that lead to a widespread adoption of SAFs and allow the aviation sector to reach net-zero tailpipe emissions by 2060.

The goal of this section is to assess the extent to which measures can reduce CO_2 emissions. The three scenarios are each built around different levels of implementation of policy measures and are only meant to represent plausible futures. They assume the same population and income growth trends (ITF, 2023a). The differences in demand, energy and emissions projections in the scenarios stem from differences in the level of implementation of policy measures.

Figure 2 shows the projections of CO_2 emissions from global international and domestic passenger aviation to 2060. Under the Baseline scenario, emissions are set to continue increasing as demand grows and the adopted policies are insufficient to decouple demand and CO_2 emissions growth. Under the High Ambition scenario, emissions peak in 2040, then fall by 20% towards 2060 relative to the 2019 level. The NZE scenario shows that reaching net-zero aviation by 2060 is within reach, although this entails the immediate need to globally adopt very ambitious policies that support widespread adoption of SAFs.

Figure 2. Global tailpipe GHG emissions from aviation to 2060, by scenario



Note: Figure depicts ITF modelled estimates. Baseline, High Ambition and Net Zero Emissions (NZE) refer to the three scenarios modelled, which represent three levels of ambition for decarbonising aviation. Trajectories shown are on a tank-to-wake basis.

Modelling the impact of different policy scenarios on aviation demand and emissions

Parameters that affect demand and emissions projections

Projections of aviation CO_2 emissions rely on the ITF Non-urban passenger transport model from ITF's Policy Ambitions and Sustainable Transport Assessment (PASTA) modelling framework (ITF, 2023a). It is a global multimodal model that represents intercity (domestic and international) passenger travel activity between 1,191 centroids[4] distributed across the world and enables the assessment of the evolution of travel activity and emissions under different policy scenarios. Each centroid is associated with a city-

[4] *Centroids*, connected by network links, represent zones (countries or their administrative units) where goods are consumed or produced.

airport. All large and medium-sized airports with international operating codes as classified by IATA (IATA, 2019) are represented, and later clustered to a city-airport where several airports exist within the same city or within 100 kilometres inside the same country. The four-step transport modelling framework used to represent aviation demand and emissions is summarised in (ITF, 2023a).

Broadly speaking, CO_2 emissions (G) are dependent on the level of travel activity (A) in passenger-kilometres; the modal share composition (S); the energy intensity of each mode (I), in megajoules (MJ) per passenger-kilometre (pkm); and the fuel's carbon intensity (F), in grams of carbon per MJ of energy consumed. The relationship between these parameters is represented mathematically by the "ASIF" equation (Schipper & Marie-Lilliu, 1999), as illustrated in Figure 3. The ITF Non-urban passenger transport model follows a bottom-up approach that assesses each of these components for every centroid from 2015 to 2060 on an evolving global transport network.

Figure 3. ASIF equation for CO_2 emissions

$$G = A * S * I * F$$

G	A	S	I	F
CO_2 emissions	Travel activity	Modal share composition	Modal energy intensity	Fuels carbon intensity

Source: Adapted from (Schipper et al., 2000)

The four parameters shown can be described as follows:

- A - Passenger travel activity depends on trip generation. Trip generation is mainly dependent on GDP and population growth and influenced also by tourism attraction as well as changes in costs and ticket prices. Scenario measures that directly target changes in passengers' behaviour (such as teleconferencing) have a lesser impact on trip generation. Passenger travel activity measured in passenger-kilometres also depends on the destination and routing choice, i.e. how many kilometres are travelled per trip.
- S - Modal share composition represents the share of total travel by mode. As the energy and carbon intensity of different modes varies considerably, shifts in travel from one mode to another have an important impact on overall emissions. Mode choices are mainly affected by the availability of transport modes, travel time and prices associated with modes available. Regulatory policies (e.g. carbon pricing or ticket taxes) and technological developments or improvements (e.g. aviation clean fuels and aircrafts or upgrading railways operations and multimodal integration) that affect time and pricing of the mode alternatives, as well as the development of new infrastructure that creates new available transport modes (e.g. the creation of high-speed rail connections) affect the mode share composition.
- I - The modal energy intensity of each mode, measured in MJ per passenger-kilometre, is linked to vehicle technology and operations efficiency. For aviation, the aircraft fleet is globally defined, and its energy efficiency evolves over time depending on the energy efficiency improvement of new aircraft entering the fleet and operations improvements (such as air traffic management systems or increases in capacity utilisation of airplanes) defined under each scenario.
- F - The fuels carbon intensity is the combination of the specific carbon intensity of the fuel combined with the blend-in share. It is defined by the number of grams of CO_2 emitted per MJ of energy consumed. For aviation fuels, the adoption rates of SAFs considered within the different

policy scenarios directly affect the fuel carbon intensity. Moreover, the development of new technologies for zero-emission aircraft and their use will also impact the carbon intensity in routes operated with this new aircraft.

Although policy measures included in the modelling are mainly linked to one of the ASIF components, there are rebound effects to other components. For example, the adoption of SAFs and zero-emission aircraft will impact costs that will ultimately increase ticket prices. This increase will impact air travel activity, either by affecting the travel activity itself (activity suppression due to higher costs) or by affecting the modal share composition (shift to an alternative transport mode due to an increase in air transport costs).

Policy measures considered in each scenario

The projections of air travel activity and emissions reflect the impact of various policy measures implemented across the modelled scenarios. These policy measures differ by world region, with varying implementation timelines and levels of deployment based on each region's commitment to decarbonise aviation. Countries are grouped into three world regions (Europe, Other OECD countries + China, and Other countries) representing leaders and followers of this transition. Table 1 outlines the assumptions for the implementation of each policy measure under each scenario.

Table 1. Policy measures implementation by scenario

	Baseline Scenario			High Ambition Scenario			Net Zero Scenario		
	Europe	Other OECD + China	Other	Europe	Other OECD + China	Other	Europe	Other OECD + China	Other
Energy intensity MJ/pkm (annual % improvement for new aircraft) 2019-2060	1.1			1.3			1.3		
Carbon price (USD/tCO_2)									
2030	92 / 0*	0	0	125	125	96	200	200	200
2060	120 / 0*	0	0	300	300	200	400	400	400
SAF adoption (%)									
2030	6 / 0*	0	0	8	8	0	8	8	0
2060	63 / 0*	0	0	84	58	10	100	100	100
SAF to kerosene cost ratio									
2030	2.1	-	-	2.1	3.3	-	2.1	3.3	-
2060	1.9	-	-	1.9	2 .3	2.3	1.8	2.3	2.3
Electric aviation (% pkm)									
2030	0				0			0	
2060	0				0.7			0.7	

	Baseline Scenario			High Ambition Scenario			Net Zero Scenario		
	Europe	Other OECD + China	Other	Europe	Other OECD + China	Other	Europe	Other OECD + China	Other
Hydrogen aviation (% pkm)									
2030	0			0				0	
2060	0			6.5				6.5	
Air ticket taxes (% of airfare)									
2030	5	3.5	2	10	10	6.5	10	10	6.5
2060	20	13	7.5	40	40	21	40	40	21
Development of HSR									
2030	0	1	0	0	1	0	0	1	0
2060	1	1	0	2	2	1	2	2	1
Multimodality									
2030	0	0	0	1	1	0	1	1	0
2060	0	0	0	1	1	0	1	1	0
Teleconferencing (% reduction pkm by 2060 High Ambition vs Baseline)	0	0	0	7.5	7.5	0	7.5	7.5	0

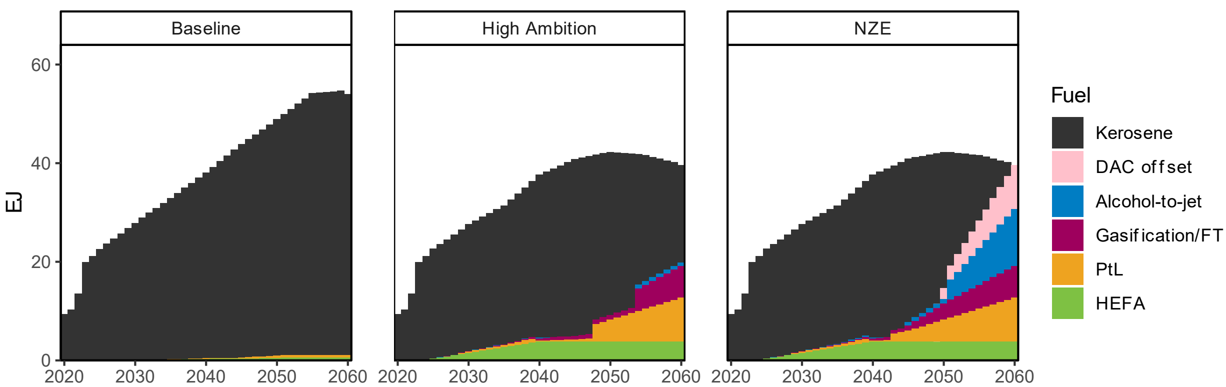
* Value adopted for intra-European flights / Value adopted for flights that start in Europe and end outside Europe.

Notes: For Multimodality, a value of 1 represents that multimodal integration hubs are extensively developed. This considers the integration of rail and bus services within airports creating in this way seamless transfers. Development of high speed rail (HSR) takes a value of 0, 1 or 2 depending on the number of new HSR connections created. The modelling approach that defines the development of new HSR connections is detailed in a forthcoming publication - (ITF, 2025). The Baseline scenario includes future HSR plans registered by the International Union of Railways (UIC, 2023) while the High Ambition and NZE scenarios include more ambitious rail development plans from 2030 onwards.

Figure 4 shows the modelled fuel consumption in each scenario (a full methodology is included in Appendix A). Within the ITF fuel choice model, each region chooses to adopt the lowest-cost fuel, accounting for policy effects such as financial incentives and penalties for non-compliance. In the Baseline scenario there is a limited adoption of SAFs into global fuel demand and kerosene remains the default option. There have been several important announcements and initiatives involving targets for SAFs blending around the world; however, only a limited number include the necessary financial conditions to lead to widespread adoption. The European Union ReFuelEU regulation includes targets for SAF adoption, along with financial penalties for non-compliance (see Annex A for more information). However, these are currently limited to intra-European flights (roughly 45% of European aviation demand). The financial penalties for non-compliance would be sufficient to meet these targets and therefore lead to adoption of SAF in intra-European flights. The Inflation Reduction Act (IRA) in the USA provides financial incentives for the production of aviation fuels, including tax credits for hydrogen and biofuels. However, these are currently valid until 2027 and are not expected to be sufficient on their own to lead to cost parity of alternative fuels with conventional kerosene.

In the High Ambition scenario, higher carbon pricing (or policies that provide equivalent market signals) lead to significantly higher adoption of alternative fuels. Tax credits in the IRA are assumed to be extended for an additional decade in the USA, and the scope of ReFuelEU is assumed to cover all flights departing from Europe. These conditions provide the financial certainty necessary for fuel producers and consumers to adopt a variety of fuels. HEFA fuels, which are the most cost-competitive, have the most significant early adoption until limitations on their sustainable supply are met. Other bio-based fuels, such as alcohol-to-jet and gasification/Fischer Tropsch fuels, are adopted when carbon prices are sufficiently high, until they too are exhausted. Reaching net zero (tank-to-wake) emissions by 2060 would require even higher effective carbon prices to send sufficient price signals for market adoption. Fuels produced using sustainable biomass as a feedstock are unlikely to be sufficient to cover the entirety of global fuel demand. Reaching such high ambitions would therefore require the adoption of carbon-based power-to-liquid fuels or direct air capture offsets, both of which are expensive and unproven at significant scale. All of these fuels would have to be deployed at an unprecedented speed. This extremely ambitious speed of deployment means the ITF Net Zero Emissions (NZE) by 2060 scenario for aviation differs from the ICAO long term aspirational goal (LTAG) for 2050.

Figure 4. Aviation fuel consumption in each scenario

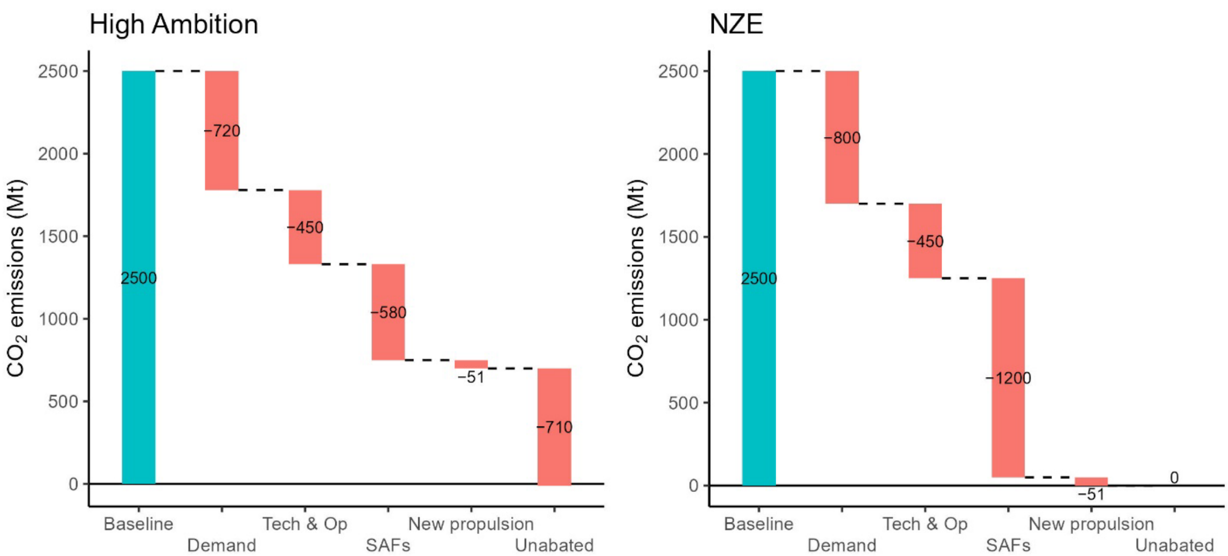


Notes: DAC = Direct Air Capture, FT = Fischer-Tropsch, PtL = Power-to-liquid, HEFA = Hydrotreated Esters and Fatty Acids. Figure depicts ITF modelled estimates. Baseline, High Ambition and Net Zero Emissions (NZE) refer to the three scenarios modelled, which represent three levels of ambition for decarbonising aviation. Full details of model methodology included in Annex A.

