International Transport Forum

Decarbonising Air Transport

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Decarbonising Air Transport

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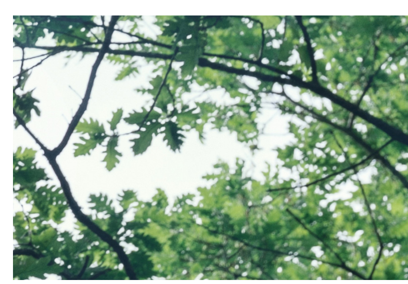

Decarbonising Transport

The International Transport Forum

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Case-Specific Policy Analysis Reports

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The report draws on desk research and insights from the ITF Workshop “Decarbonising air transport”, held on 24-25 February 2020 at the Organisation for Economic Co-operation and Development (OECD) in Paris, France (https://www.itf-oecd.org/decarbonising-air-transport-workshop). The event gathered 59 participants (see Annex) from governments, industry, academia, and civil society. The Workshop examined different policy, technology, and operational measures that can be applied regionally, nationally, and internationally to decarbonise air transport. The discussion focused on CO_2 emissions from direct aircraft fuel burn as well as airport infrastructure and operations. It excluded CO_2 emissions from aircraft manufacturing and non-CO_2 climate impacts. The Workshop was organised under the Chatham House Rule to encourage free debate.

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This work is part of the ITF Decarbonising Transport (DT) initiative, a key instrument developed by the ITF to help governments and industry to translate climate ambitions into actions. The initiative (https://www.itf-oecd.org/decarbonising-transport) brings together a partnership that extends far beyond the ITF's member countries. It includes work streams aiming to:

- track progress to evaluate how current mitigation measures contribute to reaching objectives for reducing greenhouse gas (GHG) emissions from transport
- develop in-depth sectoral and focus studies to identify effective policies in specific modes (e.g. road transport) and thematic areas (e.g. cities)
- bring policies together in a catalogue of effective measures to support countries to develop their GHG emission mitigation strategy in transport
- support the policy dialogue, leveraging on extensive engagement with the United Nations Framework Convention on Climate Change (UNFCCC), including the ITF’s designation as a focal point for transport of the Marrakech Partnership for Global Climate Action (MP-GCA).

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Glossary

Term	Definition
Air transport	The transportation of passengers and cargo using aircraft.
Annex I countries	A group of 37 developed countries committing to greenhouse gas emissions reductions under the Kyoto Protocol.
Aviation	All activities surrounding and including air transport, such as the design, development, production, operation and use of aircraft, and the activities of airports and air navigation service providers.
Biofuels	Liquid or gaseous fuels derived from biomass.
Carbon intensity	The amount of CO_2 emitted per unit of activity. The carbon intensity of air transport refers to the CO_2 emissions generated per unit of air transport activity, generally expressed per revenue passenger kilometre (RPK) or revenue tonne-kilometre (RTK). The carbon intensity of fuels is the amount of CO_2 emitted per unit of energy content.
Carbon leakage	Transfer of production activities towards global areas with less stringent climate policies, leading to the relocation of CO_2 emissions. See Box 5.
Carbon offset	A tradeable certificate or other instrument representing an amount of carbon removed from the atmosphere in a durable, quantifiable, verifiable way through intentional action.
Carbon offsetting	A mechanism allowing entities to pay for CO_2 emissions reduction projects carried out by other entities and claim the CO_2 emissions reductions themselves. See Box 3.
Double counting of emission reductions	The situation occurring when a tradeable certificate of emission reductions is counted by both selling and purchasing entities.
Electrofuels	Synthetic fuels obtained from the combination of hydrogen and carbon derived from electricity.
Energy intensity	The amount of energy consumed per unit of air transport activity. In air transport, activity is generally expressed in revenue passenger kilometre (RPK) or revenue tonne-kilometre (RTK).
Energy vector	Substance or system that contains energy and allows its storage, transport, transmission, conversion and use.
Fuel shuffling	A practice whereby regulated entities under an emission-reduction scheme, such as an ETS or an LCFS, benefit from selling less carbon-intensive products in the regulated area and more carbon-intensive products to non-regulated markets, leading to minimal, if any, change in net-emission reductions.
Fuel tankering	A cost-saving practice used by airlines, which consists of carrying excess fuel on board flights to avoid refuelling in countries with higher fuel costs, leading to excess fuel burn and CO_2 emissions. See Box 13.

Term	Definition
Kyoto Protocol	The first climate agreement of the United Nations Framework Convention on Climate Change (UNFCCC), which set GHG emissions reduction targets for 37 industrialised countries, called Annex I countries, operationalising the commitment that bound member states to act in the interests of human safety, even in the face of scientific uncertainty.
Low-carbon aviation fuels (LCAF)	Petroleum-based aviation fuels characterised by lower life cycle GHG emissions than a baseline emissions value for conventional jet fuel.
Low-carbon fuel standard (LCFS)	A policy measure that sets a decreasing threshold for the life cycle carbon intensity of fuel and integrates a market-based mechanism for regulated entities to trade credits and deficits to meet the carbon intensity requirement.
Paris Agreement	Following the Kyoto Protocol, the Paris Agreement is the second legally binding climate agreement of the UNFCCC, involving all signatory countries. It entered into force in November 2016. It aims to limit the increase in global average temperatures to well below 2°C above pre-industrial levels and to continue efforts to limit the temperature increase to 1.5°C.
Radiative forcing	Measure of the influence of greenhouse gases on the radiant energy impinging on the Earth. Positive forcing contributes to global warming and thus climate change. Effective radiative forcing is used to include the effect of fast feedback and adjustments, e.g. from clouds and aerosols, in addition to greenhouse gases.
Rebound effect	The effect occurring when energy efficiency improvements do not translate directly into energy savings due to efficiency improvements lowering operating costs and stimulating demand as a result.
Revenue passenger kilometre (RPK)	The number of kilometres travelled by paying passengers. It is an indicator of passenger transport activity and it usually refers to all flights operated by an airline in a given year.
Revenue tonne-kilometre (RTK)	The revenue load in tonnes multiplied by the distance flown. It is an indicator of freight transport activity and it usually refers to all flights operated by an airline in a given year.
Sustainable aviation fuels (SAF)	In this report, SAF are drop-in biofuels and synthetic fuels (synfuels) with a lower life cycle carbon intensity than conventional jet fuel.
Surface access	Trips to and from the airport made by passengers and airport staff.
Synthetic fuels (synfuels)	Hydrocarbon fuels produced through chemical processes combining carbon and hydrogen.

Note: Definitions of policy and technology-related measures are given in tables 4, 5, and 6.

Acronyms

Acronym	Term
A-CDM	Airport collaborative decision-making
ACI	Airport Council International
ANS	Air navigation services
ANSP	Air navigation service provider
APU	Auxiliary power unit
ASA	Air Services Agreement
ASTM	American Society for Testing and Materials
ATC	Air traffic control
ATJ-SPK	Alcohol-to-Jet synthetic paraffinic kerosene
ATM	Air traffic management
BtL	Biomass-to-Liquids
BWB	Blended wing body
CAEP	ICAO Committee on Aviation Environmental Protection
CANSO	Civil Air Navigation Services Organisation
CDM	Clean Development Mechanism
CER	Certified emissions reduction under the CDM
CO_2	Carbon dioxide
CORSIA	Carbon Offsetting and Reduction Scheme for International Aviation of the International Civil Aviation Organisation (ICAO)
DAC	Direct air capture
DT	Decarbonising Transport initiative of the International Transport Forum
EASA	European Union Aviation Safety Agency
EEA	European Economic Area
EEU	Eligible emissions units under CORSIA

Acronym	Term
EIA	US Energy Information Administration
ETIP	European Technology and Innovation Platform
ETS	Emissions Trading Scheme
EUAAs	European Union Aviation Allowances in the EU ETS
FAA	Federal Aviation Administration
FABs	Functional Airspace Blocks
FT	Fischer Tropsch
FTG	ICAO Fuel Task Group
FT-SPK	Fischer Tropsch synthetic paraffinic kerosene
FT-SPKA	Fischer Tropsch synthetic paraffinic kerosene with aromatics
GHG	Greenhouse gas
GMBM	Global market-based measure
HCC	High Council on Climate (Haut Conseil pour le Climat)
HEFA-SPK	Hydro-processed esters and fatty acids synthetic paraffinic kerosene
HFS-SIP	Hydro-processed fermented sugar synthetic iso-paraffinic kerosene
HVAC	Heating, ventilation and cooling
HVO	Hydro-treated vegetable oil
IAS	International aviation and shipping
IATA	International Air Transport Association
ICAO	International Civil Aviation Organisation
ICCT	International Council on Clean Transportation
IEA	International Energy Agency
ILUC	Indirect land-use change
IMO	International Maritime Organisation
IPCC	Intergovernmental Panel on Climate Change
ITF	International Transport Forum at the Organisation for Economic Co-operation and Development (OECD)

Acronym	Term
JADC	Japan Aircraft Development Corporation
LCAF	Low-carbon aviation fuels
LCFS	Low-carbon fuel standard
LUC	Land-use change
MEPC	Marine Environment Protection Committee
MJ	Mega joule
Mt	Million metric tonnes
NDC	Nationally Determined Contribution
OECD	Organisation for Economic Co-operation and Development
R&D	Research and Development
RF	Radiative forcing
RPK	Revenue passenger kilometre
SAF	Sustainable aviation fuel
SARP	Standards and Recommended Practices
SDGs	United Nations Sustainable Development Goals
SES	Single European Sky
SESAR	Single European Sky ATM Research
SIP	Synthetic iso-paraffinic kerosene
SPK	Synthetic paraffinic kerosene
TAB	Technical Advisory Board
TCAD	Transport Climate Action Directory
UHBR	Ultra high bypass ratio
UNFCCC	United Nations Framework Convention on Climate Change

Executive summary

What we did

This report provides an overview of government policies to decarbonise the air transport sector. The report first reviews the contribution of air transport to global carbon emissions and efforts to contain them. It then examines technologies and operational improvements that can increase energy efficiency and reduce carbon emissions, focussing on barriers to widespread adoption. The report further details government policies to accelerate the decarbonisation of air transport, covering instruments in use and actions that could be adopted at the international, supra-national and national levels. Finally, the report charts a possible pathway for decarbonising the aviation sector, identifying a range of actions that governments and industry can undertake.

What we found

CO_2 emissions from fuels consumed in domestic and international air transport accounted for around 2.5% of all energy-related CO_2 emissions before the Covid-19 crisis. These emissions were distributed unevenly across countries: the United States alone accounted for almost a quarter of the global total, while less developed countries with half of the world's population account for only around 10% of direct CO_2 emissions from air transport. Although the total carbon emissions from air transport are small compared, for example, to food or clothes production or road transport, they are expected to rise rapidly once the industry recovers from the Covid-19 pandemic.

Indeed, over the past few decades, and despite significant fuel-efficiency improvements achieved by the sector, the number of flights taken has been increasing so rapidly that the sector's carbon emissions have been on an upward trajectory. At the same time, abatement options in air transport have been limited by the reliance of aircraft on carbon-intensive fuels. No sector is exempt from tackling climate change, and as a significant consumer of fossil fuels, aviation is no exception.

Airports, airlines, other industry stakeholders, and governments have been increasing efforts to mitigate carbon emissions from air transport. Many initiatives to mitigate carbon emissions from domestic and international flights have been implemented nationally. On a regional level, the European Union's Emissions Trading System (ETS) covers intra-EU flights, while ICAO's Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA) covers international air transport. The aviation industry is also taking action to decarbonise, notably through industry associations, the International Air Transport Association (IATA) and Airports Council International (ACI). In 1990, aviation industry experts created the Air Transport Action Group (ATAG) to work together on sustainable development issues for the sector.