The impact of decarbonising aviation on global demand and emissions

The High Ambition scenario shows a decrease of 72% in CO_2 emissions by 2060 compared to the Baseline scenario, while the NZE scenario shows a decrease of 100%. Figure 5 presents the contribution of each of the implemented policy measures within these scenarios toward reducing emissions. It presents total TTW CO_2 emissions in 2060 under the Baseline scenario and the contribution of each group of policies to reach 2060 projected emissions under the High Ambition and NZE scenarios, respectively. The main contributions to emissions reduction come from demand suppression and the adoption of SAFs. Demand suppression is triggered by the increase of air ticket prices (due to SAFs adoption, carbon pricing and increased air taxes), the shift to alternative modes such as high-speed rail, and travel behavioural changes associated with teleconferencing. The reduction of the energy intensity due to technological and operational improvements, and the use of zero-emission aircraft also contribute to the overall emissions reduction. Under the High Ambition policy scenario, by 2060 the unabated CO_2 emissions are still high, confirming that the level of implementation of policies considered under this scenario is not sufficient to reach the aspirational goal of net-zero aviation. In contrast, under the ITF's NZE aviation scenario, aviation tailpipe emissions decline to zero by 2060.

Figure 5. CO_2 emissions reduction from the different policies in 2060 under the High Ambition and Net Zero Emissions aviation scenarios

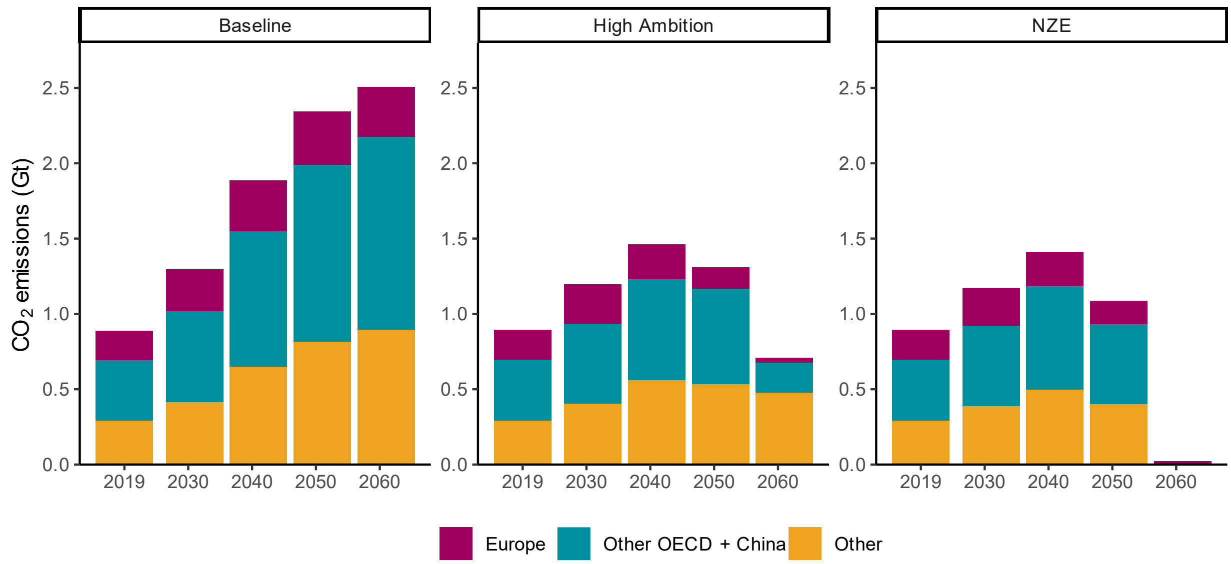


Note: Figure depicts ITF modelled estimates. Baseline, High Ambition and Net Zero Emissions (NZE) refer to the three scenarios modelled, which represent three levels of ambition for decarbonising aviation.

Considerable differences exist between the world regions in terms of air transport demand and related CO_2 emissions. At present, the OECD countries + China represent 67% of global aviation passenger demand and emissions (Figure 6 and 7). Under the current growth paradigm reflected in the Baseline scenario, the contribution of these countries to global aviation demand and emissions only declines to 64% by 2060. However, under a High Ambition scenario where stricter policies are enforced, OECD + China countries decouple demand from emissions growth, reducing their contribution to total aviation emissions in 2060 to 32%.

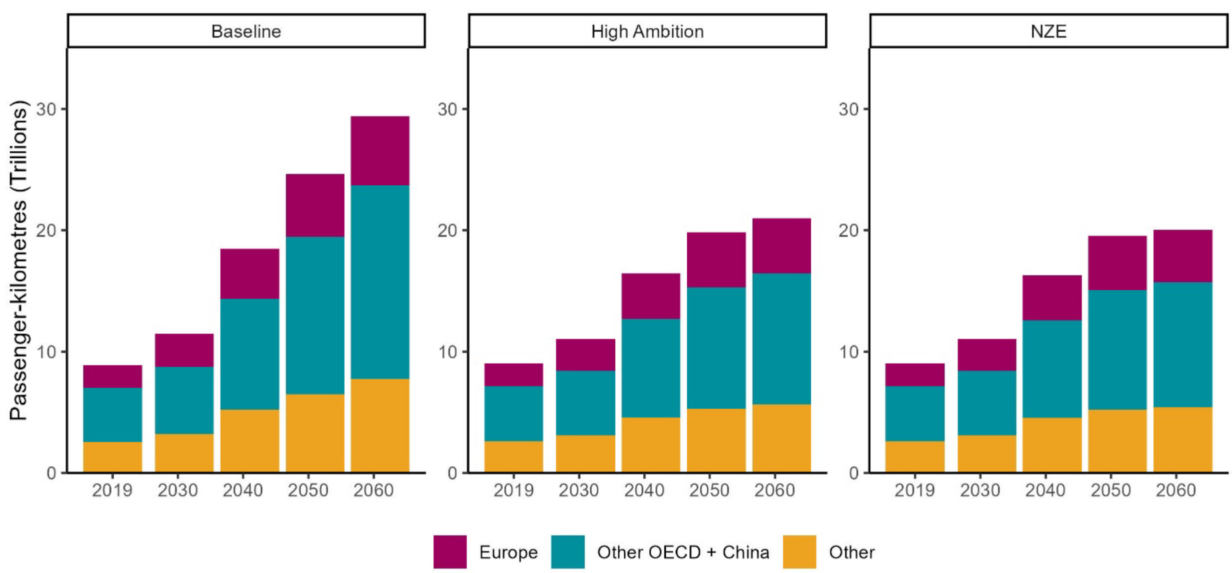
Global demand for aviation increases by 3.2 times between 2019 and 2060 under the Baseline scenario and by 2.3 and 2.2 times under the High Ambition and NZE scenarios, respectively (Figure 7). A decrease of 28% and 32% in the total projected growth of air transport demand for 2060 is observed in the High Ambition and NZE scenarios compared to the Baseline scenario. This difference between scenarios is triggered by the full set of policy measures considered within the scenarios: increases in air ticket prices, mode shift to alternative transport modes and changes in passengers' travel behaviour.

Figure 6. Air transport CO_2 emissions by world region



Note: Figure depicts ITF modelled estimates. Baseline, High Ambition and Net Zero Emissions (NZE) refer to the three scenarios modelled, which represent three levels of ambition for decarbonising aviation.

Figure 7. Air transport demand by world region



Note: Figure depicts ITF modelled estimates. Baseline, High Ambition and Net Zero Emissions (NZE) refer to the three scenarios modelled, which represent three levels of ambition for decarbonising aviation.

The broader impacts of decarbonising aviation

Air transport plays an important role in fostering social and economic development, and it is expected to continue growing. Unfortunately, this freedom of transport movement comes with a cost: its associated CO_2 emissions and warming effects have severe consequences for the climate. Although decarbonising aviation is extremely challenging and will require decades of globally co-ordinated, efficient and effective policies, it remains reachable, as demonstrated in the NZE scenario. The adoption of cleaner fuels, the development of new zero-emission aircraft (electric and hydrogen propelled) and the regulatory measures necessary to make aviation carbon-neutral will, however, lead to higher costs. Technological and operational efficiency improvements will not be enough to offset these expected cost increases, and these will likely be transferred to ticket prices.

By 2060, air ticket prices under the NZE and High Ambition scenarios will be, on average, 25-30% higher than in the Baseline scenario, due to the increased costs associated with decarbonising aviation. This, together with the increased availability of cleaner alternative modes in some regions - rail transport activity in 2060, measured in passenger-kilometres, under the High Ambition scenario is almost 30% higher than in the Baseline scenario (forthcoming ITF, 2025) - means that air passenger-kilometres in 2060 under the NZE scenario are expected to be around 30% lower than in the Baseline scenario.

These changes in aviation demand growth projections may have broader implications for societal welfare, the wider economy, the tourism industry, and the labour market. The following sections of the report explore each of these areas, shedding light on the potential broader consequences of decarbonising aviation, while providing policy insights to mitigate potential adverse effects and capitalize on opportunities arising from the transition.

Exploring the impacts of decarbonising aviation on connectivity and operations

Air transport plays a pivotal role in fostering global development, contributing significantly to economic integration, world trade, tourism and employment creation. Aviation enables countries to form vital economic linkages, facilitating the exchange of goods, services and knowledge. The concept of air connectivity, which refers to how well a country is linked to other nations through air routes, is particularly crucial for economic growth. Tourism, for instance, relies heavily on aviation, with 58% of global international tourists arriving by air (ATAG, 2020). Moreover, air connectivity enhances productivity by influencing the level and location of private investments, improving business operations, and supporting the flow of information and expertise across borders (Venables, 2016).

The existing literature presents a strong correlation between air connectivity and economic development, though the exact causality is sometimes debated (Green, 2007). In remote regions, where alternative transportation options are limited, the evidence is more definitive - air transport is a key driver of economic activity and growth. Research has shown that improved air connectivity can boost local economies, especially in geographically isolated areas where aviation is the main link to the global market (Baker et al., 2015; Çağri Özcan, 2014). For these regions, robust air services are indispensable for tourism, trade, and even basic mobility.

In recent decades, the expansion of air travel has increased the number of city-pair connections globally, reaching over 23 000 unique links in 2019. This growth has been accompanied by decreasing costs for both passengers and freight, driven by technological advancements and operational efficiencies (IATA, 2021a). However, the impact of decarbonisation policies on extensive and affordable air connectivity remains uncertain. The implications of such policies on airports and airlines operations (Box 1) also remain uncertain. This section will explore how regions and geographies may experience varying effects from such policies and provide insights into mitigating the potential negative consequences of decarbonisation measures on countries' connectivity.

Box 1. How do aviation decarbonisation policies impact airlines?

When a market-based or regulatory decarbonisation policy is imposed, airlines can respond in multiple ways. One way to reduce CO_2 emissions is to invest in more fuel-efficient aircraft. In the past, carriers have continuously pursued this strategy as a way to reduce their operating costs. Airlines can also purchase aviation fuels with lower fuel lifecycle CO_2 emissions. Among those, SAFs are expected to become more widely available in the near future. Furthermore, airlines can adjust their operations - for example, by cancelling less profitable routes or reducing the flight frequency on specific routes while maintaining or increasing aircraft size. Airlines can also increase their airfares to pass on at least some of the additional costs of decarbonisation measures to their customers. Since airlines differ in their flight networks, business models, geographic location, and fleet composition, their individual responses to, and economic impact from, decarbonisation policies will differ.

The University College London (UCL) Air Transportation Systems Laboratory has been developing models that simulate the global air transportation system and how passengers and competing airlines behave under different policy interventions. The underlying key assumption is that each airline, similarly to most other producers of goods and services, maximises its profits, whereas passengers maximise their utility. Airlines seek to maximise profits by choosing the airfare for each itinerary, specifying the flight frequency and aircraft type they operate on each route in their network, and investing in new aircraft. At the same time, passengers can maximise their utility by choosing whether to travel, which mode to use if they travel, and (if flying) choosing airline and itinerary (including departure, arrival and stopover airports).

Using this model, the results indicate similarities but also important differences between competing airlines in the way they respond to and are affected by climate policy. A common industry response to any stringent CO_2 mitigation policy is that airlines invest in and utilise more fuel-efficient aircraft whilst increasing their airfares. UCL observes the largest fare increase for full-service carriers, which reduces their passenger demand to the largest extent. Those airlines that experience demand losses decrease their overall flight frequency, allowing them to retire older and less efficient aircraft from their fleet. This can significantly reduce CO_2 but, as full-service carrier fares go up and frequency of service goes down, UCL finds a shift of passengers towards low-cost carriers. As a result, depending on the policy, some low-cost carriers can even experience an increase in demand. UCL also finds that full-service carriers make use of operational changes by reducing the flight frequency on specific routes while either maintaining aircraft size or using larger aircraft instead. Low-cost carriers do not have that degree of freedom as they largely operate one size and type of aircraft to reduce costs for pilot training, scheduling, and maintenance, concentrating on lower frequency services with high load factors. Instead, they achieve their emissions targets by purchasing newer aircraft and/or greener aviation fuels. As a result, low-cost carriers may be the first customers of SAFs under CO_2 policy. To support this energy transition, SAFs should be made readily available at low-cost carrier airports, such as London Stansted or Paris Orly, and not limited to large international hubs dominated by full-service carriers.

Despite these changes in demand and operations, CO_2 mitigation policy does not necessarily decrease any particular airline's profits. For full-service carriers, their increased airfares, more streamlined fleet and efficient network act to offset at least some of the loss in passenger demand. For low-cost carriers, their increased airfares and market shares can offset the extra costs of SAFs. However, higher fares and fewer flights will be a less desirable outcome for passengers.

Different types of policy interventions (i.e., market-based measures or regulations) will lead to slightly different outcomes, including for airline profits. In general, UCL's model predicts that policies which give airlines a clear CO_2 emission limit, whilst allowing them maximal degrees of freedom to adjust their business to meet that limit, result in more profitable outcomes for all airlines. In contrast, policies which restrict or enforce the methods by which airlines decarbonise result in less profitability for all airlines for the same amount of CO_2 reduction.

Source: Written by Khan Doyme, Lynnette M. Dray, Andreas W. Schäfer (University College London)

Air connectivity varies across world regions and geographies

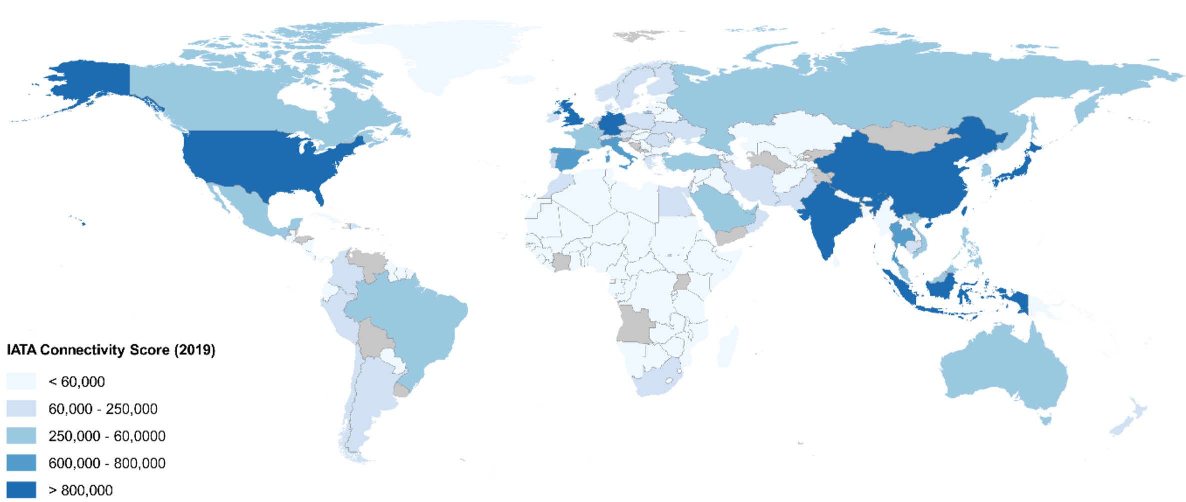
Measuring air connectivity

The term *air connectivity* reflects the ease with which various global destinations can be accessed via air travel. Several metrics exist to quantify air connectivity, each capturing distinct aspects, such as travel time, cost, number and quality of connections, frequency of service, and reliability. Additionally, some of these metrics consider opportunities at the destination, such as its population or economic significance. These metrics are designed for different purposes and used by different stakeholders in the aviation industry. For passengers, air connectivity primarily represents the ability to travel from origin to destination as efficiently as possible, minimizing time and layovers. For airports, on the other hand, measuring connectivity helps assess the value of specific air connections to support airports' business development and strategic planning initiatives.

This report adopts IATA's Air Connectivity Index, which assesses the extent to which a country is integrated into the global air transport network. This metric offers policymakers a valuable tool for understanding how well their country is connected, informing policy decisions that affect economic and infrastructure development (IATA, 2021a).

The IATA Air Connectivity Index calculates connectivity based on the number of available annual seats to each destination. These available seats are then weighted by the size of the destination airport, measured by the total number of passengers it handles annually. This weighting provides an indication of the economic importance of the destination and the onward connections it offers. The connectivity index for an individual airport is calculated as the sum of destination-weighted available seats to all other airports. The overall country-level air connectivity index is then derived by summing the connectivity indices of all airports within the country (IATA, 2021a). This comprehensive metric provides insights into a country's global air connectivity and is a useful tool for exploring the potential impacts of aviation decarbonisation policies on air connectivity.

Figure 8. IATA Air Connectivity Index (2019)



Source: Author's own elaboration based on data from IATA (IATA, 2021a)

Figure 8 shows countries' global connectivity as calculated by IATA based on the previously described connectivity index (IATA, 2021a). The most connected country in the world in 2019 was the United States, followed closely by China. Regional connectivity is the largest in Asia, which is characterised by various countries with growing markets, such as China, India and Indonesia. The second most connected region is North America.

An absolute air connectivity score is not necessarily a measure of quality. The level of connectivity depends to some extent on the size of a country's economy. Larger economies will naturally be connected to a greater number of destinations and offer more available seats compared to smaller countries. Therefore, various alternative measures of air connectivity, which adjust for the size of a country's economy or population can be used to measure and analyse the level of air connectivity.

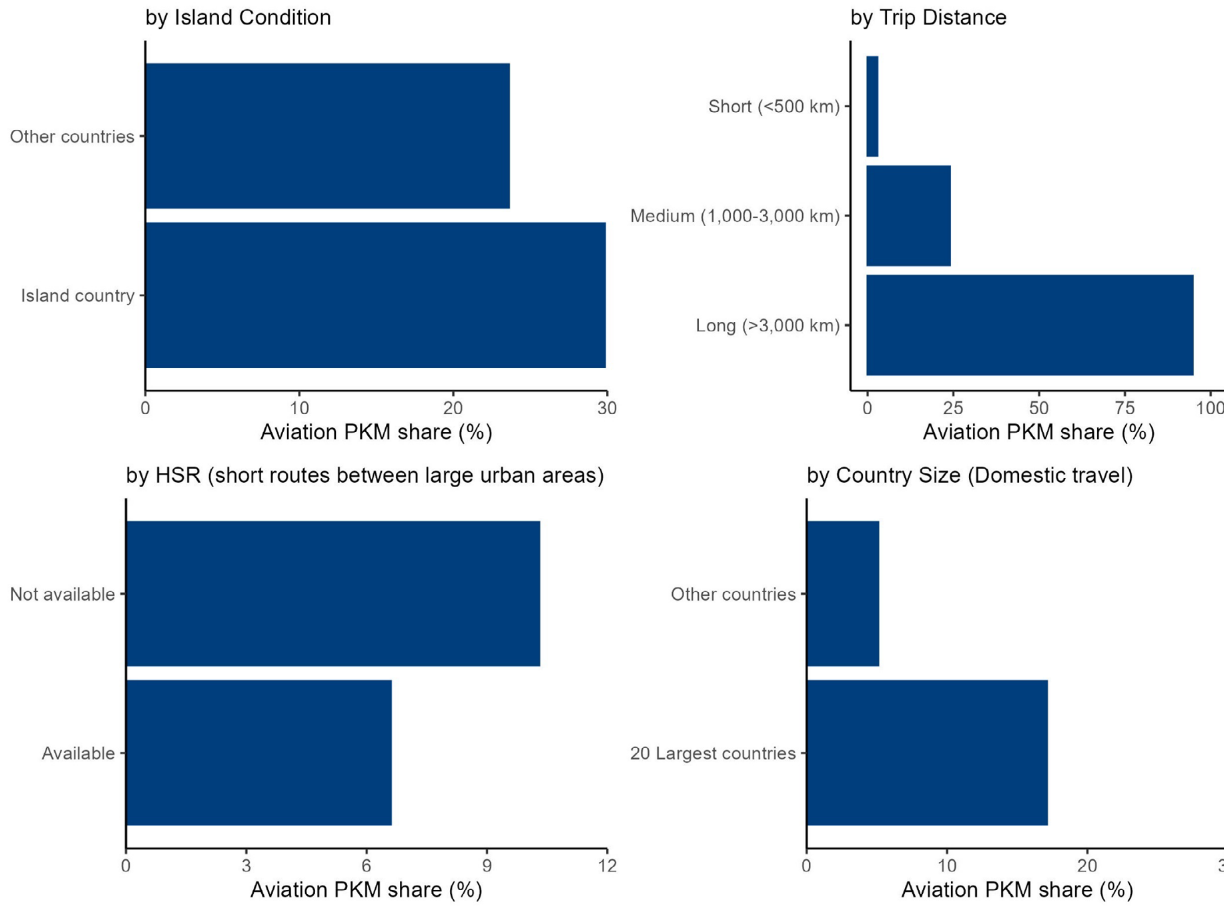
When examining air connectivity adjusted by the economic size of a country (by GDP), Aruba, the Maldives, and Palau have the highest connectivity levels relative to the size of their economies. In contrast, the United States, which has the highest absolute connectivity indicator, ranks 45th after adjusting for GDP. According to the IATA Air Connectivity index calculated for 2019, the top 20 most connected countries in the world (adjusted by GDP) are small states - almost all islands that are highly dependent on inbound tourism.

Differences in connectivity dependence on air transport

While global differences in air connectivity between countries have already been highlighted in Figure 8, it is important to identify the contexts in which aviation plays a crucial role in enhancing transport connectivity. Trade-offs between the types of transport modality and environmental and social concerns are some of the main issues regarding transport connectivity.

Dependence on air transport is derived by calculating the share of air transport demand relative to the total transport demand (measured in passenger-kilometres) (forthcoming ITF, 2025). Figure 9 illustrates that in island states, air transport on average accounts for almost 30% of total intercity transport activity, whereas in non-island states, this figure drops to just over 20%. For long-distance journeys (over 3 000 kilometres), air transport is almost exclusively relied upon. In contrast, for medium-distance (1 000 - 3 000 kilometres) and short-distance trips (less than 500 kilometres), air travel constitutes only 26% and 3%, respectively.

Figure 9. Dependence on air transport connectivity



For short distance trips between large urban areas where HSR could be a viable alternative, when direct HSR exists, the dependence on air transport declines by almost 40% (mode share of air passenger-kilometres declines from 10% to 6.5%). However, competitive HSR options are mainly limited to Europe, China, Japan, and Korea. Additionally, in the 20 largest countries by land area, domestic air transport represents 18% of total transport activity. For smaller countries, this average decreases to 5%.

This analysis highlights that air transport is essential for connectivity in specific contexts, particularly where alternative modes of transport are either limited or non-existent. These contexts must be carefully considered when evaluating the potential impacts of decarbonising aviation, as transport connectivity in these cases is heavily dependent on air travel.

Potential impacts of decarbonising aviation policy measures on air connectivity

Global aviation exhibits significant disparities in air transport connectivity across different countries and regions, with wealthier regions being substantially more connected than their less affluent counterparts. As noted earlier in this report, by 2060, air ticket prices under the ITF's Net Zero scenario are projected to be, on average, 25-30% higher than in the Baseline scenario due to the increased costs associated with decarbonising aviation. This, together with the increased availability of cleaner alternative modes like high-speed rail in some regions, means that air passenger-kilometres in 2060 under the Net Zero scenario are expected to be around 30% lower than in the Baseline scenario, and could potentially affect connectivity.

To assess the impact of these decarbonisation pathways on connectivity, we employed the connectivity index developed by IATA, using projected demand instead of seat capacity, since future seat availability remains uncertain. Demand, which can be forecasted long-term, serves as a reliable proxy for seat capacity. As shown in Figure 8 earlier, today, regions such as UCAN (United States, Canada, Australia and New Zealand), Europe, and ENEA (East and Northeast Asia) exhibit the highest connectivity indexes. When adjusted for population, these disparities become even more pronounced. However, when projecting this index to 2060 for the different decarbonisation scenarios as in Table 2, it shows that connectivity will continue to grow across all world regions. Connectivity under the ITF's NZE scenario grows at slower pace than under the Baseline scenario, observing minor differences in the relative growth across regions, which varies between 0.8 and 0.98.

Table 2. Demand-based connectivity index projection under different policy scenarios

World region	ENEA	Europe	LAC	MENA	SEA	SSA	SSWA	TAP	UCAN
Growth factor 2019 to 2060 (Baseline scenario)	11.3	4.1	4.4	5.3	8.4	6.8	3.7	4.8	2.7
Growth factor 2019 to 2060 (NZE scenario)	9.1	3.5	4.0	4.7	7.3	5.8	3.4	4.5	2.6
Relative growth difference between scenarios (2060 Index Baseline / 2060 Index NZE)	0.80	0.86	0.90	0.89	0.87	0.85	0.91	0.92	0.98

Note: Table presents ITF modelled estimates. Baseline and Net Zero Emissions (NZE) refer to the ITF's modelled scenarios. The world regions grouping corresponds to: Europe (European Economic Area and surrounding countries), ENEA (East and Northeast Asia), LAC (Latin America and the Caribbean), MENA (Middle East and North Africa), SEA (Southeast Asia), SSA (Sub-Saharan Africa), SSWA (South and Southwest Asia), TAP (Transition economies and other Asia Pacific), UCAN (United States, Canada, Australia and New Zealand).

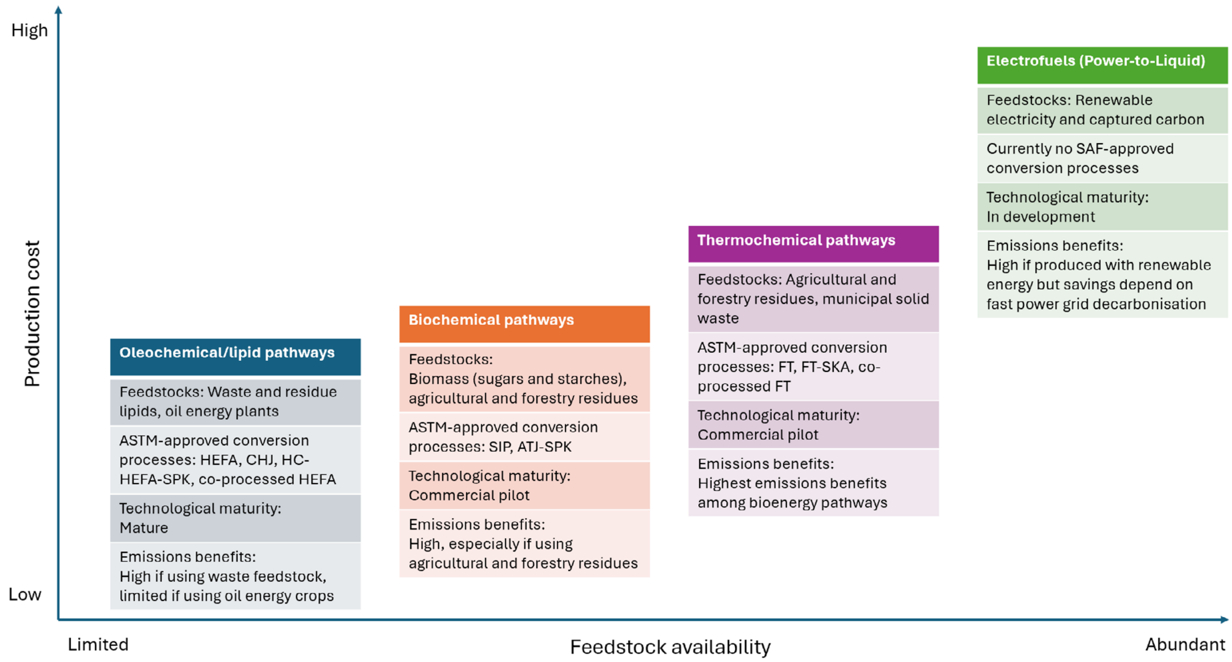
Policy insights

Scaling up production of sustainable aviation fuels is essential

To safeguard the varied and many benefits that connectivity via aviation generates, it is essential that the sector further decouples demand growth from carbon emissions growth. The ITF's NZE scenario expects major emissions reduction from SAFs, which implies an equivalent annual demand of around 500 billion litres by 2060, more than 1 000 times current production levels (IATA, 2023a). The energy sector and in particular fuel producers, airlines, airports, investors, and governments must make coordinated and sustained efforts to achieve this objective. Governments have a key role to play in establishing policy frameworks which create the market conditions necessary to facilitate a massive and rapid uptake in SAF production and use.

Several different types of SAFs exist today with varying technological maturity, production costs, feedstock availability and emissions benefits, as summarised in Figure 10.

Figure 10. Current status of key SAF production technologies



Notes: ASTM: USA-based technology standardisation body; HEFA: synthesized paraffinic kerosene from hydroprocessed esters and fatty acids; CHJ: catalytic hydrothermolysis jet fuel; HC-HEFA-SPK: synthesized paraffinic kerosene from hydrocarbon – hydroprocessed esters and fatty acids; co-processed HEFA: co-hydroprocessing of esters and fatty acids in a conventional petroleum refinery; SIP: synthesized iso-paraffins from hydroprocessed fermented sugars; ATJ-SPK: Alcohol-to-jet synthetic paraffinic kerosene; FT: Fischer-Tropsch hydroprocessed synthesized paraffinic kerosene; FT-SKA: synthesized kerosene with aromatics derived by alkylation of light aromatics from non-petroleum sources; co-processed FT: co-hydroprocessing of Fischer-Tropsch hydrocarbons in a conventional petroleum refinery.