Governments have an important role in decarbonising the sector while allowing for air connectivity and its benefits to be delivered to the users of aviation and our economies and societies. Governments can incentivise faster energy-efficiency improvements, the development and deployment of alternative propulsion systems, and the use of low-carbon fuels and other energy vectors. They can also incentivise accelerated improvement in the operational efficiency of aircraft and airports. Phasing out fossil-fuel subsidies, phasing in carbon prices, and internalising the costs of carbon emissions into consumer and firm decision making are important to enabling the green energy transition.

What we recommend

Integrate clear decarbonisation requirements into government support packages helping the sector recover from the Covid-19 crisis

The Covid-19 crisis impacted the entire aviation sector in a profound and unprecedented way. Many governments stepped in and supported the sector during the crisis. Government support to the sector in the aftermath of the Covid-19 crisis should be compatible with the long-term policy objectives of fostering efficient aviation markets and decarbonisation of the sector. Covid-19 recovery plans should be tied to clear decarbonisation requirements to achieve this goal.

Establish a clear long-term vision for decarbonising air transport by setting and monitoring emissions reduction targets aligned with the Paris Agreement

While domestic targets can and have already been embedded in many national strategies, a long-term CO_2 emissions reduction target for international civil aviation is yet to be set. Important work on the subject has started under the auspices of ICAO. Governments should support these efforts, accelerate them, and drive progress towards the future long-term target by setting and monitoring their own short-term and medium-term targets.

Support an international approach to mitigating the climate change impacts of aviation while implementing decarbonisation policies domestically and on a regional level

Governments should continue working together at ICAO to develop a common approach to mitigating the climate-change impacts of international aviation. However, given the urgency of addressing the climate crisis and the challenge of reaching ambitious global agreements, governments should also implement domestic policies to decarbonise the sector and consider agreeing bilateral and multilateral action with like-minded countries to accelerate decarbonisation of the sector.

Introduce carbon pricing in aviation to drive an efficient transition to a greener aviation sector

Carbon pricing is crucial to driving an efficient transition to a greener aviation sector. Beyond ICAO's Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA), carbon prices can be introduced through carbon taxes on fuel and market based-mechanisms like emissions trading schemes. Other instruments are policies that combine CO_2 pricing and regulatory mechanisms, including low-carbon fuel standards and the combination of fuel-blending mandates and non-compliance penalties. Carbon taxes on fuel can be introduced through multilateral taxation agreements or via amendments to air services agreements between specific jurisdictions. Carbon pricing is most effective when applied across the entire economy, not just a single sector. It is less disruptive if it uses progressive increases rather than sudden price shifts. Low-carbon fuel standards and fuel-blending mandates combined with non-compliance penalties can cover the entire fuel pool. Still, these instruments can also be used to target the aviation sector specifically. Finally, coordination and additionality among different carbon pricing measures need to be ensured for the policies to be effective.

Put in place timely and ambitious fuel quality requirements to encourage the take up of sustainable aviation fuels

To ensure adequate take up of fuels that can deliver environmental benefits, governments need to put in place fuel specifications with effective sustainability criteria. The criteria should take into account life cycle greenhouse gas emissions as well as direct and indirect land-use changes. For international aviation, it is important that the work started on defining CORSIA eligible fuels (CEF) continues and covers new forms of sustainable aviation fuels. On renewable fuels of non-biological origin (such as electrofuels), in particular. For domestic flights, governments should consider best practice solutions, such as California's low carbon fuel standard or the recast of the EU renewable energy directive.

Strengthen the effectiveness of regulatory frameworks to further energy efficiency improvements of aircraft

Governments should continue requiring improvements in the fuel efficiency of new aircraft through imposing progressive fuel efficiency standards. Fleet-wide national fuel efficiency standards or fleet renewal schemes can also accelerate a shift towards more energy-efficient aircraft while ensuring compliance with the internationally agreed improvements established for new aircraft by ICAO. Fleet-wide standards can also be designed to continue to ensure cost-effective fuel efficiency improvements over time. Energy efficiency improvements can also ensure greater cost competitiveness for the sector.

Encourage research, development and deployment of alternative propulsion systems and clean fuels, supported by clear policy frameworks for de-risking industry investments to ramp up fuel production

To enable cost-effective decarbonisation of air transport, governments and industry should work together to enhance the availability and affordability of more energy-efficient aircraft and cleaner energy. Governments can accelerate the development and deployment of new technologies that will enable decarbonisation of the sector by providing funding for research as well as government incentives for the take up of new technologies by the sector. Such support can come in different forms, including direct research grants, development of government research programmes, and de-risking industry investments in ramping up the production of a sufficient quantity of sustainable and low carbon fuels. Support can be funded from general government budgets or with earmarked revenue from carbon taxation. Ambitious, mission-oriented research and innovation programmes for net-zero flight by mid-century are required.

Factor in the non-CO_2 climate impacts of air transport when designing decarbonisation policies

Non-CO_2 greenhouse gas emissions from air transport have a significant climate forcing impact and need to be mitigated. As these impacts are not yet fully quantified, governments should support further research on non-CO_2 greenhouse gas emissions from air transport. In the meantime, swift policy action can foster the adoption of available technologies to mitigate non-CO_2 impacts of aviation. Among these are quality improvements for conventional fuels, high-quality sustainable aviation fuels and targeted flight diversion to avoid ice-supersaturated areas.

Carbon emissions from air transport

Climate change is the defining issue of our time. Scientific evidence consistently highlights social and environmental pressures associated with it. Weather is more extreme and less predictable. Droughts and rising sea levels threatening low-lying regions with catastrophic flooding occur more frequently globally. These create a loss of biodiversity with potential impacts on human health, food security, water supply and economic development (Stocker et al., 2013; IPCC, 2018).

Aviation is a major contributor to global CO_2 emissions, despite the momentous impacts of the Covid-19 pandemic. In the absence of significant policy action, this sector is still expected to produce strong growth of CO_2 emissions. Inaction to curb such emissions will correlate with investment instability and global financial risks. Increasingly, climate risk is an investment risk due to the strong link between rising greenhouse gas emissions suppressing socio-economic development (Fink, 2020; Hildebrand and Donilon, 2020).

The Covid-19 pandemic that hit the world in 2020 is accelerating shifts in investment, as major global economies are increasingly considering the reliance on job-intensive, inclusive and far-sighted strategies to shape their economic recovery, including consistent portions of expenditure earmarked for green investments.

The Paris Agreement is currently the centrepiece of internationally agreed action on climate change mitigation. It limits global average temperatures to below 2°C though ideally 1.5°C compared to pre-industrial levels (UNFCCC, 2015). Achieving the Paris Agreement targets with no or limited overshoot requires net-zero CO_2 emissions to be achieved by 2050, with significant emission reductions occurring by 2030. This is around 45% less than 2010 levels by 2030 (IPCC, 2018).

Like all other sectors, the aviation sector is required to step up its accountability in response to the climate challenge. In turn, policy makers, businesses and all other stakeholders must take concrete and effective action now to reduce greenhouse gas emissions.

Before the Covid-19 pandemic

In 2019, fossil fuel combustion in commercial flights emitted close to 1 billion tonnes of CO_2 ($GtCO_2$) globally, similar to the domestic emissions of Japan. As for other sectors, additional CO_2 emissions also originated from fuel production processes, aircraft manufacturing, airport construction and operations, as well as the servicing activities needed to provide air transport services. Unique to aviation, the CO_2 emissions from the combustion of fossil fuels by aircraft have a warming impact on the climate at around three times the rate of that associated with direct CO_2 emissions alone (Box 1).

Pre-Covid-19, direct emissions of CO_2 from air transport were made up of 40% for domestic and 60% for international air and around 2.5% of total energy-related CO_2 emissions (ITF, 2019a; IEA, 2019a, 2021a). Direct CO_2 emissions from aviation were distributed unequally across countries: the United States alone accounted for almost a quarter of the global total, while less-developed countries containing half of the world's population accounted for 10% of direct CO_2 emissions from air transport (ITF, 2019a; ICCT, 2019).

Before 2020, activity growth in aviation outpaced energy efficiency improvements. This led to continuous increases in energy use from air transport (Figure 1). Abatement options were limited by air transport's reliance on energy-dense liquid fuels with high carbon content; therefore CO_2 emissions from air transport closely follow energy use trends.

Box 1. Additional impacts of CO_2 emissions from aviation

Aircraft emit gases and aerosol particles into layers of the Earth's atmosphere, cooling or warming it. The substances emitted by aircraft affect atmospheric composition and cloudiness, significantly adding to air transport's overall climate impact. Most of these substances have a shorter lifetime in the atmosphere than CO_2, but their effect on climate is significant.

Uncertainty regarding non-CO_2 climate impacts of air transport is several times higher than that of CO_2 when measured with effective radiative forcing. Notwithstanding this higher level of uncertainty, non-CO_2 impacts of CO_2 emissions from aviation were estimated to account for two-thirds of the total effective radiative forcing of the CO_2 emissions occurring from aircraft fuel burn (Lee, 2018b). Overall, air transport was estimated to have contributed to around 3.5% of net anthropogenic effective radiative forcing (Lee et al., 2021).

Taking immediate action on short-lived climate forcers can, in the short term, contribute significantly to limit warming to 1.5°C above pre-industrial levels (IPCC, 2018). For example, aircraft could be required to divert to the extent possible from flying over ice-supersaturated areas. This would incur additional fuel use but would deliver a significant reduction in the climate-change impacts of contrails (EASA, 2020a; Teoh et al., 2020). However, limited action has so far taken place in this regard.

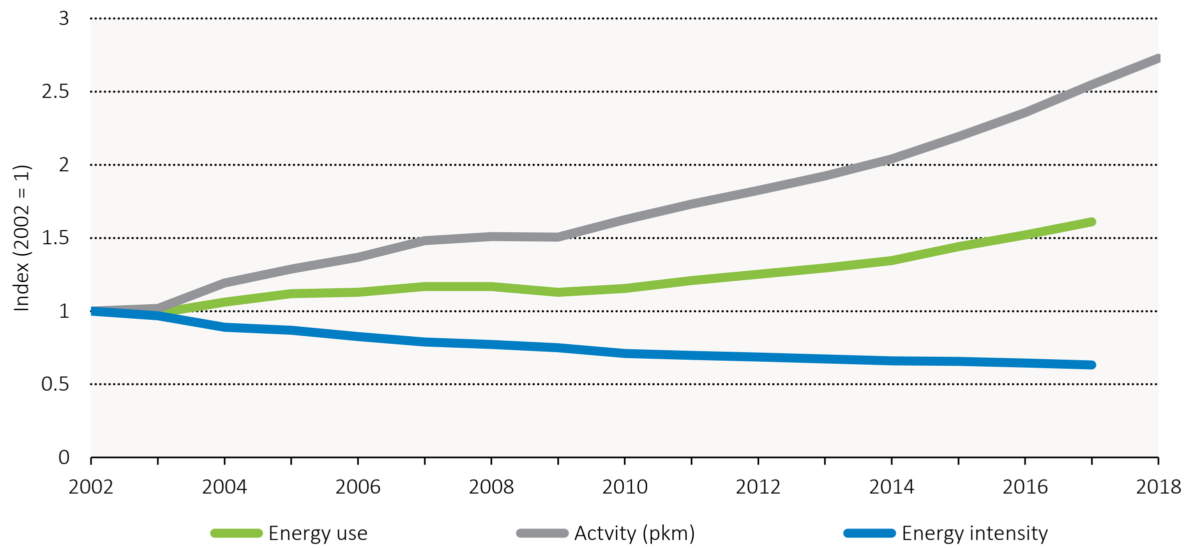
Other solutions include fuel quality improvements, achievable through the reduction in aromatic components and the increased reliance on synthetic fuels (including SAF) (EASA, 2020a) and new engine combustors technology, capable of reducing particle emissions (Teoh et al., 2020). Uncertainty still surrounds impacts associated with NO_X emissions and the trade-off between NO_X abatement and energy efficiency improvements (EASA, 2020a and Skowron et al., 2021).