Source: Author's own elaboration based on data from (ICAO, 2023a; ITF, 2023c)

Different countries may choose to prioritise development of different types of SAFs due to their specific resource endowments, but at a global level, the scale-up of all production technologies and feedstock types that deliver credible emissions reductions will be necessary to meet the LTAG by 2050. Government support measures should strike a balance between incentivising the continued rollout of more mature production pathways, like HEFA, in the short-term while simultaneously targeting technologies that may be less commercially viable today, but offer the potential of delivering large emissions reductions at scale in the future, like electrofuels (ITF, 2023c).

Taking both a "carrot" and "stick" approach, where financial incentives are coupled with strong regulatory requirements, works best to scale up production while avoiding sharp price increases in the short-to-medium term (IATA, 2023b; ITF, 2023c). Given the amount of investment required to bring SAF production facilities online, governments should ensure that any support measures are sufficiently robust and stable over time to generate adequate confidence in future demand for offtake agreements.

As of 2024, the EU, UK and USA have the most comprehensive policy frameworks to support SAFs production - and also produce the most SAFs - suggesting good policy can help stimulate production. These frameworks must be further strengthened over time, and many more countries must significantly increase their policy ambition on SAF support measures if the sector is to decarbonise.

Specific policies which should be considered as part of a portfolio approach include carbon pricing (ETS and carbon tax), low-carbon fuel standards and fuel-blending mandates (accompanied by non-compliance penalties), financial incentives (including via public finance to de-risk private investment, e.g. grants, concessional loans, guarantees, and revenue certainty mechanisms like "contracts for difference"), research and development funds, and compliance with evidence-based international fuel certification schemes which take into account effects from indirect land-use change (mutual recognition of lifecycle greenhouse gas emission accounting may be a practical way forward) (Cazzola, 2024; World Economic Forum, 2020). ITF (2021) and ITF (2023b) provide more detail on the design of SAF policy support measures. Furthermore, the cost efficiency and sustainability of the supply chain for SAF distribution can be improved through adoption and harmonisation of "book and claim" procedures – which enable SAF producers to "book" supply in the market near the production point where fuel is blended, and customers to "claim" the carbon reductions associated with that SAF when purchasing fuel in another location. The ITF will release a report exploring how book and claim can support sustainable transport in 2025.

Accelerating the development of alternative propulsion technologies

Alternative propulsion technologies will also be very important in the future to maintain the benefits of air connectivity while decarbonising the sector. Provided that energy production pathways are less carbon intensive than conventional aviation fuels, these technologies could significantly reduce emissions of greenhouse gases by commercial aviation. Alternative propulsion systems can be grouped into three main families of technologies: hybrid-electric aircraft, fully-electric aircraft and hydrogen-powered aircraft.

Hybrid-electric aircraft integrate electric propulsion with combustion engines to optimise engine performance in non-cruising flight stages to reduce fuel burn. As their batteries are lighter than for fully-electric aircraft, the resulting weight increase relative to conventional aircraft is less problematic for performance. For aircraft used in regional transport, depending on the configuration, estimates for fuel burn savings range from 12% to 28% with total energy-use reductions of between 7% and 12% (Zamboni, 2018).

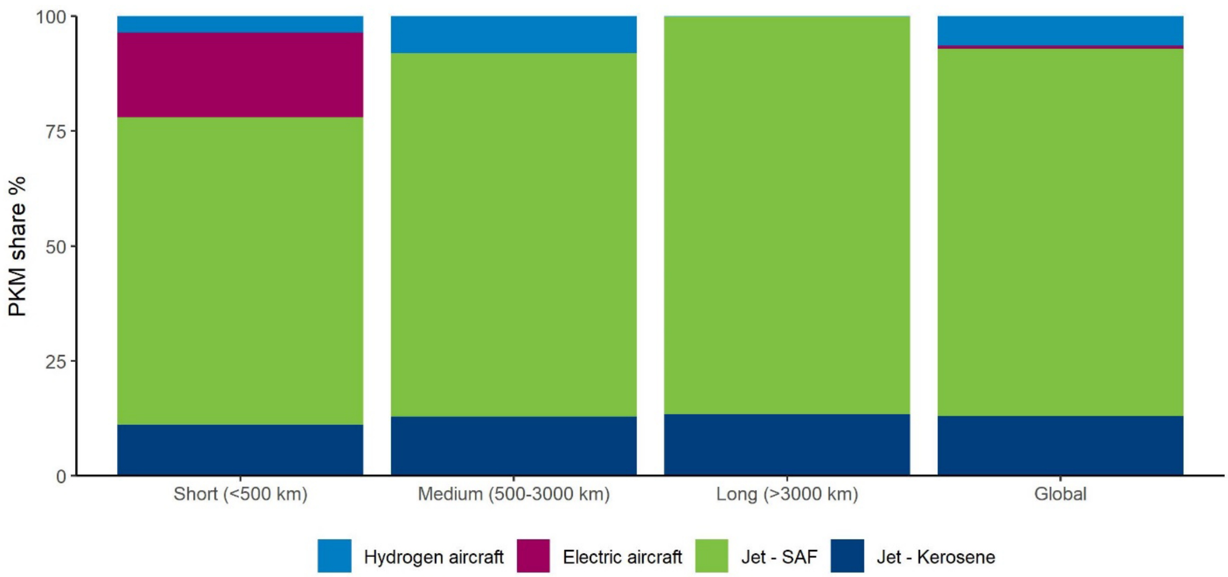
Fully-electric aircraft have zero tailpipe emissions and, if powered by renewable electricity, significantly reduce the carbon intensity of aviation. However, the weight and power of existing batteries and associated cables limit aircraft size and range. Scaling up electric aircraft to become more commercially viable depends on uncertain technological breakthroughs in battery chemistry, as well as bringing battery costs down (Schäfer, 2019).

Hydrogen-powered aircraft emit water vapour and nitrogen oxides during flight and use either combustion technologies or fuel cells. The low volumetric energy density of hydrogen and its other chemical properties means that aircraft would need larger fuel tanks kept at extremely low temperatures (and made to extremely high-performance specifications) to limit losses from evaporation (ITF, 2021b). Both electric- and hydrogen-powered aircraft would require airports to be equipped with new, costly, refuelling infrastructure (Gupta, 2015; ITF, 2023d).

Several manufactures are developing both electric- and hydrogen-powered aircraft, which could start entering the market in the 2030s. Estimates vary, but under an optimistic scenario, battery technology for electric aircraft could reach 500 watt-hours per kilogramme (Wh/kg) by 2050, allowing 19-passenger aircraft to operate routes of 350 kilometres and 90- passenger aircraft to cover 300 kilometres (Mukhopadhaya, 2022). Hydrogen-powered aircraft with a capacity of 165 passengers and a range of 3 400 kilometres could become available in 2035; however, relatively high fuel costs and additional capital expenditure requirements in comparison to conventionally powered aircraft could delay widespread adoption until 2050 (Fuel Cells and Hydrogen 2 Joint Undertaking, 2020; Mukhopadhaya, 2022). The ITF's

2023 Transport Outlook modelled these assumptions under a “High Ambition” scenario, finding that by 2050 hydrogen aircraft could account for an estimated 8% of global medium-distance passenger-kilometres and 4% of short-distance passenger-kilometres, while battery-electric aircraft could account for 18% of short-distance passenger-kilometres, see Figure 10 (ITF, 2023b). This represents a relatively high share of flights, but only a small share of energy use and emissions in the sector, most of which come from long-distance flights.

Figure 11. Share of aviation passenger-kilometres by propulsion technology and trip distance in 2050 under the ITF Transport Outlook 2023 High Ambition scenario



Source: ITF, 2023

Governments can take various actions to help accelerate the development and uptake of alternative propulsion technologies for aviation. Firstly, setting national net-zero aviation strategies which define long-term as well as interim milestones for uptake of battery-electric and hydrogen propulsion can spur private sector investment by reducing demand uncertainty. Such strategies should consider the type and length of flights taken by residents, the size of aircraft serving those markets, airport infrastructure, and future potential for production and distribution of renewable electricity and hydrogen. The Nordic region is at the forefront of the uptake of battery-electric aircraft, in part due to national goals which have galvanized various stakeholders to take action. Both Sweden and Denmark target fossil-free domestic aviation by 2030, Norway aims for all domestic flights being battery-electric by 2040, and Finland has committed to zero-emission domestic aviation by 2045.

Secondly, dedicated government research and development funding for the aviation sector can help support critical technological breakthroughs that will be necessary to bring forward the rollout of alternative propulsion technologies. Reviewing and updating regulatory frameworks, including regarding certification standards and airworthiness requirements, is equally important to create an enabling environment that will allow innovation to flourish.

Finally, as technologies mature and become available on the market, governments can spur uptake by deploying various financial measures to help address cost differentials with conventional aviation.

Examples include carbon pricing, tax breaks, subsides, low-interest loans for aircraft purchase, and preferential structuring of fees for airport and navigation services (World Economic Forum, 2023).

Preserving connectivity in remote, aviation-dependent areas

Existing research is clear that for remote areas of the world, connectivity via aviation plays an important role in facilitating economic integration, generating trade, and creating employment opportunities (Bilotkach, 2015; Çağri Özcan, 2014; Hummels, 2007; World Bank Group, 2018). Indeed, in such areas where other modes of transport are not viable, aviation can be considered a social right for communities, providing access to critical services like healthcare (Fageda & Suárez-Alemán, 2019; ITF, 2018).

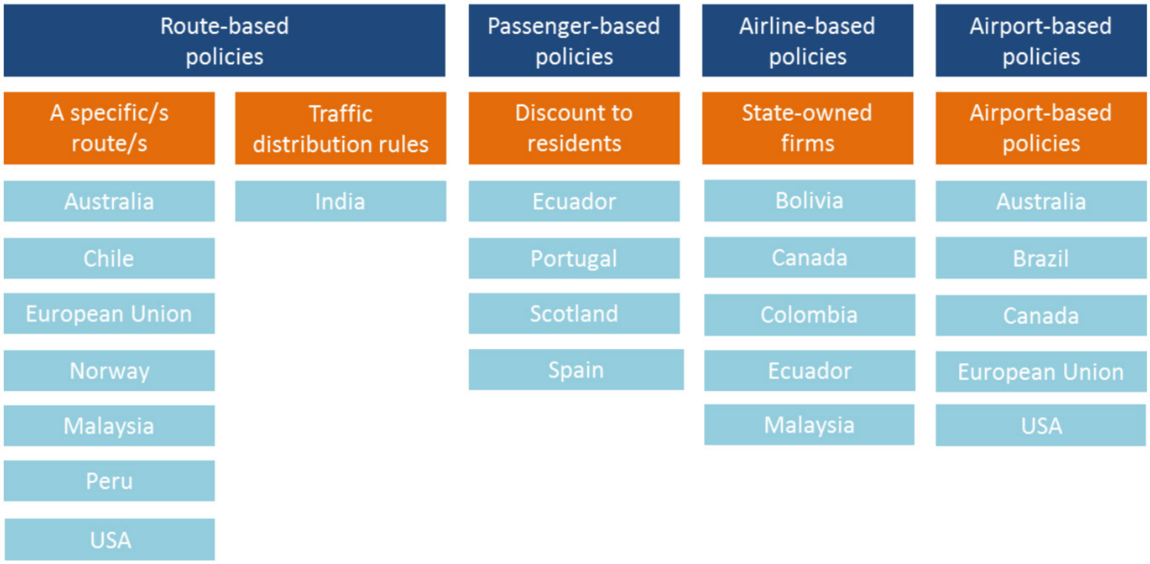
However, not all air transport routes are commercially attractive for airlines. The high fixed cost of operations, coupled with the relatively low passenger demand of remote regions with limited populations, means some routes will not be served under free market conditions (Fageda & Suárez-Alemán, 2019). The expected positive effects from improving connectivity for such regions have led governments around the world to implement policies designed to make air transport commercially sustainable. These can be categorised into four groups (Fageda et al., 2018).

- *Route-based policies* - ensuring air connectivity in some specific routes by establishing public service obligations or rules to distribute traffic among routes
- *Passenger-based policies* - through discounts to residents using some routes
- *Airline-based policies* - establishing state-owned firms which can offer below-market airfares
- *Airport-based policies* - developing carrier incentive schemes or subsidising airports.

As noted earlier, ITF modelling indicates that by 2060 under the NZE scenario, air ticket prices will be, on average, 25-30% higher than in the Baseline scenario due to the increased costs associated with decarbonising aviation. For remote, aviation-dependent regions, alternative transport modes are not readily available, so such increases in the cost of air travel could result in air routes becoming commercially unviable in more remote regions.

To preserve the important benefits that aviation provides to such areas, supporting policy measures may need to be strengthened. However, the positive impacts of these policies must be weighed against their costs. Such policies may require significant public subsidies - which puts pressure on government funding, may distort the decision-making of airlines and provide them with weak incentives to be efficient, and may unintentionally restrict competition if routes are overprotected. Governments must therefore be clear about the public policy objectives they are seeking to achieve through these measures, and rationalise their support accordingly in light of potential increasing demands from remote aviation-dependent regions (Fageda et al., 2018; ITF, 2018). Figure 12 provides examples of countries in which such policies are currently established, with respect to the four policy categories.

Figure 12. Policies around the world to support remote region air connectivity



Source: (Fageda et al., 2018)

The use of public service obligations may be preferable to other measures because any distortion is restricted to the specific routes affected and conditions are well defined in a competitively tendered contract. The state-owned firm and resident discount policies may require significant subsidies since they affect a relatively large number of routes. Traffic distribution rules do not require the use of public funding but could create domestic market distortion. Finally, airport grants are typically limited in terms of scope and obligations for ongoing public funding (Fageda & Suárez-Alemán, 2019; ITF, 2021a).

Investment in infrastructure development for alternative cleaner modes

For short-haul air travel, switching to less carbon-intensive rail travel can be an effective way to reduce emissions while maintaining the benefits of connectivity. However, consumers are likely to switch only if travel time, cost, frequency, and reliability of services are comparable or more favourable than aviation (ICCT, 2022). For regions that already have well-developed passenger rail networks, such mode shift could complement measures to decarbonise aviation. In Europe, around 7% of intra-European short- and medium-haul flights could be substituted by rail with no increase in travel time, while 17% of the same flights could be substituted by rail if travel time increased by only 20% (Avogadro et al., 2021). Other estimates suggest that intra-EU flights could decrease by 25% if HSR were available between all major cities in the region (Transport & Environment, 2020).