Demand for commercial passenger air transport grew 5% per year, on average, between 2000 and 2019. This was fuelled by the rise in global average income and population and led to a 50% increase in direct CO_2 emissions, at an average rate of 2% annually.

Air transport has, however, reduced its energy intensity more than other modes, with a 2.8% annual decrease on average since 2000 (IEA, 2020b). This was achieved by operational improvements that increased load capacities which reduced the share of empty-seat km and by increases in energy efficiency, resulting in lower energy-use per aircraft km. The latter became possible by changes in seat capacity available per aircraft and technical improvements that reduced fuel use for different generations of aircraft.

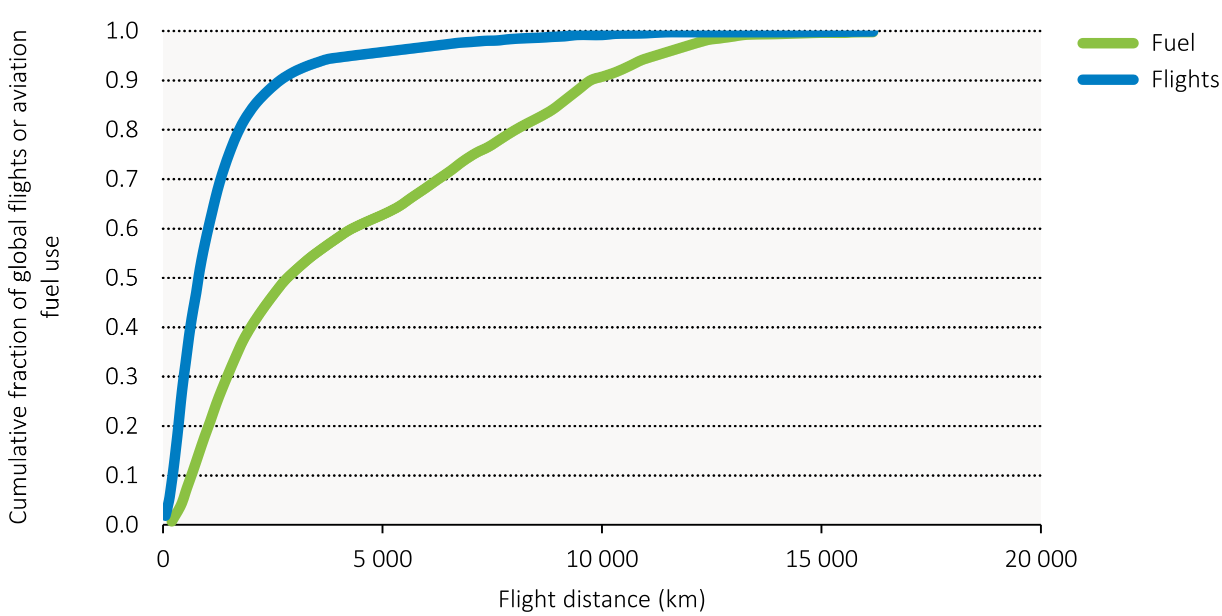
Despite these significant energy-efficiency improvements, air transport remains one of the most energy-intensive transport modes. Additionally, its unique facilitation of long-distance travel[1] radically expands the size of its carbon footprint: the percentile of longest-distance flights, all over 8 000 km, accounted for 20% of all aviation fuel used in 2014 (Figure 2) (Van Manen, 2019).

Figure 1. Change in energy use, activity and energy intensity of passenger air transport, 2002-18



Source: Adapted from IEA (2018a); IEA (2020a); ICAO (2019a).

Figure 2. Cumulative distributions for flights and fuels in the global commercial aircraft fleet in 2014



Source: Adapted from Van Manen (2019).

Impacts of Covid-19 and prospects for future developments

Aviation has been one of the hardest-hit sectors by the Covid-19 pandemic. Its effects will likely delay an increase in activity, even if the aviation sector has shown strong resilience to past crises. Lockdowns globally brought air transport to a virtual standstill in April 2020, with many countries experiencing a 90% drop in flights. This created significant financial challenges for the industry as a whole, and governments needed to provide support measures for the sector in many cases (ITF, 2020). Estimates from 2020 suggest a 67% drop in available seats over the year (OAG, 2020; ICAO, 2020a) and a 60% fall in the total number of air passengers (ICAO, 2020a).

Before the Covid-19 pandemic, the projected average annual growth of revenue passenger kilometres (RPK) in aviation ranged from 4.1% to 4.6% (Table 1). In the same timeframe, energy use and direct CO_2 emissions from international air transport were also set to triple between 2015 and 2050 in the absence of technological and operational improvements (ICAO, 2019b).

Table 1. Selected long-term industry forecasts of annual average increase in revenue passenger kilometres

Source	Pre-Covid-19	Post-Covid-19
ACI, CANSO, IATA, ICAO and ICCAIA	4.1% (2015-45)	No data available
Airbus	4.3% (2019-38)	No data available
ATAG		2.7% (2019-40) to 3.0% (2019-50)
Boeing	5.1% (2018-28) to 4.6% (2018-38)	3.7% (2019-29) to 4.0% (2019-39)

Note: ACI: Airports Council International; ATAG: Air Transport Action Group; CANSO: Civil Air Navigation Services Organization; IATA: International Air Transport Association; ICAO: International Civil Aviation Organisation; ICCAIA: International Coordinating Council of Aerospace Industries Associations.

Source: Adapted from ACI et al. (2019), Airbus (2019), ATAG (2020), Boeing (2019) and Boeing (2020).

The sector's robust pre-Covid-19 growth in passenger demand challenged its alignment with Paris Agreement targets. This, combined with limited and costly abatement options and a lack of economic incentives to decarbonise, has also raised concerns about the share of the cumulative global CO_2 budget that aviation may account for by 2050 – between 4% and 15% in scenarios limiting global temperature increases to less than 2°C (Lee, 2018a).

Current air travel demand projections suggest that, in the medium term, the economic crisis will continue to dampen demand for air transport. Industry forecasts do not expect a return to pre-Covid-19 passenger activity levels until at least 2024 (ATAG, 2020; IATA, 2020 and Boeing, 2020). In the long term, the Air Transport Action Group (ATAG) expects a 2.7% average annual increase between 2019-40 and a 3.0% annual growth from 2019-50 (Table 1), marking a 16% reduction in air-traffic levels compared to pre-Covid-19 forecasts in its central traffic scenario to 2050 (ATAG, 2020). Boeing also revised its projections downwards, suggesting a drop of the long-term average annual growth rate of revenue passenger kilometres to 3.7% between 2019-29 and 4.0% between 2019 and 2039 (Table 1) (Boeing, 2020).

Despite the possibility of a structural decrease in demand, aviation's resilience to prior crises and shocks show indeed that growth in demand for air travel is likely to remain relatively strong in the long term (IEA, 2020a; ITF, 2020). ATAG also expects the sector to transport over ten billion passengers annually in 2050, more than double the 2019 passenger levels (ATAG, 2020). This figure suggests that aviation is bound to remain a significant contributor to CO_2 emissions, even after the Covid-19 pandemic, especially in the presence of an economic rebound and absence of policy action aiming to improve energy efficiency and reduce the GHG emission intensity of fuels. A similar estimate is outlined in the *Recover* scenario of the ITF 2021 Transport Outlook (ITF, 2021) – Box 2.

A sustained increase in energy use and direct CO_2 emissions from aviation is equally projected in the absence of targeted policy. ATAG (2020) suggests that technology development trends, combined with investments in operations and infrastructure, would lead to direct CO_2 emissions approaching 1.5 Gt from commercial aviation in 2050. These indications are more optimistic than the results outlined in the *Recover* scenario of the ITF 2021 Transport Outlook, where direct CO_2 emissions from aviation reach 1.8 Gt (ITF, 2021). The ITF analysis, summarised in Box 2, suggests that increased policy action and an acceleration in clean technology are essential for a transition that could decouple aviation activity from GHG emission growth, even if the ITF *Reshape* and *Reshape+* scenarios would be requiring negative emissions in other sectors to meet aviation industry goals and even more to be compatible with a net-zero pathway for 2050.

Box 2. Three post-pandemic trajectories for the aviation sector

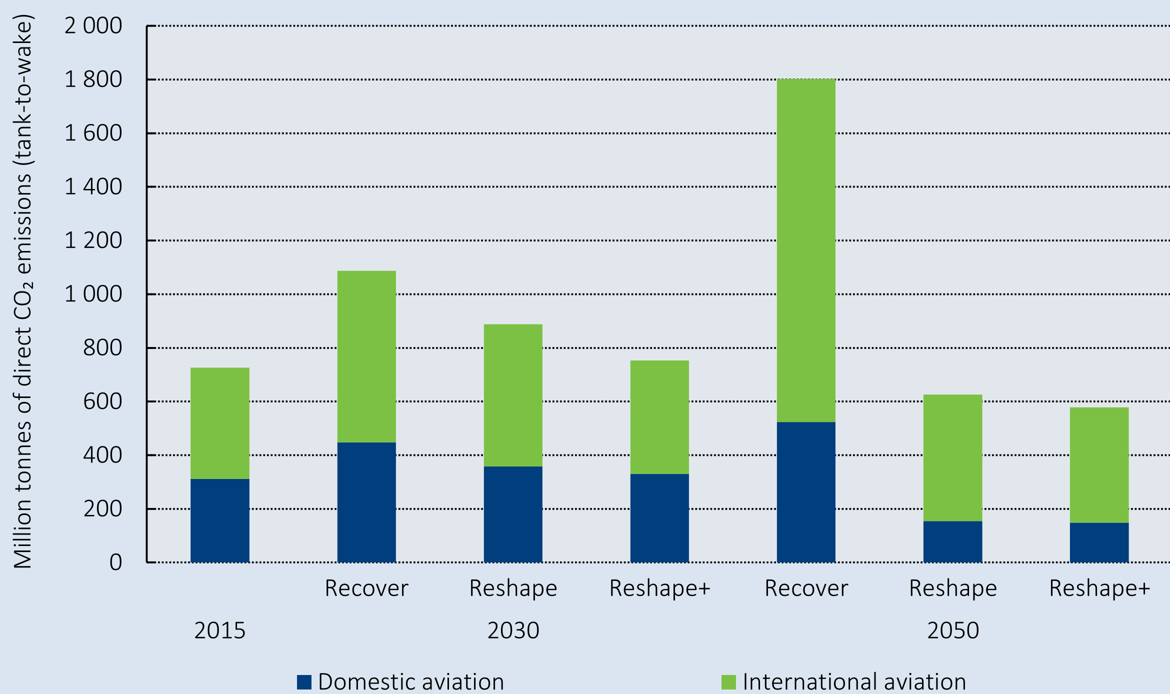
The International Transport Forum's (ITF) *2021 Transport Outlook* tests three scenarios that outline possible post-pandemic trajectories for the sector. The scenarios combine policy decisions, technological trajectories, and potential long-term impacts of the pandemic. The *Recover* scenario assumes a return to pre-pandemic behaviour, coupled with policies already agreed or planned at the time of its publication (May 2021). The *Reshape* scenario also assumes a return to a pre-pandemic behaviour concerning flying, but with increased adoption of ambitious policy measures for GHG emission reduction and faster technological development and adoption. The *Reshape+* scenario depicts certain long-term pandemic impacts, such as reduced business travel, accelerating the adoption of emission mitigating policies and technologies.

The three scenarios depict two diverging ways forward for aviation. Demand and CO_2 emissions rebound and continue growing under the assumptions of *Recover*. By 2050, aviation moves 10.5 billion passengers and produces 1.8 Gt of CO_2. In contrast, the new technological developments and supporting policies of the *Reshape* and *Reshape+* scenarios allow demand to decouple from GHG emissions. The number of passengers continues to grow but at a slower pace, reaching between 8.2 and 8.8 billion travellers in 2050; CO_2 emissions, on the other hand, decline to around 600 Mt (Figure 3).

The assumptions included in these scenarios, especially in *Reshape* and *Reshape+* require the uptake of ambitious policies across the transport spectrum. These include setting a high cost of carbon, adding a tax to air tickets, and mandating the use of a particular share of SAF, among others. The projected CO_2 reductions will also rely heavily on the development and adoption of hybrid-electric aircraft and, to a smaller degree, all-electric aircraft.

Aviation in the *Reshape+* scenario is also influenced by reductions in business and long-distance leisure travel, which come as lingering long-term effects of the Covid-19 pandemic. Despite these developments, the ITF *Reshape* and *Reshape+* scenarios fall short of current aviation industry targets, promoting a 50% reduction in air transport emissions by 2050 compared to 2005 levels (ATAG, n.d.). The ITF scenario results indicate that meeting this target would require stronger policy action, more profound technological transitions or compensation with negative emissions in other sectors. These would likely need to be accompanied by net-zero emissions for aircraft manufacturing, airport infrastructure construction and operational activities enabling air transport. Similar considerations (with increases in scale) also apply to cases requiring deeper cuts in aviation to achieve net-zero emissions across the economy by mid-century.

Figure 3. CO_2 emissions from air transport according to ITF 2021 Transport Outlook scenarios



Source: ITF (2021).

Current policy context

Airports, airlines, other industry stakeholders and governments have been increasing efforts to mitigate carbon emissions from air transport. This chapter reviews the most relevant of these efforts. It starts from a review of the two mitigation schemes covering international air transport CO_2 emissions. The European Union's Emissions Trading System (ETS) and the International Civil Aviation Organisation's (ICAO) Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA). The following sections consider a selection of initiatives implemented at the national level to mitigate CO_2 emissions from aviation. These cover domestic flights and may also address international flights. The last section of this chapter focuses on actions by the aviation industry to decarbonise the sector, paying specific attention to the initiatives of industry associations such as the Air Transport Action Group (ATAG), the International Air Transport Association (IATA) and Airports Council International (ACI).

Aviation and international climate agreements

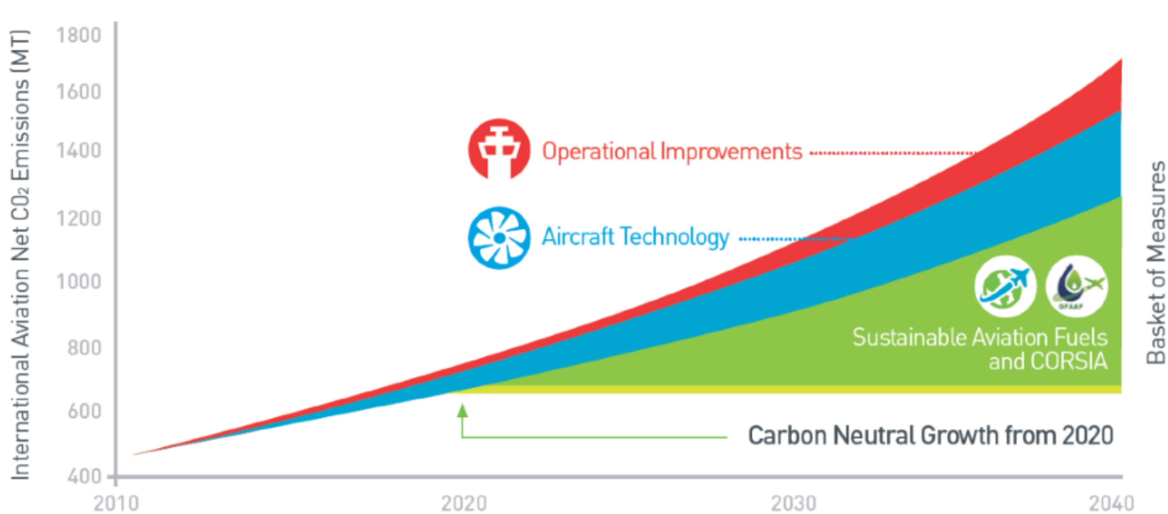
In 1997 the Kyoto Protocol set greenhouse gas (GHG) emissions reduction targets for 37 industrialised countries (UNFCCC, 1998). These "Annex I" parties worked as ICAO members to reach an agreement on reducing CO_2 emissions from international aviation. Similarly, the International Maritime Organisation (IMO) was designated as the organisation through which Annex I parties should work to reach an agreement on CO_2 emissions from international shipping. In this context, ICAO member states adopted two global aspirational goals in 2010: to achieve average fuel efficiency improvements of 2%[2] per annum between 2020 and 2050 and carbon-neutral growth from 2020 to 2040 (ICAO, 2010).

The Paris Agreement superseded the Kyoto Protocol in 2015 and expanded its scope to the global level. It is the keystone of current international climate-change policies. Its stated aim is to limit the increase in global average temperatures to well below 2°C above pre-industrial levels and to continue efforts to limit the temperature increase to 1.5°C (UNFCCC, 2015). As indicated in the decision to adopt the Paris Agreement, the IPCC developed, in 2018, a Special Report on global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways. It indicated that all sectors must reach net-zero CO_2 emissions by 2050 if there is to be no or limited overshoot of the 1.5°C target, or net zero by 2070 to keep within a 2°C global average temperature increase (IPCC, 2018).

Unlike the Kyoto Protocol, the Paris Agreement does not explicitly mandate the responsibility of reducing CO_2 emissions from international aviation and shipping (IAS) to countries through ICAO and IMO.[3] Nevertheless, the IMO adopted an initial Strategy on the reduction of GHG emissions from ships in 2018. This includes the objective to curb GHG emissions from international shipping. They are to peak as-soon-as-possible then to reduce by at least 50% by 2050 (using 2008 emissions as a benchmark) and pursuing efforts towards phasing them out to align with Paris Agreement goals (IMO, 2018a; IMO, 2018b).[4] To date, no agreement on a long-term emissions reduction target has been reached under the auspices of ICAO. However, recognising that the 2010 aspirational goals fall short of the emission reductions needed to deliver on Paris Agreement targets, the ICAO Council is assessing the feasibility of a long-term aspirational goal for international aviation that aligns with these targets. It will present progress on this work at the 41st Session of the ICAO Assembly in 2022.[5]

ICAO member states also adopted a basket of measures to achieve these aspirational goals in 2016 (ICAO, 2016a).[6] They consist of reducing fuel consumption through more efficient aircraft technology and operations, reducing the carbon intensity of fuel through SAF from biofuels, and a voluntary global market-based measure (GMBM) based on carbon offsetting under the form of a Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA).[7] Figure 4 illustrates the contribution of each of these pillars, as expected by ICAO prior to Covid-19 and the revision of the baseline year for carbon-neutral growth from 2020 to 2019.

Figure 4. Contribution of measures for reducing international aviation net CO_2 emissions



Note: The carbon-neutral growth baseline year was modified to 2019 in 2020, in light of the impact of the Covid-19 pandemic on international air transport. CORSIA applies only to 88 volunteering states, including major air transport markets such as Australia, Europe, Japan and North America. Other large air transport markets such as Brazil, China, India and Russia are expected to join CORSIA by the industry in 2027 (Aviation Benefits, 2020).

Source: ICAO (2019a).

Under CORSIA, airlines can reduce or offset increases in international air transport emissions exceeding a baseline value. This value, originally set as an average of 2019 and 2020 CO_2 emissions from international air transport, in 2020 was replaced by 2019 emission levels alone, in response to the impact of the Covid-19 crisis on international air transport activity (ICAO, 2020b). Airlines can also reduce emissions using lower-carbon CORSIA-eligible fuels[8] and offset them by purchasing emission units consisting of carbon credits or offsets (Box 3). Reporting on the use of these emission units will be required from airlines starting in 2025 (ICAO, 2019c).

CORSIA was designed for implementation in phases, with a pilot period (2021-23) and a first phase (2024-26) that applies to states that have volunteered to participate. This is followed by a second phase (2027-35) applying to states that account for the vast majority of total international aviation activity (ICAO, 2019b).[9] However, due to the impacts of the Covid-19 pandemic on aviation activity (and CO_2 emissions), airlines will very likely only need to reduce emissions or purchase carbon offsets after the pilot period, in phase one (2024-26) or phase two (2027-35) of CORSIA.

Box 3. Carbon offsetting

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 GHG 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 (SDGs), such as alleviating poverty and preserving biodiversity (Cames et al., 2016).

However, offsets also come with significant drawbacks regarding environmental integrity, large-scale availability, limited capacity to incentivise technology transitions and the entrenchment of carbon-intensive forms of energy in the aviation sector, with detrimental impacts on its exposure to climate-related financial risks. An assessment of the Kyoto Protocol's Clean Development Mechanism (CDM) – which enabled Annex I countries to achieve emission reductions through investments in low-carbon solutions in non-Annex I countries, similar to the case of offsets – found that 73% of potential 2013-20 certified emission reductions (CERs) had a low likelihood of being additional. This means that they would not have occurred without the investment from the offsetting project and not over-estimated in terms of carbon-emission reductions (Cames et al., 2016). Some credits from the CDM and other emission-reduction programmes have also been found to have negative environmental and social impacts locally (Carbon Market Watch, 2018; Schneider et al., 2019). For example, afforestation projects have been shown to deprive local communities of natural resources, worsening existing hunger and poverty issues. Furthermore, the permanence of emission reductions from avoided deforestation is difficult to guarantee, as carbon stored in trees can be lost due to human or natural disruption, including fire and storm damage (Galik et al., 2014).

In the context of the Paris Agreement, an additional issue for the environmental integrity of carbon offsets is the potential for double-counting.[10] The agreement's bottom-up approach, under which countries set their own emissions reduction targets, can incentivise countries to set low NDCs and sell the surplus as offsets in case of overachievement, undermining climate ambition (Schneider and La Hoz Theuer, 2018).

The low cost of CORSIA-eligible offsets – between USD 0.15/tCO_2-equivalent (Clean Development Mechanism) and USD 4/tCO_2-eq (Gold Standard) on average in 2019 (World Bank, 2021) – is also unlikely to be high enough to significantly affect demand or provide a sufficient incentive to invest in new technology and fuels, particularly when considering that the carbon price will only apply to emissions above the baseline. The pre-Covid-19 analysis estimated that carbon offsets would have accounted for just 0.2% and 0.5% of total international aviation revenues in 2025 and 2030, respectively, assuming a price of USD 6 per tCO_2-eq (ICAO, 2016c).

Carbon offsets also offer the possibility of a longer life to carbon-intensive forms of energy like fossil fuels. This has the advantage to extend the possibility to rely on this comparatively cheaper forms of energy. However, the same compensation mechanisms imply that carbon offsetting does not reduce in-sector emissions.