A shift from short-haul flights to all-rail services, including but not limited to HSR, could be encouraged by reducing the cost of rail relative to air transport and improving rail services (e.g. by increasing frequency or reducing travel times), although this can require significant public investment. In the case of building new HSR lines, the overall net impact on GHG emissions of construction, maintenance, and operations needs to be considered before the investment is made. For instance, in the USA, replacing one-third of short-haul flights in ten designated HSR corridors in 2030 is estimated to result in just a 1% decrease in domestic air transport CO_2 emissions (Jamin et al., 2004). In Spain, a life-cycle assessment of the entire national HSR network under 2016 traffic conditions found that the launch of the Catalonia and Andalusia corridors leads to a net environmental benefit in terms of CO_2 equivalent (CO_2eq) emissions after 9-12 years of operation. However, for lower-demand corridors, results differed - the Levante corridor needs between 14 and 21 years for CO_2eq emissions deriving from construction to be compensated, and the Northern corridor gives rise to no compensation in the lifetime of the infrastructure (Kortazar et al., 2021). In general, the result will depend on such factors as the GHG emissions during the construction phase, GHG emissions from operations, expected travel volumes and the replacement potential of other transport modes (IEA, 2019).

Rail can also act as a feeder service for air transport and substitute for some short-haul connecting flights. The rail and air industry can encourage intermodality by providing seamless air-rail travel for passengers through integrated ticketing and on-board services such as integrated baggage handling. Many such initiatives exist in Europe, North America and Japan. A memorandum of understanding between IATA and the International Union of Railways, signed in 2020, is expected to further develop integrated ticketing between air and rail to this end (UIC, 2020).

Exploring the impacts of decarbonising aviation on tourism

Tourism is one of the most significant drivers of global economic growth, contributing approximately 10% to both global GDP and employment (UN Tourism, 2023). As the sector continues to expand, it offers substantial economic opportunities but also generates negative externalities, particularly concerning its environmental impact and contribution to climate change. Tourism is estimated to account for around 8-10% of global greenhouse gas emissions, with high-income countries responsible for most of this (Tourism Panel on Climate Change, 2023). Around 75% of the tourism sector's CO_2 emissions stem from transport, with air travel alone contributing 40% (UNWTO & ITF, 2019). While aviation has been pivotal to the global tourism industry's success—connecting distant destinations and fuelling economic growth—it also poses a serious challenge for the sector to meet its decarbonisation goals outlined in the Glasgow Declaration for Climate Action in Tourism. These goals include halving emissions from tourism by 2030 and reaching net zero before 2050 (One Planet Sustainable Tourism Programme, 2021).

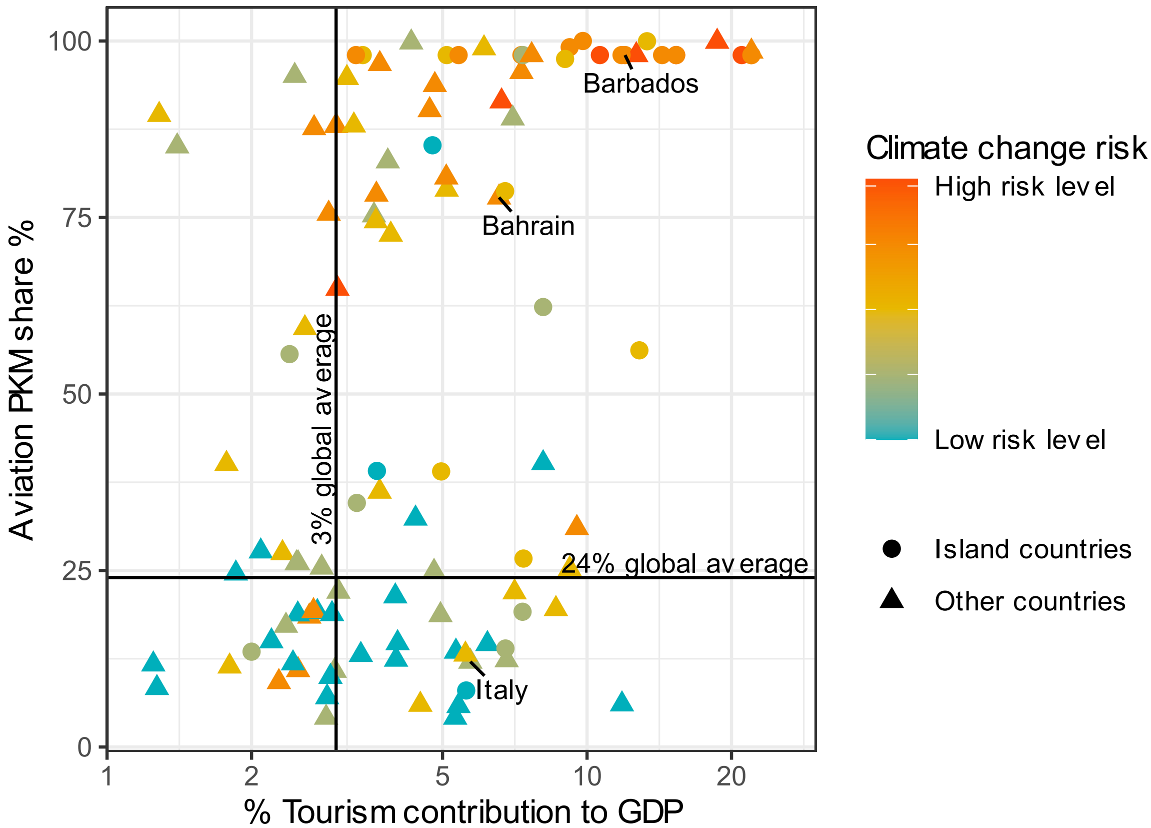
In addition to its climate impact, the tourism sector is also heavily exposed to multiple and often cumulative climate impacts. Risks include wildfires, heatwaves, floods, and other extreme weather events which affect visitors, businesses and local communities both by the initial impact but also from the loss of infrastructure and time it takes for tourism to recover, as well as broader impacts like biodiversity loss which damages key attractions that draw visitors (OECD, 2024b).

Impacts are not distributed evenly among tourism destinations

Figure 13 illustrates the relationship between tourism's contribution to national GDP (x-axis), reliance on air transport connectivity (y-axis, measured as the share of air passenger-kilometres to total passenger-kilometres), and the climate change risk index for tourism (Scott & Gössling, 2018) for several countries. The countries located in the top-right quadrant of the figure are those whose dependence on air transport connectivity exceeds the global average of 24% (ITF, 2025 forthcoming), and where tourism's direct contribution to national GDP is more than the global average of 3% (UN Tourism, 2023). These states are potentially more susceptible to the impacts of decarbonising aviation on tourism. Notably, most of these countries are also among the most vulnerable to climate change risks.

This paradox is particularly pronounced for Small Island Developing States (SIDS), where tourism plays a critical role in national GDP but is heavily dependent on carbon-intensive air travel. These countries are also some of the most vulnerable to the effects of climate change. As the world moves towards net-zero emissions, it is crucial to prioritise equity considerations, ensuring that these vulnerable destinations are supported in transitioning to low-carbon solutions without undermining necessary climate mitigation efforts.

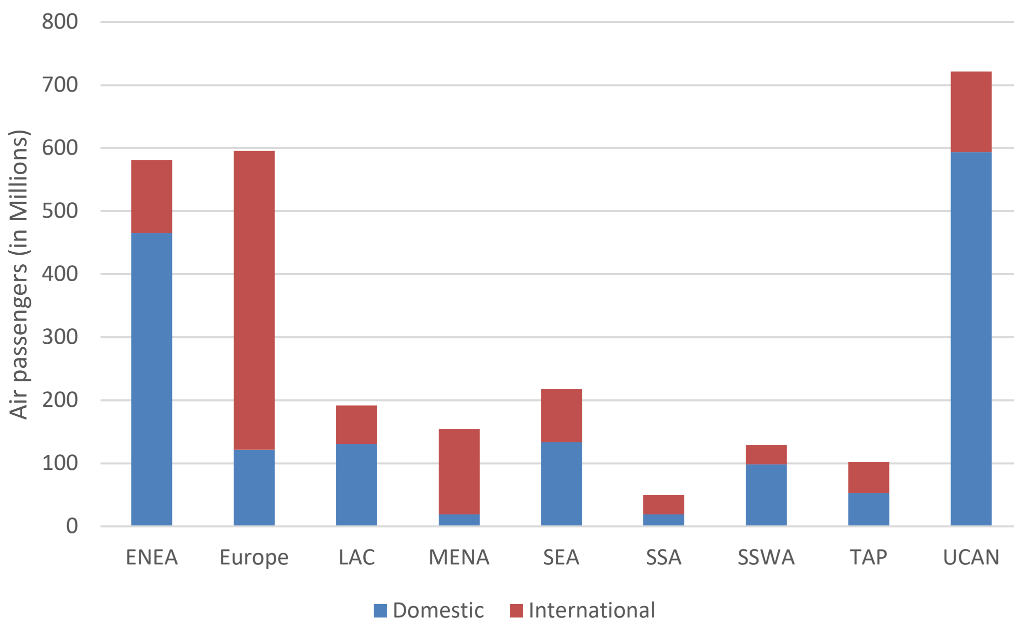
Figure 13. GDP from tourism, air travel dependence and climate risk across countries.



Source: Author's own elaboration based on data from ITF, UNWTO, OECD, WTTC and (Scott & Gössling, 2018)

Air transport passenger departures are highly concentrated in the most developed world regions. Figure 14 shows that air passengers departing from Europe, UCAN (United States, Canada, Australia and New Zealand) and ENEA (East and Northeast Asia) represent almost 70% of global departures. Furthermore, Table 3 sets out the balance between inbound and outbound international air passenger flows, with Europe being the only world region that has an equal balance. Table 3 also shows that the UCAN, ENEA and MENA (Middle East and North Africa) regions generate 20-30% more aviation passengers than those that they attract. On the other hand, SSWA (South and Southwest Asia), LAC (Latin America and the Caribbean), and SEA (Southeast Asia) attract a much larger share of international air passengers that what they generate. There are also significant differences in the distance travelled by inbound passengers to arrive at the destinations. Travellers arriving to countries located in SEA, SSWA and LAC experience on average longer trips. As aviation decarbonises, the distance of travel is likely to carry more weight in the traveller's destination choice since ticket costs increases are expected. This demonstrates differing vulnerability stemming from decarbonising aviation for tourism destinations located in different world regions.

Figure 14. Outbound air passengers by world region (2019)



Note: Figure presents ITF modelled estimates for 2019. The world regions grouping corresponds to: Europe (European Economic Area and surrounding countries), ENEA (East and Northeast Asia), LAC (Latin America and the Caribbean), MENA (Middle East and North Africas), SEA (Southeast Asia), SSA (Sub-Saharan Africa), SSWA (South and Southwest Asia), TAP (Transition economies and other Asia Pacific), UCAN (United States, Canada, Australia and New Zealand).

Table 3. Inbound, outbound and average distance of air travellers.

World region	ENEA	Europe	LAC	MENA	SEA	SSA	SSWA	TAP	UCAN
Percentage difference between inbound and outbound international air travellers	-27%	-2%	51%	-37%	18%	44%	162%	16%	-20%
Average travelled distance of inbound air travellers (km)	662	464	1000	812	1103	1026	620	843	986

Note: Table presents ITF modelled estimates for 2019. The world regions grouping corresponds to: Europe (European Economic Area and surrounding countries), ENEA (East and Northeast Asia), LAC (Latin America and the Caribbean), MENA (Middle East and North Africa), SEA (Southeast Asia), SSA (Sub-Saharan Africa), SSWA (South and Southwest Asia), TAP (Transition economies and other Asia Pacific), UCAN (United States, Canada, Australia and New Zealand).

Policy insights

For destinations where alternative modes of transport are feasible

For destinations where alternative modes of transport are feasible, government and industry should work together to shift the pattern of tourism-based trips to achieve more sustainable outcomes. This involves promoting more near-by tourism (whether domestic or arrivals from more proximate inbound international markets) where alternatives to aviation, like high-speed rail, are available. Increasing the cost and quality competitiveness of rail in comparison to air travel should be the focus, however, softer measures, like providing information to consumers on the carbon intensity of different travel options, can also help generate mode shift.

Several countries are investing in rail networks, including the reestablishment of night trains. In Europe, for example, the EU’s Rail Baltica project aims to integrate Estonia, Latvia and Lithuania into the European rail network while the introduction of GreenCityTrip sleeper trains now connect travellers from the Netherlands with 15 European cities (OECD, 2022). In France, Spain, and Germany initiatives have been launched to replace short domestic flights with train connections. However, unlike aviation which is a highly competitive marketplace in Europe, rail is dominated by state-run companies who operate under near monopolistic conditions and often prioritise investment for domestic services rather than improvements in international connectivity. Technical barriers like standardised signalling across borders also inhibit growth. The result is relatively poor international connectivity and services which are on average twice as expensive as flights.

For regions like Europe that have existing rail infrastructure, governments need to make rail more competitive with air travel for tourism by liberalising the sector to increase efficiency, increasing public funding to improve service attractiveness, and introducing carbon pricing measures that apply to aviation. Government and the tourism industry can also work together to generate additional demand for such services. For example, in 2022 the Netherlands Board of Tourism and Conventions published their climate action roadmap, “The Road to Climate-Neutral Tourism”, which, among other things, calls for reducing dependence on aviation. The industry has supported this by shifting its inbound marketing efforts from far away to nearby countries (OECD, 2024b).

Information provision can also help people make more sustainable travel choices for tourism by clearly understanding the relative carbon intensity of different modes. Box 2 sets out an innovative approach which has been rolled out in Norway and has potential to be replicated in other countries.

Box 2. Measuring tourism-related transport emissions in Norway

Norway has developed a tool, CO2rism, for estimating the amount of transport-related CO_2 emissions associated with visitors travelling to and within Norway. It is one of several operational tools designed to support a shift to more sustainable tourism planning and development under the National Tourism Strategy 2030. It takes a passenger-based approach and was developed by Innovation Norway in collaboration with the Norwegian Institute for Air Research. The CO2rism tool is used by destinations to gain insights into the emissions profile of different tourists. By combining emissions data with data on tourist arrivals, the main transport mode from different source markets, and tourist travel patterns, the calculator estimates CO_2 emissions connected to each of the markets. Length of stay is also calculated, with information provided on daily emissions.

Source: (OECD, 2022)

For destinations where aviation is the only feasible option

For some destinations, alternative modes to aviation are not feasible due to geographic constraints, be that inaccessible land, sea, or very long distances. Some such countries are also highly dependent on inbound tourism from other countries as a driver of economic prosperity, and do not have populations of sufficient size or wealth for domestic tourism to offset a potential decrease in international arrivals due to decarbonisation. For countries in this position, it is important for government to work closely with the aviation and tourism industries to do two key things 1) accelerate efforts to bring SAF use and alternative propulsion aircraft online and 2) incentivise longer stays from international inbound tourism.

Regarding the first point, the section of this report titled "Exploring the impacts of decarbonising aviation on connectivity and operations" outlines various policy measures governments should consider to help scale up SAF production and use, and accelerate development of alternative propulsion technologies. In addition, for aviation dependent tourism destinations, governments should consider building closer partnerships with national carriers to accelerate decarbonisation efforts. Box 3 sets out the case of Air New Zealand, which provides an example of the steps ambitious airlines can take to decarbonise, as well the limitations they face without more robust global industrial and policy support.

Box 3. Air New Zealand's decarbonisation efforts

In 2022, Air New Zealand announced a Science Based Targets initiative (SBTi) validated target to reduce its carbon intensity (measured as emissions per revenue tonne kilometre) 29.8% by 2030 from a 2019 baseline as part of its "Flight NZ0" decarbonisation roadmap to achieve net-zero emissions by 2050. The airline identified five key levers for decarbonisation which covered SAF deployment, alternative propulsion aircraft on domestic routes, accelerated fleet renewal, improving in-flight and ground-based operational efficiency, and credible carbon removal solutions. This emissions target was more ambitious than the global aviation industry's 5% fuel-specific emissions reduction target over the same period.

Recognising SAF as the biggest decarbonisation lever for long-haul flights, in 2021 Air New Zealand and the New Zealand government signed a memorandum of understanding to run a closed request for proposals (RFP) process for innovation leaders to demonstrate the feasibility of operating a SAF plant at a commercial scale in New Zealand. This was followed in 2023, by the airline and government providing co-funding of over NZD 2 million to carry out more detailed studies to investigate the technical, environmental, supply chain and economic factors involved in domestic SAF production from woody biomass and municipal solid waste, partnering with global SAF company LanzaJet. Findings are expected by early 2025. Air New Zealand has also taken bold steps to accelerate deployment of alternative propulsion aircraft, signing strategic agreements with nine aircraft developers following a product requirements document (PRD) process, setting a public-facing goal to replace its Q300 fleet with next generation aircraft from 2030, and ordering BETA ALIA electric aircraft to begin domestic commercial cargo operations from 2026.

However, Air New Zealand retracted its 2030 target and withdrew from the SBTi network in 2024 as many of the levers needed to meet the target- including the availability of new aircraft, the affordability and availability of alternative jet fuels, and global and domestic regulatory and policy support- are outside the airline's direct control and remain challenging. The airline remains a signatory to the Clean Skies for Tomorrow ambition statement, supporting 10% SAF in 2030, and still aims to deliver net-zero emissions in 2050, as part of supporting the ICAO 2050 LTAG. It has also begun work to set a new near-term emissions reduction target that better reflects the challenges relating to aircraft and SAF availability.

Source: (Air New Zealand, 2021, 2023, 2024; MBIE, 2023)

Regarding the second point, incentivising longer stays from international inbound tourism represents a win-win for helping to reduce the carbon intensity of these trips while increasing their economic contribution to the host economy. Such efforts are doubly important in an era where the typical length of stay for tourists is shrinking for tourism destinations, with visitors instead often opting for shorter breaks to multiple destinations. Reasons for this include increasing availability of low-cost flights coupled with higher disposable income of travellers and strong marketing strategies by competing destinations (Almeida et al., 2021; The Travel Foundation, 2023).

In recent years, many destinations have also been experiencing overcrowding, where local infrastructure in particularly popular cities or regions has struggled to accommodate vastly inflated arrival numbers. As a result, efforts to sustainably disperse visitors and better spread the benefits of tourism both within and across destinations are becoming more common and are increasingly part of the strategic agenda for tourism, as is the integration of tourism into wider national and regional development agendas (OECD, 2024b). Such efforts are also complementary to reducing the carbon intensity of arrivals by air through encouraging tourists to stay longer in the country, exploring areas which they may not have previously considered. Box 4 sets out one example of such an initiative in Japan, noting that to optimise emissions savings, governments should also incentivise sustainable land transport modes for visitors, like rail and use of electric vehicles where possible.

Box 4. Japan’s Tourism Nation Promotion Basic Plan 2023-25

The plan focuses on attracting longer-staying visitors and fostering regional revitalisation by developing more offerings and funding events, tourist accommodation and facilities beyond the main tourist destinations. In 2023, 11 “Model Tourist Destinations” were designated in regional areas with the aim of encouraging international tourists to explore Japan beyond its main cities and to attract travellers to rural areas where they can experience nature, history and unique culture. Although developing a more diverse tourism offering requires investments in tourism and community infrastructure to support increased visitation, doing so can have significant economic and social benefits for local communities.

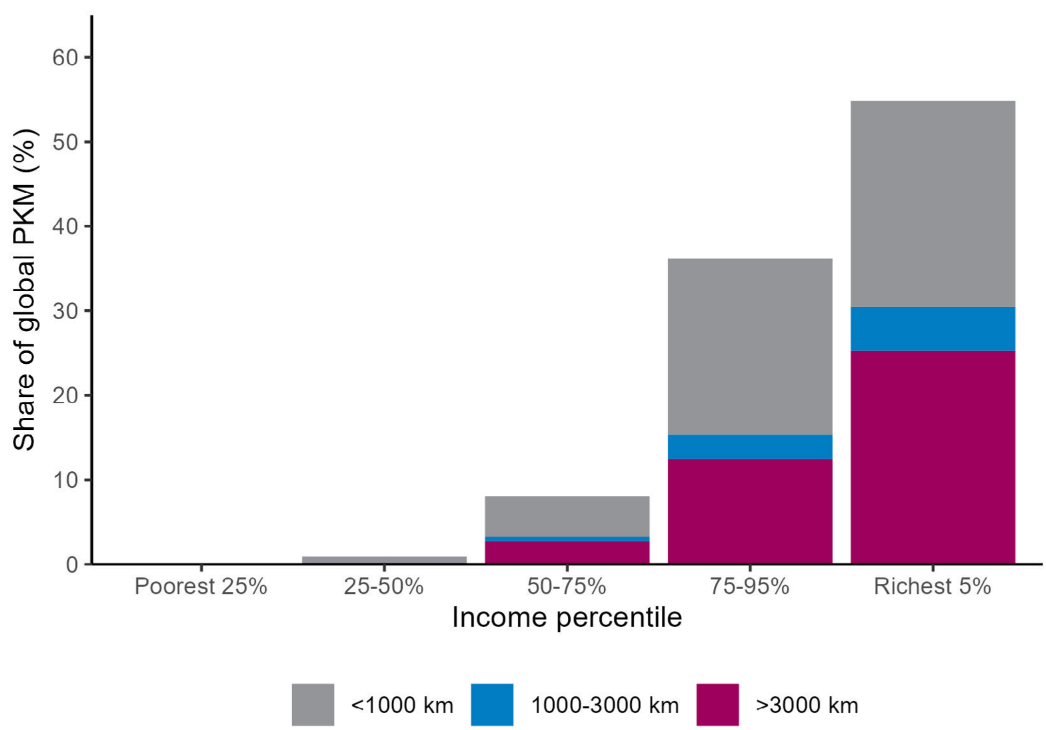
Source: (Ministry of Land Infrastructure Transport and Tourism, 2024; OECD, 2024b)

Exploring the impacts of decarbonising aviation on equity

In 2022, aviation accounted for 2% of global energy-related CO_2 emissions (around 80% of the pre-pandemic peak in 2019 of around 2.5%). Aviation emissions have grown faster in recent decades than rail, road or shipping (IEA, 2024). Even if less than many other industries, it is disproportionately driven by a small fraction of the world's population. Studies reveal that a minority of high-mobility individuals are responsible for most air travel, in terms of trip frequency, distance covered, and emissions caused. This inequality is stark even in countries where flying is relatively common (Gössling & Humpe, 2020; Ivanova & Wood, 2020). For example, in the UK, one-half of the population does not engage in air travel every year, while 15% of the population accounts for 70% of all flights (Hopkinson & Cairns, 2021). In many low-income countries, the proportion of the population flying annually is even lower.

Figure 15 shows that the wealthiest 25% of the world's population is responsible for over 90% of aviation-related travel activity (measured in passenger-kilometres) and resultant CO_2 emissions. The wealthiest 5% alone accounts for more than 55% of aviation activity and emissions, and tends to take longer trips - accounting for 60% of global passenger-kilometres for trips over 3 000 kilometres.

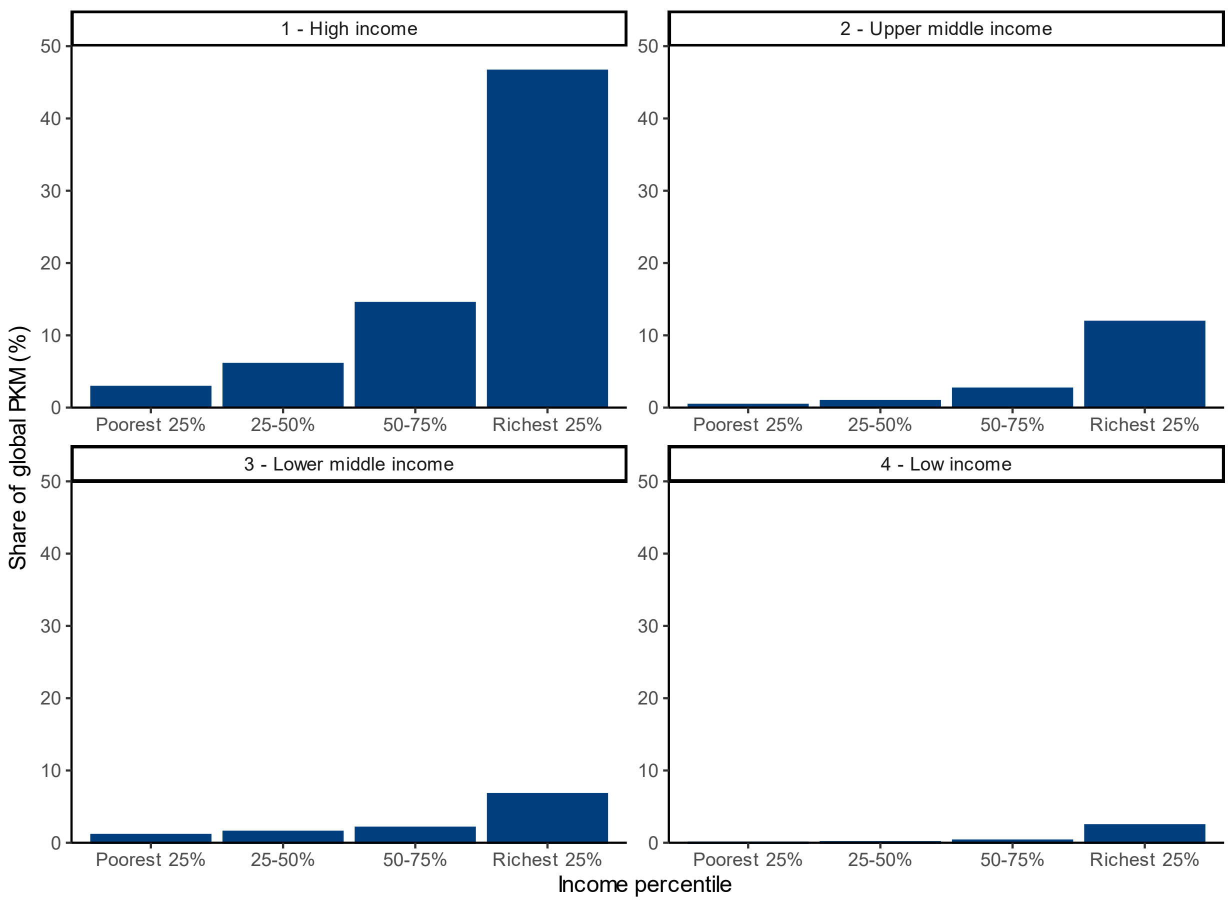
Figure 15. Air travel activity access by global income percentile



Note: Figure depicts ITF modelled estimates for 2019 (the base year). For this analysis, country-level income distributions were embedded into the ITF modelling framework. Income distributions were sourced from (World Inequality Database, 2022) and modelled at a country level representing the average income and the Gini coefficient. Air travel costs are calculated within the ITF modelling framework. Finally, the values for individuals participating in air travel by income group presented in the "Elite Status" report (Hopkinson & Cairns, 2021) for several countries were used to calibrate the model.

Furthermore, as Figure 16 illustrates, the distribution in access to air travel between different countries is uneven. In high income countries, the wealthiest 25% of the population contributes to 45% of global aviation activity, whereas in low- and lower-middle-income countries, it drops to 8-10%. Globally, individuals under the median income (income percentile 50) barely participate in air travel. This cohort in high-income countries contributes to only 9% of total aviation activity, while in the rest of the country groupings (upper-middle, lower-middle, and low-income) it is negligible.

Figure 16. Access to air travel by income and country grouping



Note: Figure depicts ITF modelled estimates for 2019 (the base year). Income classifications ("Low-income", "Lower-middle-income", "Upper-middle-income" and "High-income") are based on the World Bank's World Development Index.

As observed by (Gössling & Cohen, 2014), the significant contribution of a small group of highly mobile, affluent travellers to overall emissions is absent from much public discourse. Instead, air travel is portrayed as a global norm (Gössling et al., 2019), masking the reality that it remains inaccessible to a large portion of the world's population. This skewed perception of air travel has significant implications for how policies aimed at decarbonising aviation are perceived.

Costs of decarbonising aviation are progressively distributed

The equity implications of decarbonising aviation are intricately tied to the unequal distribution of air travel. Policies designed to reduce aviation emissions, which typically put upward pressures on air ticket prices, inherently affect wealthier frequent flyers more than the average population, in absolute terms. The strong link between income and air travel means that the costs of such policies are progressively distributed, with higher-income groups bearing a larger share of the cost – consistent with the "polluter pays principle" (Büchs et al., 2014; Büchs & Mattioli, 2024). This makes economic measures, such as carbon pricing or air taxes, potentially progressive tools in tackling emissions without unduly burdening low-income populations. This differs from carbon pricing for many other goods, which is typically regressive in nature (pre-redistribution of revenue) (Büchs & Mattioli, 2024).

Despite the broader societal expansion of air travel in recent decades, particularly among disadvantaged groups (low-income, low-education, and non-white communities), the overall inequality in air travel remains substantial. The growth of low-cost airlines (Dobruszkes & Mondou, 2013), the social normalisation of flying (Gössling et al., 2019), and the accelerated dispersion of social networks (Mattioli et al., 2021) have enabled more people from disadvantaged backgrounds to fly. Indeed, air travel among disadvantaged groups has increased more than among non-disadvantaged groups, relative to the amount of air travel each group undertook in the past. However, in absolute terms, wealthier individuals have contributed much more to the growth in air passenger kilometres (Büchs & Mattioli, 2021).

This persistent inequality means that decarbonisation policies targeting aviation will not disproportionately burden disadvantaged groups, who account for a relatively small share of air travel. Table 4 shows that under the Baseline scenario, the larger growth of air travel activity towards 2060 could allow relatively more individuals from low-income cohorts to fly than the NZE scenario. Access to air travel of low-income cohorts is 37% higher in the Baseline scenario compared to the NZE scenario, while it is only 33% higher for high-income cohorts. Therefore, in the NZE scenario, inequality in access to air travel is marginally increased. However, avoiding this marginal increase in inequality by not taking action would come at the high environmental cost of not reaching net-zero emissions by 2060. Furthermore, decarbonisation would not fundamentally change the structural inequality in access to air travel.