CORSIA's effectiveness will ultimately depend on the quality of the carbon offsets accepted by ICAO, the definition of sustainability criteria for CORSIA-Eligible Fuels (CEF), and how the scheme is administered and implemented by volunteering countries.

Fuel eligibility criteria for CORSIA-eligible fuels

Sustainability criteria for CEF have yet to be finalised. Of the twelve criteria recommended by ICAO CAEP in 2017, ten relating to areas such as water and food security were set aside by the Council for further work. The two remaining sustainability criteria[11] relate to life cycle CO_2 emissions and indirect land-use and change (ILUC), excluding non-GHG criteria (ICAO, 2019e). CAEP's ongoing work on the ten non-GHG criteria will be subject to the Council's approval at the end of CORSIA's pilot phase in 2023 (ICAO, 2019e).

CORSIA-eligible emissions units

Eligible emissions units (EEUs) from eight programmes are accepted under CORSIA's pilot phase (2021-23) (ICAO, 2020c; ICAO, 2021a). These include the UNFCCC's Clean Development Mechanism (CDM), the Verified Carbon Standard and the Gold Standard.[12] ICAO's Technical Advisory Board (TAB) recommended that ICAO should not accept all types of EEUs from these programmes and requested further specific actions from them to align with ICAO's criteria,[13] as only the CDM was found to meet all of the criteria. The governance framework ensuring the application of these criteria indicates that carbon offsetting programmes should publicly disclose who is responsible for the administration of the programme and how decisions are made.

EEUs can be issued to projects that started on 1 January 2016, with emission reductions occurring until 31 December 2023 (ICAO, 2021a). Start dates are critical because they affect supply and prices: the earlier the start date of accepted projects, the more credits are available at a lower price. Certified emission reductions (CERs) from the CDM are already in over-supply, leading to low and declining prices, a fall in project registrations and falling CER issuance. The likely weak or inexistent demand for offsets in CORSIA's pilot phase may further drive carbon offset prices down.

Governance of CORSIA

Issues regarding whether the CORSIA agreement is legally binding and ICAO's capacity to enforce it have been raised. Resolution A39-3 on CORSIA policies and practices, adopted at ICAO's 39th triennial assembly (ICAO, 2016bb), does not make use of the word "mandatory", as no ICAO resolutions are legally binding (Mendes de Leon et al., 2015). In practice, CORSIA is being implemented through Standards and Recommended Practices (SARPs), which have the potential to provide a better governance structure than a legal resolution alone and ensure environmental integrity. However, SARPs must be implemented in national law to become binding and their relatively uncertain legal status affects enforceability. Furthermore, states can decline to participate in CORSIA by "filing a reservation" to the Resolution or "filing a difference" with ICAO (Mendes de Leon et al., 2015).

ICAO's CORSIA is currently the only global market-based measure that addresses CO_2 emissions from international civil aviation. It therefore has a prime position to set a level playing field that moves aviation towards decarbonisation. However, the absence of several major air transport markets from the voluntary phase of CORSIA limits the scheme's global coverage of international air transport emissions. This voluntary basis currently omits commitment from around half of international air transport activity.[14] As of the end of 2020, several major air transport markets such as Brazil, China, India, and Russia had not yet joined CORSIA, with industry forecasts not expecting these countries to join the scheme before the second phase, starting in 2027 (Aviation Benefits, 2020).

Regional schemes to reduce carbon emissions from aviation: The EU Emissions Trading System

The European Union (EU) currently hosts the only CO_2 emissions reduction scheme for international air transport as part of the EU Emissions Trading System (EU ETS).

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. In phase three of the EU ETS (2013-20), companies failing to surrender their allowances were fined EUR 100 (USD 118) per tCO_2, adjusted for EU inflation from 2013 onwards. Following penalty payment, non-surrendered allowances are added to the following year's compliance target (European Commission, 2015).

Direct CO_2 emissions from intra-European Economic Area (EEA) flights have been included in the EU ETS since 2012. This accounts for flights between the EU, Iceland, Norway, and Liechtenstein. The Swiss ETS was linked to the EU's in January 2020, also including aviation (European Commission, 2019b). The UK's departure from the EU ETS does not affect flights between the United Kingdom and European Union. These remain within the scope of the EU ETS, following a derogation in the EU ETS Directive (European Commission, 2020a; World Bank, 2021). Similar to the Swiss ETS, the UK ETS may also later be linked to the EU's (HM Government, 2020).

The EU ETS covers over 40% of all EU GHG emissions, with a focus on energy-intensive economic sectors, including power stations and industrial plants in addition to aviation (European Commission, 2021d). The European Parliament has recently approved the inclusion of CO_2 emissions from the maritime sector in the EU Emissions Trading System (ETS) and the European Commission also proposed to gradually extend the current EU ETS to the maritime sector[15] (European Commission, 2021b; European Commission, 2021g). Further developments will follow negotiations with member states on the final shape of the legislation (European Parliament, 2020).

The EU ETS initially covered all flights arriving at and departing from EEA airports from 1 January 2012. Later that year, the EU agreed to exclude extra-EEA flights until end-2023 to facilitate CORSIA negotiations and support the development of a global scheme for international aviation emissions. In light of CORSIA's 2021 implementation date and as part of the "Fit for 55" policy package proposed in July 2021, the European Commission proposed to maintain the current EU ETS coverage for intra-EEA flights (also including departing flights to Switzerland and to the United Kingdom) and to introduce appropriate CORSIA-related provisions for flights that are currently not covered by the EU ETS. These include flights to and from third countries and by EU-based airlines between two third countries (European Commission, 2021f). The European Civil Aviation Conference (ECAC) Directors General and the Council of the European Union have shown a strong commitment to a GMBM (ECAC, 2016; Council of the European Union, 2019). However, the Council has called on ICAO to ensure the scheme's environmental integrity, notably by avoiding the double-counting of emission reductions. Currently, ETS allowances are not accepted under CORSIA and offsetting credits will not be accepted under the EU-ETS from 2021 (EASA, 2019l; European Commission, 2021f).

Since the inclusion of aviation in the EU ETS, the majority of aviation allowances have been allocated freely to avoid carbon leakage, and carbon prices were initially relatively low. Only around 15% of EU aviation allowances were auctioned in phase three (EASA, 2019). Average annual allowance prices did not exceed USD 10 (EUR 8) per tCO_2 between 2012 and 2017, but have since risen strongly, reaching around USD 30 (EUR 25) per tCO_2 on average in 2020 and approaching USD 50 (EUR 40) per tCO_2 in the first-half of 2021

(World Bank, 2021). Full auctioning at current carbon prices with the current emissions cap could raise around EUR 1 billion per year (Graichen and Graichen, 2020). The initial low pricing of EU ETS allowances spurred debates on the scheme's effectiveness (OECD, 2018a). However, evidence suggests that it saved around 1.2 billion tCO_2 between 2008 and 2016 (3.8%) across the entire EU economy relative to a situation with no carbon markets (Bayer and Aklin, 2020). The recent proposal to revise the EU ETS, part of the "Fit for 55" package of the European Commission of July 2021, also includes a phase-out of the free emissions allowances currently received by the aviation sector for intra-EU flights (and also for other sectors, as long as they are covered by the parallel proposal of establishing a Carbon Border Adjustment Mechanism (European Commission, 2021g).

National measures

This section points to a wide range of national policies implemented by governments to accelerate the decarbonisation of their economies and their transport sectors, including aviation.

Initiatives include cross-sectoral and transport sector-specific policies, notably fuel and carbon taxation, emissions trading schemes, and low-carbon fuel standards. Aviation-specific policy instruments such as ticket taxes and aviation fuel-blending mandates have also been implemented in recent years, many of them for revenue generation rather than climate impact mitigation reasons.

Some governments have also supported long-term decarbonisation projects for aviation through specific research and technology development funds. Some of these funds aim at accelerating the development and deployment of the most promising technologies, such as flights running on electricity, hydrogen, electrofuels or hydrogen-based fuels.

Carbon pricing and fuel taxes in aviation

Fuel and carbon taxes and emissions trading schemes (ETS) are core policy instruments for decarbonising the economy, including transport. While fuel excise taxes, levied per unit of fuel, are commonplace in road transport (OECD, 2019), most governments currently exempt jet fuel used on international routes from tax (see Box 4 for more details). Carbon taxes and ETS are becoming widespread. They directly or indirectly price CO_2 emissions from fuel and other emissions sources via different mechanisms.

Over 60 cross-sectoral carbon-pricing initiatives have already been or are planned for implementation. These entail 29 ETS and 35 carbon tax schemes and cover around 22% of global GHG emissions (World Bank, 2021). ETS generally focus on emissions from the industry and electricity sectors (OECD, 2018a). The EU ETS (including Switzerland, the United Kingdom and other countries in the EEA) are the only initiatives covering international CO_2 emissions from air transport. Domestic aviation is included in the ETS of New Zealand and South Korea (Ministry for the Environment New Zealand, 2019; Asian Development Bank, 2018; European Commission, 2021f). Shanghai's ETS is the first among eight Chinese ETS pilots to include aviation (ETS in China, 2021; European Commission, 2021f; World Bank, 2021).

The Chinese ETS, operational since July 2021 but only for the electricity sector, is the world's largest (Liu, 2021; World Bank, 2021; IEA, 2020c).

Box 4. Taxation of fuels used for international flights

A legal framework for international aviation, which eventually led to the creation of ICAO, was created by the 1944 Chicago Convention. Signatory countries agreed to exempt jet fuel already on board aircraft landing abroad, without mentioning fuel uplifted on aircraft departing an airport (ICAO, 1994). The ICAO Council resolved that fuel taken onboard an aircraft flying to another state should also be exempt in 1993 (ICAO, 1994). However, ICAO resolutions are only binding when integrated into national law, and countries can reserve their positions on them, as was the case of Germany, Norway, Sweden and Switzerland regarding ICAO Policy Document 8632 (CE Deft, 2019; ICAO, 2016d).

In practice, most national governments agree to exempt jet fuel for commercial airline use sold on their territory from tax through bilateral air services agreements (ASAs) negotiated between countries. The exemption extends to international carbon taxes, which effectively tax fuel use. ASAs exempt countries from taxing aviation fuel, but individual states or provinces can levy taxes on jet fuel sold for international flights, as is done, for instance, in the US states of California and Florida (Faber and O'Leary, 2018). Jet fuel used on intra-EEA flights is regulated by the 2003 Energy Taxation Directive, currently under revision, which allows EEA states to waive this exemption by entering bilateral agreements (CE Delft, 2019).

There are no legal obstacles to taxing jet fuel used on domestic routes, including for carbon taxes. Yet, as of 2019, few countries were found to apply carbon and/or fuel excise taxes to jet fuel. These include Argentina, Armenia, Australia, Canada, India, Ireland, Japan, Norway, Myanmar, Saudi Arabia, Switzerland, Philippines, Thailand, Vietnam and the United States (OECD, 2019; CE Delft, 2019). Tax rates vary by country and also – namely for the United States – by State (CE Delft, 2019). In 2019, excise taxes ranged from EUR 0.01 to EUR 0.77 per litre of fuel (OECD, 2019). Average tax rates applying to domestic jet fuel are much lower than those applying to road transport fuels. In some countries, fuel excise and carbon taxes combined can reach EUR 300 per tCO_2 (OECD, 2019), showing scope for increased tax rates on jet fuel.