Table 4. Growth difference under the Baseline and NZE scenarios

	Income 25%	Income 50%	Income 75%	Income 90%
Relative growth difference between scenarios (2060 pkm Baseline / 2060 pkm NZE)	1.37	1.37	1.33	1.33
Absolute growth difference between scenarios (2060 pkm Baseline - 2060 pkm NZE)	2.7 billion pkm	9.1 billion pkm	207.1 billion pkm	7 755.2 billion pkm

Note: Table presents ITF modelled estimates. Baseline and Net Zero Emissions (NZE) refer to ITF modelled scenarios.

Policy insights

Policy measures to decarbonise aviation that increase air ticket prices are often seen as disproportionately affecting low-income groups. However, this argument is largely unfounded in most circumstances and delays climate action. In view of this, proposals by some governments to reduce air passenger duties are questionable from a climate change and social justice perspective (Aviation Environment Federation, 2021; The Guardian, 2024). Instead, policy design could more effectively and fairly target frequent flyers, who are typically wealthier, while sparing occasional flyers from undue financial burdens.

Frequent air miles taxes (which take flight emissions and number of flights into account), and frequent-flyer levies (FFLs) are more equitable solutions compared to flat taxes (Büchs & Mattioli, 2024). The International Council on Clean Transportation (ICCT) estimates that a FFL would generate 81% of its revenue from individuals who take more than six flights per year, with 67% of the revenue coming from high-income countries. In contrast, a flat tax would see 41% of revenue collected from frequent flyers and 51% from high-income countries. This indicates that, although both tax approaches are progressive, the FFL is more targeted, reducing the risk of pricing out lower-income individuals from air travel.

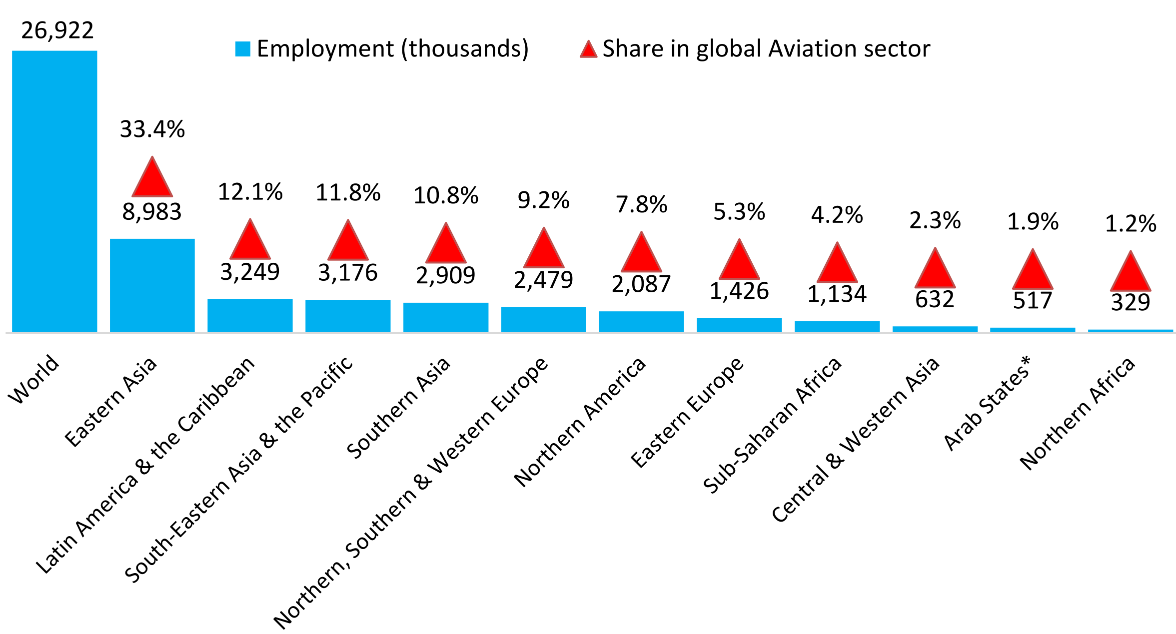
The issue of equity extends beyond commercial aviation to private jets, which are far more carbon intensive. Private jets account for around 4% of global aviation emissions but are responsible for disproportionately high environmental impacts per passenger (Gössling & Humpe, 2020). In 2019, 10% of all flights departing from France were via private jets, with half of them covering distances of less than 500 kilometres. To address the disproportionate impact of private aviation, taxes on private jet fuel and tickets (based on flight distance and aircraft weight) could help account for their outsized climate impact (Transport & Environment, 2021). Moreover, stricter requirements for private jets to use higher shares of SAFs and, in time, transition to zero-emission aircraft (electric or hydrogen propelled) should be considered.

Exploring the impacts of decarbonising aviation on the labour market

Estimates for the scale of global employment attributable to the civil aviation sector vary. According to the Air Transport Action Group (ATAG), in 2019 the industry provided 11.3 million "direct jobs." This comprised: 3.6 million jobs in airlines (flight and cabin crews, executives, ground services, check-in, training and maintenance staff); 237 000 jobs in air navigation service providers (air traffic controllers, engineers and executives); 1.3 million jobs in civil aerospace (engineers and designers of civil aircraft, engines and components); 648 000 jobs in airport operations (planning, engineering and security); and 5.5 million jobs in other on-airport roles (retail, car rental, government agencies such as customs and immigration, freight forwarders and some catering). In addition to this, ATAG estimates there are 18.1 million "indirect jobs" generated through the purchase of goods and services from companies in the air transport industry supply chain, 13.5 million "induced jobs" through the spending of wages, and 44.8 million aviation-enabled tourism jobs (ATAG, 2020).

According to the latest International Labour Organisation (ILO) estimates, the aviation sector accounts for 26.9 million jobs, or 0.8% of global employment. Of this, as shown in Figure 17, Asia and the Pacific regions collectively account for more than half (56%) of the global employment (which is equivalent to more than 15 million jobs), followed by the Americas (20%), Europe and Central Asia (17%), Africa (5%), and the Arab States (2%) (ILO, 2024b). The ILO data disaggregates between six occupational groups for the aviation sector: aircraft pilots and related associate professionals, air traffic controllers, technicians, mechanics and repairers, travel attendants and stewards, and freight handlers.

Figure 17. Global aviation sector employment by sub-region



*Employment coverage was less than 50% in the Arab States

Source: ILO calculations based on data from the ILO Harmonized Microdata Repository

Decarbonisation may change aggregate in-sector employment levels

As noted earlier in this report, by 2060, air ticket prices under the ITF's Net Zero scenario are projected to be, on average, 25-30% higher than in the Baseline scenario due to the increased costs associated with decarbonising aviation. This, together with the increased availability of cleaner alternative modes like high-speed rail in some regions, means that air passenger-kilometres in 2060 under the NZE scenario are expected to be around 30% lower than in the Baseline scenario. While air passenger-kilometres are still expected to grow strongly between 2024 and 2060 along with associated jobs, the demand suppression and substitution effect of decarbonisation may mean fewer jobs in the aviation sector than might otherwise be the case.

Assuming a linear relationship between the volume of air passenger-kilometres and the number of associated jobs in the aviation sector, and using the ILO's estimate of approximately 26.9 million aviation jobs globally in 2024, the simple estimates set out in Table 5 can be made for aggregate in-sector employment levels by 2060 under the ITF's Baseline and NZE scenarios.

Table 5. Estimates for global aggregate aviation in-sector employment, 2060

	Air passenger-kilometres	Associated aggregate in-sector employment*
Baseline scenario (A continuation of the status quo, where only policies that are already adopted are reflected)	30.45 trillion kilometres	90 million jobs (235% increase on 2024)
Net Zero Emissions (NZE) scenario (Further policy interventions that lead to a widespread adoption of SAF and allow net-zero aviation to be achieved by 2060)	20.71 trillion kilometres	61 million jobs (127% increase on 2024)

*"In-sector employment" is considered to cover the ILO's classification of occupational groups (aircraft pilots and related associate professionals, air traffic controllers, technicians, mechanics and repairers, travel attendants and stewards, and freight handlers).

Using these same assumptions, estimates can also be made for the distribution of aviation jobs into the three country groups set out in Table 6.

Table 6. Aviation in-sector employment by country group, 2060

	Europe	Other OECD countries + China	Other countries
Baseline scenario	16 million jobs	42 million jobs	32 million jobs
Net Zero Emissions (NZE) scenario	11 million jobs	28 million jobs	22 million jobs

The above estimates are illustrative of the potential scale of the change in aggregate aviation in-sector employment by 2060. Several important variables which may affect employment levels are not included in these estimates - particularly the impact of higher load factors or larger aircraft, changes in technology from alternative propulsion systems, and the use of more advanced computing to improve both ground and air-based operational efficiency. In addition, these estimates do not include changes in aggregate employment for jobs in the wider aviation supply chain, like fuel production.

Skills requirements will change

To make decarbonisation a reality, the skills profile of jobs in the aviation sector will need to evolve. This will include a wide variety of roles, including airport workers implementing and operating adapted or new systems to re-fuel aircraft with electricity, hydrogen or SAF; flight crews handling aircraft with alternative propulsion systems; technicians and mechanics keeping new aircraft types operating in safe conditions; and air traffic controllers harnessing advanced real-time data analysis methods and artificial intelligence to enhance the efficiency of ground and air-based operations. As the effects of climate change are felt over coming decades, aviation workers will also need to adapt to several operational challenges, including increasing air turbulence, extreme heat disrupting airport functioning, and rising sea levels threatening the resilience of airport infrastructure (European Commission, 2024b; The International Transport Workers Federation, 2022).

To help prepare the way, governments, the private sector, labour organisations, and the education sector will need to collaborate. Skills forecasting to better understand demographic changes and the requirements necessary for different roles in the future, followed by the establishment and delivery of up-skilling and re-skilling programmes, are sensible first steps. The European Commission's "Pact for Skills", part of the European Skills Agenda, is a good example of such collaboration. The Pact aims to support public and private sector organisations with upskilling and reskilling so they can take advantage of the green and digital transitions. Members of the Pact have access to three dedicated services: a networking hub (to promote their activities, and find partners or relevant EU tools), a knowledge hub (which organises webinars, seminars, peer learning activities and provides updates on EU policies and instruments), and a guidance hub (which offers information about EU and national funding opportunities as well as advice on partnering with national and regional authorities) (European Commission, 2024b). Box 5 sets out how the Pact has been applied in the European Aerospace and Defence sector – one of 14 industrial ecosystems identified in the EU Industrial Strategy.

Box 5. European Commission Aerospace and Defence ecosystem Large-Scale Skills partnerships

In 2020 top leaders of the European aerospace and defence industry called for the creation of a Large-Scale Skills partnerships in close cooperation with universities and vocational educational and training organisations, to address the impacts of the Covid-19 pandemic, challenges related to sustainable aviation, rapid digitalisation, and boosting sector attractiveness for young people and women. Concrete action along three main axes were identified at a cost of around EUR 1 billion over 10 years:

1. Skills forecasting with the objective of anticipating all main skills gaps to address over 5-10 years. As of 2023, eight priority key skills clusters were identified; behavioral/transversal skills, carbon neutrality, circular economy, cybersecurity, data analytics, artificial intelligence, modelisation based system engineering, and high-performance computing.
2. The establishment of up-skilling and re-skilling programmes for emerging and transforming jobs targeted at around 200 000 EU employees (30% of current workforce), by 2026.
3. Talent development and engagement partnerships to boost attraction, development and retention of workers, given estimates that an additional 300 000 jobs will be required by 2030.

Several major industry organisations are involved in the initiative, including Airbus, Rolls Royce, ATR, and Saab AB, as well as various associations and educational establishments spanning Belgium, Denmark, France, Germany, Italy, the Netherlands, Poland and Spain.

Source: (European Commission, 2024a)

Much of the growth in aviation demand and associated jobs out to 2060 will take place in the Asia-Pacific, Middle East, Africa and Latin American regions. Governments in mature and emerging aviation markets alike will need to make concerted efforts (similar to the EU's approach) to partner with a wide variety of stakeholders to ready the industry for decarbonisation.

SAF scale-up offers industrial development opportunities

In addition to helping to decarbonise air travel, the scale of up SAF production will stimulate economies around the world. In comparison to oil and gas production, where 90% of output is centred in only 22 countries, there are fewer places in the world where some production of SAF will not be possible given the diversity of potential feedstocks- ranging from agricultural and forestry residues, municipal solid waste, to eventually renewable electricity and captured carbon through the power-to-liquid pathway (ATAG, 2021; IEA, 2023a).

As noted earlier, to reach net zero aviation, around 500 billion litres of SAF will need to be produced annually by 2060. Assuming the capacity of an average production facility is around 120 million litres of SAF per year, this is equivalent to approximately 4 000 - 5 000 facilities globally (ATAG, 2021). The number of required facilities could be lower if the energy industry develops a hub-and spoke model, with regional production of alcohols and hydrogen which are then converted into SAF at central hubs (ATAG, 2021). While cost estimates vary, this level of production may call for investment of between USD 1-1.5 trillion, which annualised is equivalent to around 6% of yearly oil and gas capital expenditure (noting that facilities will produce and monetise fuels and co-products additional to SAF, so revenues from aviation will only support a portion of this investment) (ATAG, 2021; IEA, 2023b).

This transition will also generate jobs – both new ones and re- or up-skilled incumbent positions to repurpose existing fossil-fuel-based facilities. New jobs may be required to gather, process and transport feedstock or to design, construct and operate facilities, as well as other roles across the wider SAF supply chain. Under the ITF's NZE scenario, estimates suggest this could generate up to 14 million jobs in SAF production worldwide - with around 1.4 million people employed in the production facilities themselves and up to 12.6 million in the construction of facilities, collecting feedstocks and logistics (ICF Report for ATAG Waypoint 2050, 2021). This compares to around 1.1 million total jobs under a Baseline scenario where SAF scale-up is limited to around 40 billion litres by 2060, reflecting only policies that are already adopted.

Job creation from large-scale SAF production could provide livelihoods for groups that previously did not participate in the global energy market, including rural inhabitants of middle- and low-income countries. It may also offset, to some extent, the lower rate of job creation for in-sector aviation employment under a NZE scenario. Beyond emissions savings, countries may also see benefits of investing in SAF production to improve domestic fuel-supply resilience and national balance-of-payments positions as they move from fuel importers to exporters (International Transport Workers Federation, 2022).

Policy insights

An international Just Transition Task Force is needed for aviation

In the context of decarbonisation, the ILO defines a Just Transition as greening the economy in a way that is as fair and inclusive as possible to everyone concerned, creating decent work opportunities and leaving no one behind. It involves maximising the social and economic opportunities of climate action, while minimising and carefully managing any challenges – including through effective social dialogue among all groups impacted, and through respect for fundamental labour principles and rights (ILO, 2024a).