Implementing a tax on fuel uplifted for international flights would require the bilateral amendment of ASAs between countries. Two concerns regarding their implementation are the risk of carbon leakage (Box 5) and reduced competitiveness for firms in jurisdictions implementing fuel taxes (ICAP, 2020). Establishing an international fuel tax across several countries for flights within an established perimeter, as is the case in the EU ETS for intra-EEA flights, could help limit these risks. The proposal by the European Commission for a revision of the energy taxation Directive, included in the "Fit for 55" policy package, goes in this direction, as it includes a provision to end the mandatory tax exemption concerning international aviation fuel (European Commission, 2021e). A global carbon tax or trading scheme would also eliminate these risks.

Box 5. Carbon leakage in air transport

Carbon leakage refers to the displacement of CO_2 emissions occurring when production activities move from jurisdictions with more to that of less stringent climate policies. This can be causing an overall increase in CO_2 emissions (in comparison with a benchmark without policy). Negative leakage, leading to CO_2 reductions outside of the regulated jurisdiction, can also occur. For example, via increased investment in mitigation technologies, driven by advantages from scale for the production of goods that are compliant with strict regulatory requirements established in major markets, as well as productivity benefits induced by innovation (Porter and van der Linde, 1995).

Most leakage analyses have focused on industrial sectors such as energy and manufacturing. Ex-ante modelling for sectors covered by the EU ETS showed leakage rates between 2% and 73% (Graichen et al., 2013). Rates vary depending on the policies analysed, the use of preventative measures against carbon leakage, and the underlying assumptions of the models.

Few studies analyse carbon leakage in aviation, and no system-wide estimates have been provided in the literature, with the exception of one network-based analysis of aviation carbon leakage (Dray and Doyme, 2019). Focusing on the effect of emissions abatement policy in the United Kingdom, Dray and Doyme (2019) observe that aviation may behave differently to other sectors with respect to carbon leakage due to its global nature, the difficulty of emissions abatement, and passengers' capacity to choose which routes to fly. The analysis suggests that passenger behaviour tends to result in negative leakage, while airline behaviour (e.g. fleet swapping, fuel tankering) tends to result in positive leakage.

The outcome of each climate policy depends on the balance of positive and negative leakage, the geographic scope, and the policy type. Overall, the most negative leakage impacts have been associated with carbon pricing and the most positive with differentiated landing charges favouring more fuel-efficient aircraft. The lower leakage associated with carbon pricing is the result of carbon pricing's effect on demand (Dray and Doyme, 2019).

Value added tax

International air transport is mostly excluded from value added tax (VAT). Specifically, it is "zero-rated", meaning that air transport service providers do not charge taxes on sales and receive full VAT refunds on the inputs used to provide the service. There are two main challenges to levying VAT on international air transport services: the first is determining the service's "place of supply", which allows a jurisdiction to levy VAT; the second consists in levying the appropriate amount based on the consumer's country of residence and transferring the proceeds to the relevant government (Keen, Parry and Strand, 2013).

VAT or sales tax are commonly applied on domestic air transport tickets, but often at reduced rates (Keen and Strand, 2007; CE Delft, 2019). All EU countries apply VAT to domestic airfares (Hemmings, 2020). Australia applies a goods and services Tax (GST), which is similar to the VAT. A general sales tax is also charged on New Zealand domestic airfares. Sales tax applies to airfares and passenger charges in Canada and the United States for North American flights, excluding flights from Canada to Mexico. As of 2019, VAT was also applied in Indonesia, Thailand and Vietnam, and a GST in Malaysia (CE Delft, 2019).

Ticket taxes

Ticket taxes[16] 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 airport category. 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 under certain circumstances.

Many countries levy ticket taxes for revenue-raising or emissions mitigation purposes. The UK's Air Passenger Duty (APD), levied on all UK-departing flights since 1994, raises revenue from aviation (Seely, 2019). Rates vary between GBP 13 (USD 18) and GBP 528 (USD 725), depending on distance and class of travel (UK Government, 2020). The French government started levying an "ecotax" ranging between EUR 1.5 (USD 1.8) and EUR 18 (USD 21) 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 introduced a ticket tax between CHF 30 (YSD 32) and CHF 120 (USD 130) on all flights (excluding transit) departing its territory (Ambassade de France en Suisse, 2020). 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. Other countries, including Australia, Austria, Germany, Italy, Japan, Norway, Sweden, and the United States, have similar revenue-raising taxes in place (Faber and Huigen, 2018; CE Delft, 2019).

While ticket taxes may or may not be intended as environmental measures, they do incentivise the industry to reduce emissions by affecting the cost of travel and hence the demand; though this effect may be very small. Additional effects may result from ticket taxes designed to integrate environment-related parameters.

Low-carbon fuel standards and fuel-blending mandates

Low-carbon fuel standards (LCFS) support the deployment of alternative fuels. They decrease the carbon intensity of fuel by setting a decreasing life cycle-based carbon intensity target for fuel sold in the jurisdiction and allow regulated entities to trade credits to achieve the target. Regulated entities are fuel suppliers or companies producing, importing, distributing or selling fuel.

LCFS originated in California (United States), as discussed in Box 6. They are now also in place in Oregon (United States) and British Columbia (Canada). Brazil's RenovaBio policy and Canada's proposed nationwide Clean Fuel Standard both draw from the LCFS (Agência Nacional do Petróleo Gás Natural e Biocombustíveis, 2020; Murphy, C., 2020). The US Congress has also expressed interest in a nationwide LCFS (Select Committee on the Climate Crisis, 2020).

Fuel-blending mandates are an alternative policy instrument to reduce the carbon intensity of fuel. They can require blending by volume or life cycle GHG emission reductions. Biofuel-blending mandates are already common for road transport fuels. Ethanol blending in gasoline is required, for instance, in Brazil (27% by volume), Argentina (12%), and India (5%) (IEA, 2018b). Biodiesel blending, which comes with significant sustainability challenges, is required in countries including Indonesia (30%), Argentina and Brazil (10%), and Malaysia and Thailand (7%) (Christina, 2019; IEA, 2018b).

Box 6. The California Low Carbon Fuel Standard

The California Low Carbon Fuel Standard (LCFS) was implemented in 2011. The LCFS required a 10% reduction in the carbon intensity of transportation fuels sold in California by 2020 and now requires a 20% reduction by 2030 as part of California's strategy to achieve its overall target of reducing GHG emissions 40% below 1990 levels by 2030 (CARB, 2018). The policy's most recent evaluation shows the share of alternative transportation fuels sold in California grew from 6.1% in 2011 to 8.5% in 2017 (Witcover, 2018).

Sustainable aviation fuel (SAF) producers were granted opt-in status in 2018, allowing them to generate credits – though conventional aviation fuel does not generate deficits – in the standard's compliance market. This raises market balance issues, as an oversupply of credits reduces their prices as well as the incentive to generate credits while transferring revenue from gasoline and diesel consumers to air transport consumers. This raises equity issues as gasoline and diesel consumption are more spread out across the income distribution than that of jet fuel in California.

The European Union also has obligations for renewable fuels in transport (10% by energy content in 2020, and 14% in 2030), as does the United States, where most gasoline contained up to 10% ethanol by volume in 2019 (IEA, 2018b; EIA, 2020). These objectives have also recently been the subject of a proposed revision of the Renewable Energy Directive (RED), integrated into the EU's "Fit for 55" policy package presented in July 2021. The proposal is articulated in two components. This revision, applicable to all sectors, including transport (European Commission, 2021h) and the introduction of a blending mandate specifically targeting the aviation sector, is included in the "Refuel EU" Regulation (European Commission, 2021i).

The RED revision includes the following:

- an updated 2030 EU target of at least a 40% share of energy from renewable sources in the EU's gross final consumption of energy in 2030
- an increase in the ambition level of renewables in transport to a 13% GHG intensity reduction in the same timeframe
- the establishment of a sub-target for advanced biofuels from at least 0.2% in 2022 to 0.5% in 2025 and 2.2% in 2030
- a new 2.6% sub-target for renewable fuel of non-biological origin (RFNBOs), which include hydrogen and electrofuels.

The accounting of the savings is based on a weighted average of volumes of fuels supplied to all transport modes and associated GHG emissions, based on a life-cycle approach, making sure that a) credits for avoided GHG emissions from CO_2 capture is not double-counted when it has already received an emission credit under other provisions of law (e.g. the EU ETS) and b) the calculation takes into account of differences in energy efficiency between vehicles. In addition, RFNBOs can only be counted towards the targets if their GHG emissions savings are at least 70%. The Refuel EU Regulation proposed, specific to aviation, includes requirements for a minimum share of SAF of 2% by 2025 and 5% by 2030, 20% in 2035, 32% in 2040, 38% in 2045 and 63% in 2050. To ensure that the fuel technologies supported under this Regulation have the highest potential in terms of innovation, decarbonisation and availability, the part of synthetic aviation fuels (the aviation equivalent of the RFNBOs) starts from 0.7% in 2030 and grows to 5% by 2035, 8% by 2040, 11% in 2045 and 28% in 2050.[17]

Both instruments limit the use of crop-based biofuels. These have limited environmental benefits, limited GHG savings potential and such biofuels are in direct competition with the food and feed sectors for access to feedstock while remaining open to fuels produced from waste lipids.

For aviation, these regulatory measures are complemented by proposals for a set of "flanking" instruments that support the intervention to address the problems and drivers identified along the SAF supply chain. They include support to raise ambition on SAF-use globally (through ICAO negotiations), facilitated processes for the certification of new SAFs, financial instruments (such as green bonds), steering financial support towards SAF development in the EU and an alliance on advanced biofuels and electro-fuels.

A crucial initiative for green finance was the creation of a common classification system, or a "taxonomy", for environmentally sustainable economic activities. The Taxonomy Regulation, from July 2020, establishes this framework in the European Union (European Commission, 2020b). This also underpins a proposal for a Regulation on a voluntary European Green Bond Standard (European Commission, 2021a).

Economic activities relevant to aviation and classified as sustainable in the EU taxonomy include the construction, modernisation, maintenance and operation of infrastructure that is required for zero tailpipe CO_2 operation of aircraft. On energy vectors used or suitable for air transport vehicles, the activities cover electricity and hydrogen as well as biofuels.[18]

Beyond Europe, Korea also plans to build up a taxonomy for green finance to channel financial flows into businesses delivering environmental benefits (UNFCCC, 2020), and the Japanese government has announced it will take measures to attract private investment into green, transition and innovation initiatives, while formulating basic principles and roadmaps for industries with large CO_2 emissions (METI, 2020). In this context, Japan will also co-operate with financial institutions in defining criteria for investments that contribute to a carbon-neutral economy. The United States Treasury is also supporting international efforts to better identify climate-aligned investments and encourage financial institutions to credibly align their portfolios and strategies with the objectives of the Paris Agreement (Shalal et al., 2021) and instructed federal agencies to measure, mitigate and disclose climate risks (White House, 2021).

Other national programmes

A range of different national programmes aiming to accelerate the decarbonisation of air transport by supporting specific technologies are also being implemented across the world. Norwegian state-owned airport operator Avinor has set an electrification target for all domestic flights by 2040, supported by the government and industry partners. Avinor and Luftfartstilsynet (2020) envision this would reduce GHG emissions by 80% compared to 2020 levels.[19] The first fully battery-electric domestic flights are expected to operate by 2030.

The French government is also supporting its aviation industry to accelerate the transition towards cleaner aircraft. As part of its EUR 15 billion (USD 17.7 billion) support package to the aviation industry following the Covid-19 crisis, the French government made EUR 1.5 billion (USD 1.8 billion) available to support R&D and innovation in the sector over a three-year period (2020-23) (Gouvernement, 2020). The objective is to further improve aircraft fuel efficiency and work towards electrification and the use of hydrogen as an energy vector. In September 2020, Airbus revealed three new aircraft concepts to achieve "zero-emission flight" – blended wing body, turboprop, and turbofan – all powered by hydrogen as a primary energy source (Airbus, 2020a).

In the United States, the Department of Energy announced it would provide USD 33 million in funding for 17 projects, as part of two Advanced Research Projects Agency-Energy's (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) (Department of Energy, 2020). These programmes aim to reduce energy use and CO_2 emissions from commercial aircraft. The funding will be split between eight REEACH and nine ASECND research projects.

Industry decarbonisation targets and strategies

Airlines, airports, aircraft manufacturers, air navigation service providers and other aviation industry stakeholders, collectively represented by the Air Transport Action Group, have carried out initiatives and set additional targets complementary to ICAO's CORSIA.

In addition to ICAO's aspirational goals of achieving 2% fuel efficiency improvements per annum and carbon-neutral growth from 2019, the industry has set a third aspirational target: to halve international air transport CO_2 emissions relative to 2005 levels by 2050, reaching around 325 $MtCO_2$ of annual emissions by mid-century (ATAG, 2008). The industry developed the four-pillar strategy adopted by ICAO, which relies on operational improvements, aircraft technology improvements, the use of SAF and market-based measures such as carbon offsetting and carbon capture and storage.

Despite the unprecedented impact of the Covid-19 pandemic, the aviation industry has shown commitment to decarbonisation in 2020. ATAG has published a roadmap charting three different pathways to achieve the industry's 2050 emissions goal (ATAG, 2020). The report suggests that the industry could achieve net-zero CO_2 emissions globally by 2060-65 (with some regions or individual companies reaching this point sooner) through the use of advanced aircraft technologies, the widespread use of SAF, improved operational efficiency and carbon offsetting. Additionally, an organisation collectively representing the entire European aviation industry recently committed to reaching net-zero CO_2 emissions by 2050 (Airlines for Europe et al., 2020). Both roadmaps hinge on government support for the sector and do not envisage strengthened carbon pricing signals. ATAG (2020) does not include any form of carbon pricing (including CORSIA) in the decarbonisation scenarios, and Airlines for Europe et al. (2020) suggest reinvesting the revenue collected from the purchase of EU ETS allowances by aircraft operators within the sector for decarbonisation.

Over twenty individual airlines and airline groups, such as Etihad, International Airlines Group (IAG) and Qantas, have also pledged to reach net-zero carbon emissions by 2050 or earlier. United Airlines was the first airline to announce a net-zero carbon commitment by leveraging investments in SAF and carbon offsetting through carbon removal technologies (United Airlines, 2020). IAG's strategy also includes the combination of technological improvements for aircraft efficiency, operational savings, SAF, offsets and carbon removals (IAG, 2021). Other airlines have already begun to purchase carbon offsets for certain flights. This is the case for Air France and JetBlue domestic flights and all EasyJet flights.

Airports across the world accounted for about 5% of total CO_2 emissions from aviation before the Covid-19 pandemic (ACI, 2017). Under the umbrella of ACI, airports have set co-ordinated climate targets and implemented initiatives to reduce their environmental impact. Since the 2009 establishment of Airport Carbon Accreditation, the global standard for carbon management in airports, 297 airports accounting for 44% of global air passenger traffic have been accredited. In 2019, ACI EUROPE and its members committed to net-zero carbon emissions from airport operations within their control by pushing absolute emissions down to the furthest extent possible and offsetting remaining emissions through investment in carbon capture and storage (ACI EUROPE, 2019a). Three Swedish regional airports operated by Swedavia have already achieved this goal without carbon capture and storage (ACI EUROPE, 2020). Airports also have an important role to play in the transition towards the use of SAF, as illustrated by Schiphol's plans to invest in the construction of Europe's first sustainable kerosene plant (Schiphol, 2019).

Technological and operational decarbonisation measures

This chapter focuses on measures that have the necessary technical characteristics to contribute to the decarbonisation of aviation.

The first set of technological options discussed are those that reduce the energy needed to fly by reducing aircraft weight, improving the thermodynamic efficiency of their propulsion systems and their aerodynamic characteristics. These technologies are discussed in two sub-groups. First, *energy efficiency improvements* consisting of changes to aircraft currently in use or using propulsion systems similar to those in commercial use today. Second, *alternative propulsion systems* consisting of technologies that require deeper modifications of the aircraft propulsion system, ranging from hybrid-electric to all-electric aircraft and that may also require a change in energy vector.

Other energy and GHG savings can be derived from *low-carbon fuels and other energy vectors*. These require switching from fossil energy to processes and feedstocks capable of meeting a number of sustainability requirements: low GHG emissions on a life-cycle basis, low impacts on direct and indirect land-use change, high energy efficiency in fuel making and large-scale availability.

A third group of technological options contributing to the decarbonisation of aviation consists of *operational improvements*. These include strategies to improve operations of aircraft and at airports to promote decarbonisation of the sector.

In addition to sustainability requirements, technology readiness, costs and the policy environment are the most influential determinants for the deployment of decarbonisation options for aviation. This section considers how differences across all these determinants could impact the way technologies become commercially available at different points in time.

Energy efficiency improvements

Many opportunities remain to further improve the energy efficiency of conventional aircraft. Despite the significant progress made on this front, key technologies that can help reduce fuel burn without requiring major changes in the propulsion systems of aircraft that are in commercial use today are summarised in Table 2.

Increasing use of composites (including, but not limited to, carbon-reinforced polymers), lighter metal alloys and novel manufacturing methods, including 3D printing, can enable the production of lighter and hence more fuel-efficient aircraft (Huang et al., 2016). Roughly half of the most recently produced civil aircraft, such as the Boeing 787 and Airbus A350, already include components made of carbon-reinforced polymers and other composite materials (Hollinger, 2016). These materials have initially been used in secondary structures and have now been integrated into the primary structures.

Table 2. Aircraft technologies to reduce fuel burn

Technology	Technology Readiness Level	Description
Composite materials	High	Composite materials are already used to produce aircraft components. Their low weight enables fuel burn reductions. New manufacturing technologies such as 3D printing will open further opportunities for application.
Ultra high bypass ratio (UHBR) engines	High	UHBR engines with a bypass ratio of 15:1 are expected to become available in the short term and can reduce specific fuel burn by 25% compared to current engines. These large engines can generally be wing-mounted and are compatible with conventional aircraft designs.
Wings with high-aspect ratio	High	Wings with high-aspect ratios (i.e. longer ratio between wing span and chord) reduce drag forces on the aircraft, making aircraft more fuel-efficient by improving aerodynamics.
Open-rotor engines	Medium	Open-rotor engines combine design principles of turbofans and turboprop engines, effectively enabling a high bypass ratio that reduces fuel burn by up-to-30% compared to current high bypass turbofan engines. Their large size requires them to be rear-mounted, departing significantly from current aircraft design. The engines are noisier than those currently in use. Both factors can pose commercialisation challenges.
Boundary layer ingestion (BLI)	Medium	Aircraft designs with BLI reduce aerodynamic drag by reducing the speed gap between slow airflows near the aircraft body (the boundary layer) and the overall aircraft speed. BLI can be enabled by one or more engines at the rear and/or close to the aircraft body and may require a specialised inlet to address airflow distortions before it gets to the fan. BLI can also be combined with other novel aircraft designs such as blended wing body or distributed propulsion with several small engines.
Blended wing body (BWB) aircraft	Low	BWB aircraft break from the conventional tubular aircraft design and could reduce fuel burn by up to 20% compared to current aircraft (Airbus, 2020b) with a high wing-aspect ratio. The high financial risk of developing clean-sheet design aircraft can hinder their development as aircraft manufacturers will tend to prefer less risky aircraft designs with incremental fuel-efficiency savings. Moreover, current airports cannot easily accommodate large BWB aircraft that would have a large wingspan. The theatre-like seating arrangement also poses security issues as some passengers will sit far from emergency exits. BWB architectures are also not applicable to model families with different sizes, constraining the flexibility of manufacturers to respond to airline demand.

Engines with high bypass ratios[20] increase fuel efficiency by reducing the difference in speed between the aircraft and the air propelled by the engine. They have a high technology readiness level. Energy efficiency improvements in aircraft engines currently used in commercial aircraft largely stem from increasing bypass ratios, reflected in engine designs with larger diameters. The most recent models are marketed as ultra-high bypass ratio (UHBR). These engines have been estimated to offer up to 30% reductions in fuel burn compared to the United Kingdom's 2017 aircraft fleet (Air Transportation Analytics Ltd and Ellondee Ltd, 2018). They can be wing-mounted with design changes that accommodate their large diameter. These engines are thus compatible with aircraft types that are currently in use, although their larger size can create some safety concerns.[21]

Open rotors, which resemble unducted turbofan engines, maximise bypass ratios while limiting weight increases and additional drag from bigger engine size, allowing energy efficiency improvements of up to 30% compared to current high bypass turbofan engines (Safran, 2017a). However, open rotor engines come with high-noise levels and operate at a cruise speed of around 0.7 Mach, which limits use to short-haul aircraft (Air Transportation Analytics Ltd and Ellondee Ltd, 2018). Due to their size, open-rotor engines also need to be rear-mounted. This requires a different aircraft design, a significant barrier to this technology's near-term integration.

Wings with a higher aspect ratio are a technology readily available and are therefore close to commercial deployment: extending the length of the wing reduces drag forces on the aircraft, making it more efficient. Recent improvements such as folding wind tip technology enable this use of this solution at airports that cannot accommodate aircraft with larger wingspans (Boeing, 2017).

Additional aerodynamic improvements can be derived from boundary layer ingestion (BLI), estimated to have the potential to reduce the aircraft fuel burn by up to 8.5% compared to aircraft flown today (NASA, 2020). BLI reduces aerodynamic drag by re-energising the slow airflows near the aircraft body (the boundary layer). It can be enabled by one or more engines at the rear and/or close to the aircraft body and may require a specialised inlet to address airflow distortions ahead of the fan.

A blended wing-body configuration departs from the traditional tubular aircraft design and is a more complex and disruptive development with lower technology readiness. Airbus's MAVERIC and Boeing-NASA X-48 collaboration are research programmes that have tested small-scale prototypes of passenger aircraft with this design (Airbus, 2020c; NASA, 2013). Airbus's programme could lead to an estimated 20% improvement in fuel efficiency. This disruptive design entails high commercial risks and uncertain returns on R&D investments for manufacturers because its high wingspan-to-height ratio makes it suitable for large aircraft only and because development costs cannot be split over a model family with different sizes. The commercial success of such designs for passenger travel will also depend on passenger acceptance of windowless aircraft and emergency exits in the theatre-like seating layout.

An ICCT review of many efficiency-improving technologies for commercial aircraft included in this section concluded that cost-effective technologies providing net savings to airlines could reduce the fuel consumption of new aircraft designs by around 25% by 2024 and 40% by 2034, compared to 2016 aircraft (ICCT, 2016). By 2024, expected fuel savings were estimated to double those resulting from market forces alone, which were projected to burn between 9% and 13% less fuel than the 2016 aircraft. These estimates did not include BLI and blended wing-body configurations.