Given the scale of change the aviation labour force must go through to achieve decarbonisation in the sector, it is important that the principle of a Just Transition is at the centre of national and international policy development over the coming decades.

Fortunately, another hard-to-abate transport sector has already cut a path forward which may help guide efforts for air transport. In 2021, during the 26th United Nations Climate Change Conference of the Parties (COP 26) in Glasgow, the International Chamber of Shipping (ICS), the International Transport Workers' Federation (ITF), the United Nations Global Compact (UNGC), the International Maritime Organization (IMO), and the ILO established the "Maritime Just Transition Task Force", to ensure that the sector's response to decarbonisation puts seafarers at the heart of the solution, supported by globally established Just Transition principles (United Nations Global Compact, 2024). Recognising that the introduction of alternative fuels necessary to decarbonise the shipping industry would require new skills for maritime workers, the Task Force commissioned a detailed study to investigate how best to support the labour force during the transition, including estimating the number of workers requiring additional training through to 2050 (DNV, 2022). Informed by the findings of this study, the Task Force then developed a 10-point action plan for international organisations, industry, workers, and academia to take concrete steps towards re- and up-skilling initiatives to meet decarbonisation targets (Maritime Just Transition Task Force, 2022).

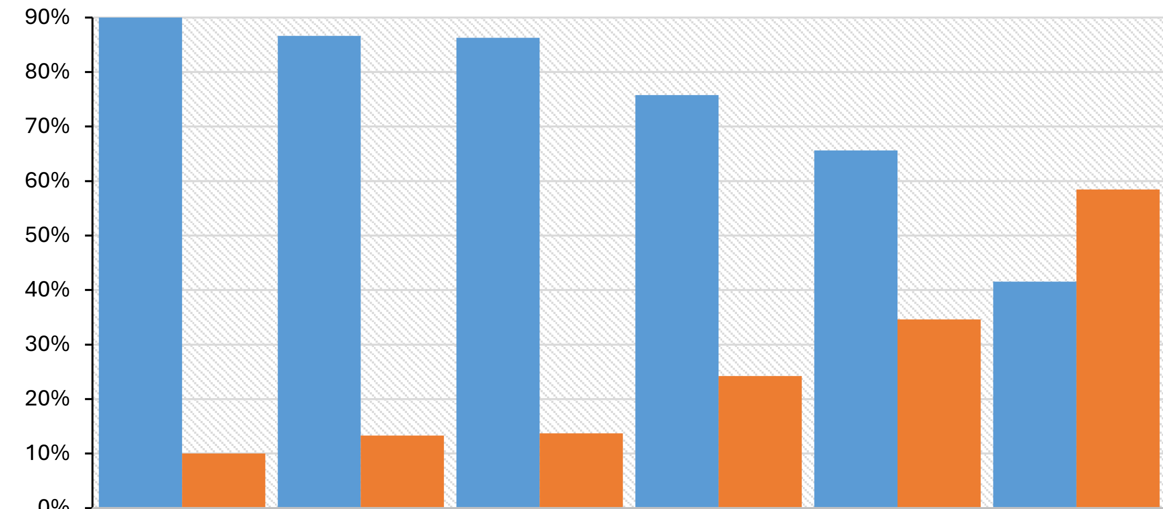
The aviation sector should follow a similar approach, establishing an international "Aviation Just Transition Task Force", initially focusing on establishing a better understanding of the scale and nature of challenges and opportunities ahead for workers in aviation and the wider supply chain. At the national level, governments could consider creating "just transition" committees comprising all key aviation sector stakeholders to undertake collective long-term workforce planning (The International Transport Workers Federation, 2022).

Labour force transition offers opportunities to improve gender balance of workforce

Currently, the aviation workforce is dominated by men. According to the latest data available from the ILO as set out in Figure 18, men account for the vast majority of more technical jobs, especially regarding air traffic safety electronics technicians, aircraft engine mechanics and repairers, aircraft pilots and related associate professionals, air traffic controllers, and freight handlers. Travel attendants are the only occupational group where women account for more roles than men, at 58%.

The global aviation industry will need to attract millions of additional highly skilled workers over the coming decades to make decarbonisation a reality, often competing with other sectors of the economy seeking similarly skilled employees (OECD, 2023a). Attracting more women into the more technical occupational groups will be important to improve the pipeline of skilled workers for the aviation industry.

Figure 18. Employment distribution by gender and occupational group, ILO latest available data



	Air Traffic Safety Electronics Technicians	Aircraft Engine Mechanics and Repairers	Aircraft Pilots and Related Associate Professionals	Air Traffic Controllers	Freight Handlers	Travel Attendants and Travel Stewards
Male	90%	87%	86%	76%	66%	42%
Female	10%	13%	14%	24%	35%	58%

Notes: Countries included in each of the occupational groups: 3153 (Aircraft pilots and related Associate Professionals): Angola, Brazil, Colombia, Czechia, France, Mexico, Peru, Philippines, Serbia, Switzerland, Thailand, Tunisia, United Arab Emirates, United Kingdom of Great Britain and Northern Ireland, Uruguay, Vanuatu, Viet Nam; 3154 (Air traffic controllers): Angola, Brazil, Chile, Colombia, Czechia, Ecuador, France, Kyrgyzstan, Maldives, Mexico, Philippines, Seychelles, Switzerland, Thailand, Timor-Leste, Tonga, United Arab Emirates, United Kingdom of Great Britain and Northern, Ireland, Uruguay, Viet Nam; 3155 (Air Traffic Safety Electronics Technicians): Brazil, Czechia, Mexico, Philippines, Serbia, Tonga, United Arab Emirates, Viet Nam; 5111 (Travel Attendants and travel stewards): Angola, Bangladesh, Brazil, Chile, Colombia, Czechia, Ecuador, Ethiopia, France, Kiribati, Lebanon, Mexico, Mongolia, Myanmar, Nepal, Pakistan, Philippines, Seychelles, Sri Lanka, Switzerland, Tanzania, United Republic of, Thailand, Tunisia, United Arab Emirates, United Kingdom of Great Britain and Northern Ireland, Vanuatu, Viet Nam; 7232 (Aircraft Engine Mechanics and Repairers): Brazil, Chile, Colombia, Czechia, El Salvador, France, Marshall Islands, Mexico, Philippines, Serbia, Switzerland, Thailand, Tunisia, United Kingdom of Great Britain and Northern Ireland, Uruguay, Viet Nam; 9333 (Freight Handlers): Angola, Bangladesh, Belarus, Belize, Bhutan, Bosnia and Herzegovina, Botswana, Brazil, Cabo Verde, Cambodia, Chile, Colombia, Costa Rica, Czechia, Dominican Republic, Ecuador, Egypt, El Salvador, Ethiopia, France, Gambia, Georgia, Guyana, Honduras, Iraq, Kiribati, Kosovo, Kyrgyzstan, Lebanon, Maldives, Marshall Islands, Mexico, Mongolia, Myanmar, Nauru, Nepal, North Macedonia, Pakistan, Palau, Panama, Peru, Philippines, Rwanda, Serbia, Seychelles, Sudan, Switzerland, Tajikistan, Tanzania, United Republic of, Thailand, Timor-Leste, Tonga, Tuvalu, Uganda, United Arab Emirates, United Kingdom of Great Britain and Northern Ireland, Uruguay, Vanuatu, Viet Nam, Wallis and Futuna.

Source: ILO calculations based on data from the ILO Harmonized Microdata Repository.

On average across OECD countries, women are over-represented in tertiary education generally, but are underrepresented in some fields of study which are important prerequisites for technical jobs in the aviation sector. Only 15% of female new entrants at tertiary level choose a science, technology, engineering or mathematics (STEM) field, compared to 41% of male new entrants (OECD, 2024a). These differences start earlier, however, with gender disparities in school performance at age 15 having long-term consequences for girls' and boys' personal and professional future (OECD, 2015b). Girls are more likely than boys to feel anxious about mathematics and are less likely to believe they can successfully perform mathematics and science tasks at designated levels, to enrol in technical and vocational programmes, or gain "hands-on" experience in potential careers through internships or job shadowing (OECD, 2015b, 2023b). Gender differences in achievement are not explained by innate ability; instead, social and cultural contexts reinforce stereotypical attitudes and behaviours that, in turn, are associated with gender differences in student performance (OECD, 2015a).

To help improve the pipeline of young women studying STEM fields and taking an interest in a potential future aviation career, aviation stakeholders across the public and private sectors could ramp up early career outreach at both secondary schools and tertiary institutes to showcase the opportunities on offer. Industry employers and education providers could also strengthen partnerships to develop job shadowing, internship, and training and apprenticeship schemes which attract more young women.

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Annex A: Scenario modelling methodology

Fuel choice model methodology

We assume that low-carbon fuels will only be adopted when it is cost-competitive to do so. Fuel prices for different SAF pathways are sourced from (World Economic Forum, 2020) and shown in Table A-1. The cost of low-carbon fuels cannot reach price parity with fossil kerosene alone. Therefore, additional policy incentives are necessary to internalise the environmental costs. The cost difference between low-carbon fuels and fossil kerosene can be reduced with carbon pricing, such as from emissions trading schemes that include aviation, and/or with financial incentives or blending mandates with financial penalties for non-compliance.

Table A-1 Fuel price assumptions (USD/Mt kerosene equivalent)

Year	HEFA	Gasification/FT	Alcohol-to-jet	PtL	Kerosene	DAC offset*
2025	1 235	1 853	2 012	2 576	600	3 444
2035	1 127	1 558	1 762	1 681	600	3 128
2045	1 083	1 470	1 664	1 357	600	2 075
2060	1 070	1 426	1 621	1 259	600	1 548

Notes: All values are in USD per million tonnes (Mt) of kerosene equivalent.

Source: (World Economic Forum, 2020)

*DAC offsets are the cost of abating the CO2 from a Mt of kerosene and are calculated assuming DAC costs of USD 1 000/tCO2 in 2025 reducing to USD 400/tCO2 by 2050.

The carbon pricing assumptions in each scenario and region are presented in Table A-2. The only emissions trading schemes that currently include aviation are in the EU and UK. Carbon prices in the EU ETS in 2024 have been approximately EUR 76/tonne of CO_2. These apply to flights in origin and destination in the EU (in-region) and do not currently apply to flights entering or leaving the EU (out-of-region). The total share of European aviation fuel demand currently covered by the EU ETS is, therefore, approximately 45%. In the baseline scenario, we assume carbon prices in Europe for in-region flights increase from today's levels to reach USD 120/tCO_2 by 2060. Flights out-of-region continue to not be covered by the EU ETS and other regions do not have any carbon pricing included.

For the high-ambition scenario, OECD countries and China have higher carbon prices that reach USD 300/tCO2 by 2060. Other emerging economies have lower carbon pricing levels that reach USD 200/tCO2. Finally, to reach net-zero aviation, even more ambitious levels of carbon pricing are needed to provide the financial incentive to adopt low-carbon fuels.

Table A-2 Carbon pricing by scenario and region (USD/tCO2)

Scenario	Region	2025	2035	2045	2060
Baseline	Europe*	84/0	100/0	108/0	120/0
	Other OECD + China	0	0	0	0
	Other	0	0	0	0
High Ambition	Europe	101	150	210	300
	Other OECD + China	101	150	210	300
	Other	63	130	158	200
Net Zero	Europe	101	159	250	400
	Other OECD + China	101	159	250	400
	Other	101	159	250	400

Note: * In-region/Out-region

Alternative fuels are only adopted in the model when their cost is lower than that of fossil kerosene. Carbon pricing is assumed to increase the cost of using kerosene in each region and thereby reduce the relative cost of using a lower-carbon alternative fuel. Additionally, several regions have financial incentives to use low-carbon fuels or regulatory blending mandates with financial penalties for non-compliance, these further reduce the relative cost of using alternative fuels.

The US Inflation Reduction Act (IRA) includes tax credits on the production of hydrogen and biofuels. The IRA Clean Fuel Tax Credits scheme offers credits equivalent to 1.75 USD/gallon for several types of biofuels, applicable both for the aviation and maritime sector (Cazzola, 2024). The IRA Clean Hydrogen Production Credit also offers credits up to USD 3 per kilogram for hydrogen and hydrogen-based fuels. However, these incentives will currently expire in 2027. A number of US states include incentives for low-carbon fuel production (via low carbon fuel standards, for example), but these are not included in this analysis. In the Baseline scenario, we assume these fuel production credits are in place until 2027 in the USA and are not extended. In the High Ambition and Net Zero scenarios, we assume they are extended until 2040 for fuel uplifted in the USA.

In Europe, the ReFuelEU aviation policy includes blending mandates for SAFs (and sub-targets for 'renewable liquid and gaseous fuels of non-biological origin', or RFNBOs), with financial penalties for non-compliance equal to twice the cost of fossil kerosene. Similar to the EU ETS, the ReFuelEU targets apply only to in-region flights in the Baseline scenario. In the High Ambition and Net Zero scenarios, the ReFuelEU targets and associated financial penalties for non-compliance are also included for out-of-region flights.

Although a number of other countries have announced blending mandates and targets to adopt SAFs, the majority do not include financial incentives or penalties for non-compliance, which are important to help fuel producers follow market signals towards the cheapest fuel. Without these additional financial motivations, SAF is not adopted significantly in the model. The ICAO CORSIA framework currently would allow for relatively affordable carbon offsets (~3-15 USD/tCO_2); however, these are excluded from the analysis due to long-standing uncertainties over their real-world carbon abatement potential (ICCT, 2018).

The long-term availability of sustainable biofuel resources is limited in order to avoid indirect land use change. The total available resources for HEFA, gasification/Fischer-Tropsch and alcohol-to-jet pathways are sourced from (World Economic Forum, 2020) and are shown in Table A-3. The model adopts the cheapest SAFs when they are cost-competitive up to the limit of their availability. For example, HEFA fuels are the first to be exhausted due to their comparatively low costs but limited availability.

Table A-3. Maximum theoretical global availability by fuel

Fuel	Availability (Mt)
HEFA	85
Gasification/FT	145
Alcohol-to-jet	260
PtL	No limit
DAC offset	No limit

Notes: Source for biofuel SAFs is (World Economic Forum, 2020)

Annex B: List of workshop participants

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International Transport Forum

Decarbonising Aviation
Exploring the Consequences

The international aviation sector has set a challenging goal to achieve net-zero carbon emissions by 2050. Reaching this target requires a substantial reduction in carbon emissions from aircraft and fuels as well as the implementation of regulatory instruments, which will impact costs that may translate to higher passenger and freight prices. As a result, changes in aviation demand growth projections could have broader implications for air connectivity, the tourism sector, equity, labour markets and the wider economy.

This project reviews decarbonisation policies and technologies to evaluate their consequences along different dimensions, and offers policy insights for governments on how to achieve net-zero aviation while mitigating any adverse impacts on different stakeholders.

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