The ICCT analysis accounted for increased costs (such as maturation, development, deployment and maintenance of technologies) and operating cost savings for single-aisle, small twin-aisle and regional jet aircraft. It accounts for different technology packages, ensuring that mutually exclusive technologies are not evaluated for the same aircraft. Its fuel price assumptions up to 2040 are consistent with the EIA (2015) Annual Energy Outlook and reach USD 153 per barrel in 2040 (in 2019 constant USD). The latest EIA (2020) jet fuel-price projections are lower than those in the 2015 edition (reaching USD 80 per barrel in 2040 and USD 95 per barrel in 2050, in 2019 constant USD). These values are in line with those used by ICCT (2016) in a sensitivity analysis. The ICCT results show that low fuel costs shift the payback period for the 2024 aircraft design from seven to eight years and from seven to eleven years for the aircraft design that include energy efficiency improvements (i.e. the 2034 configuration). This is still well within the average aircraft lifetime of around 23 years (JADC, 2019).[22]

Alternative propulsion systems

Adopting alternative propulsion systems has greater investment risk than adopting improvements that rely on propulsion systems similar to those in commercial use today. On the other hand, switching to alternative propulsion systems, particularly those that rely on electricity or hydrogen as energy vectors, presents opportunities to significantly reduce the emission of GHGs and other air pollutants, provided that energy production pathways are also less carbon-intensive and cleaner than current aviation fuels.

Alternative propulsion systems for aircraft can be grouped into three main families of technologies, summarised in Table 3 and further discussed below.

Table 3. Alternative aircraft propulsion systems

Technology	Technology Readiness Level	Description
Hybrid-electric aircraft	Medium	Integrating electric propulsion with combustion engines can optimise engine performance in non-cruising flight stages and help reduce fuel burn, especially if they allow for boundary layer ingestion. Because hybrid-electric aircraft have smaller and lighter batteries than all-electric aircraft, the weight increase relative to conventional aircraft is less of an issue for hybrid-electric aircraft.
All-electric aircraft	Low	All-electric aircraft relying on batteries for energy storage and electric motors for propulsion have zero tailpipe emissions and can significantly reduce the carbon intensity and climate impact of air transport, especially if powered by renewable electricity. However, an important limitation is the weight of the batteries, which limits the energy savings achievable, vehicle size and flight ranges. Another limitation is the current cost of batteries. Despite these limitations, several manufacturers are developing electric air taxis for less than ten passengers. Scaling-up aircraft for short-haul flights relies on uncertain technology breakthroughs in battery chemistry.
Hydrogen-powered aircraft	Low	Hydrogen-powered aircraft – which may rely on combustion technologies or fuel cells – emit water vapour and nitrogen oxides during flight, compared to all-electric aircraft, which require electricity as an energy vector and have no tailpipe emissions. The low volumetric energy density of hydrogen means that aircraft require larger fuel tanks than those in existence. To ensure that the storage volume remains manageable, they also need storage at extremely low temperatures and extremely high-performance applications to limit losses from evaporation. Hydrogen-powered aircraft could allow faster refuelling than all-electric aircraft, but hydrogen requires very deep cooling of the fuel transfer line, which increases the complexity of refuelling operations and leads to additional energy losses.

Hybrid electric aircraft

Engine hybridisation, the coupling of combustion and electric assistance, increases an engine's capacity. It optimises conditions at all flight stages[23], resulting in lower overall fuel consumption, despite weight increases due to greater engine complexity and the need for on-board electricity storage. Fuel and energy savings depend on the degree of hybridisation, including the extent to which the aircraft operates in all-electric mode and the characteristics of the electric energy storage system. Energy savings have a higher relevance for short-haul flights due to the higher share of flight time allocated to the most energy-intensive flight phases (take-off, climb, and descent) and greater relevance of all-electric flight opportunities. Recent estimates for aircraft suitable for regional transport suggest that fuel burn savings could range between

12% and 28%, depending on the configuration considered, and total energy-use reductions between 7% and 12% (Zamboni, 2018).

Engine hybridisation has a lower technology readiness level than UHBR engines, but it is an important area of development for aircraft engine manufacturers. Rolls Royce and Airbus were developing a prototype for a hybrid-electric aircraft under the E-Fan X programme with test flights planned for 2021, but the programme was discontinued in 2020 (Airbus, 2020d). Hybrid-electric propulsion can also enable the integration of all-electric propulsion systems and progressively increase all-electric aircraft ranges, as electricity storage improves in terms of safety, specific energy, weight and cost reductions.

Integrating electric propulsion in aircraft design not only paves the way for the development of all-electric aircraft but also offers opportunities to advance other novel aircraft technologies and designs. For instance, electric aircraft motors are more suitable for distributed propulsion than combustion engines as the inefficiency of the latter increases if they get smaller compared to electric motors. They can also be effective enablers of boundary-layer ingestion designs, as illustrated by the *Single-aisle Turboelectric Aircraft with an Aft Boundary-Layer propulsor* (STARC-ABL) concept under development by the US National Aeronautics and Space Administration (NASA). This design integrates electric propulsion at the tail of the aircraft, where a single engine ingests the boundary layer and reduces drag. This electric engine is powered by generators run by the wing-mounted engines (NASA, 2019).

All-electric aircraft

All-electric aircraft contribute to improved energy efficiency and energy diversification. Electrifying aircraft requires batteries with low weight and high-energy-density to be suitable for a reasonable range and aircraft size, as well as other technologies that could enable weight reduction, for example, high-temperature superconductors. The development of advanced and affordable battery cells and packs, suitable for aviation, could piggyback on the technological progress and cost reduction of battery storage that started in consumer electronics since this now underpins the large-scale deployment of electric vehicles and opens up important opportunities to fund the development of advanced technologies like lithium-sulphur and lithium-air (US DoE, 2020).

An all-electric aircraft for use in commercial aviation with an operating range of 750 km to 1 100 km and a capacity of 150 passengers would require battery cells with more than triple the density of current Li-ion batteries (Schäfer et al., 2019).[24] Challenges for all-electric aircraft also come from high-power requirements, especially for take-off, which may require the use of high-power batteries.[25] Despite these challenges, many companies have started all-electric aircraft development programmes (Box 7).

The decarbonisation potential of all-electric aircraft also critically depends on access to low-carbon energy sources. The impact of a switch to electric aircraft on climate is also affected by uncertainties in the radiative forcing effect of CO_2 emissions from fuel combustion in aircraft. Considering a specific energy consumption of 0.18 kWh/RPK, electricity with a carbon intensity below 350 g CO_2/kWh (i.e. from renewables, nuclear or fossil fuels with carbon capture and storage) would deliver net CO_2 savings (Schäfer et al., 2019). This assessment considers that the CO_2 emissions from aircraft using combustion technologies are not associated with any incremental factor in terms of radiative forcing caused by non-CO_2 warming pollutants such as water vapour, aerosols and nitrogen oxides. The net savings threshold for the carbon intensity of electricity generation increases to 650 g CO_2/kWh – roughly comparable to electricity from fossil diesel combustion – when accounting for a doubling of the radiative forcing, in line with the 1.9 factor recommended in the United Kingdom for company greenhouse gas reporting (Hill et al., 2020). The same threshold increases to roughly 1 000 g CO_2/kWh for a radiative forcing factor of 3, as indicated in Lee et al. (2021). This threshold is higher than the CO_2 emissions resulting from electricity production in highly carbon-intensive brown coal plants.

Box 7. All-electric aircraft: latest developments

Prototypes of five-seater all-electric air taxis are currently under development by companies including Rolls Royce in partnership with Airbus, Hyundai for Uber, and start-ups such as Lilium (Rolls Royce, 2020; Hawkins, 2020; Lilium, n.d.). A nine-seater seaplane retrofitted with a battery and electric motor operated its inaugural flight in 2019 in Canada, trailblazing the development for small all-electric aircraft capable of flying very short distances – in this case, 160 km (Hawkins, 2019). Most recently, the European Union Aviation Safety Agency (EASA) issued the first certification for fully electric aircraft worldwide for a two-seater aircraft by Slovenian company Pipistrel (EASA, 2020b).

Norway's state-owned airport operator Avinor, in collaboration with airline partners, aims to electrify all domestic flights by 2040 using all-electric propulsion (Avinor, 2020). Distances under 1 200 km and small aircraft deployed on most domestic routes in Norway are particularly well suited for all-electric aircraft. In this partnership, airlines pledge to operate all-electric aircraft as they become commercially available, while airports invest in charging infrastructure.

Under current market conditions, projected mid-century electric aircraft will still not be cost-effective solutions for airlines unless a carbon tax lowered breakeven prices (Schäfer et al., 2019). Initial investment costs would be higher due to the purchase of batteries, while fuel and fuel-infrastructure costs would be avoided. Maintenance costs would increase for landing gear components due to higher landing weight and possibly also include replacement batteries but decrease for the engines of all-electric aircraft.

Hydrogen-powered aircraft

Hydrogen-powered aircraft can use hydrogen as fuel in a jet engine or in a fuel cell to power an electrically driven fan. If used as a combustion fuel, it could also be burned in a multi-fuel mixture with hydrocarbons, including conventional fossil fuels. Burning pure hydrogen limits the emission of air pollutants, in particular sulphur oxide (SO_X) and particulate matter, but can still lead to significant NO_X emissions if emissions-control technologies are not implemented (e.g. air premixing, optimised burner design, or novel pathways such as flameless combustion). In the absence of energy efficiency improvements on hydrogen-powered aircraft, hydrogen use in aircraft also leads to significantly higher water vapour being released relative to conventional fossil fuels. This can affect the climate through contrail and indirect cirrus formation. Additional climate impacts relate to hydrogen production pathways, which are discussed in the following subsection on low-carbon fuels and other energy vectors.

Hydrogen's high specific energy, i.e. energy per unit weight, is three times greater than that of conventional jet fuel. Although the advantage over conventional jet fuel is reduced when also considering the weight of the fuel tank, hydrogen's high specific energy can help overcome the energy density constraints of batteries. However, the low volumetric energy density of hydrogen requires larger fuel tanks than those in current aircraft.[26] Cryogenic storage, which requires temperatures below -252°C at atmospheric pressure, is necessary to ensure that the volume of storage remains manageable. Evaporative losses arising from the large difference in temperature between the outside environment and the liquid hydrogen storage tanks require relief valves to vent the hydrogen and maintain the temperature low enough, although heat exchanges can be minimised by design with insulation technologies.

Liquid hydrogen storage in cryogenic tanks could enable faster refuelling possibilities than all-electric aircraft, but it requires deep cooling of the fuel transfer line and the establishment of a “cold finger” connection point which increases the complexity of refuelling operations and leads to additional energy losses (Gupta, Basile and Veziroglu, 2015). Similar to any fuel, hydrogen poses important safety challenges that must be addressed. While most of these challenges are well-known and can be addressed, the experience so far of handling hydrogen cannot be compared with other commercially available and widely used aviation fuels (or fuels that have similar properties to these). Hydrogen also permeates through materials, making them brittle and prone to failure. This issue narrows the scope of suitable materials to handle it and may lead to cost increases due to material requirements, higher frequency of inspections and replacements.

Even if challenges related to the safety of cryogenic storage were to be effectively addressed, the low volumetric energy density of hydrogen would still require profound changes in aircraft designs. Fuel tanks for hydrogen-powered aircraft may need to be located in the fuselage rather than in wings to meet flying range requirements, reducing the space available for passengers and thus having significant implications for commercial viability.

Despite these challenges, Airbus has recently revealed three concepts of zero-emission commercial aircraft, all relying on hydrogen as a primary power source, announcing that they could enter service by 2035 (Airbus, 2020a):

- A turbofan design (120-200 passengers) with a range of 2 000 nautical miles (over 3 700 km), capable of operating trans-continental flights and powered by a modified gas-turbine engine running on hydrogen, rather than jet fuel, through combustion. The liquid hydrogen is foreseen to be stored and distributed via tanks located behind the rear pressure bulkhead.
- A turboprop design (up to 100 passengers) also powered by hydrogen combustion in modified gas-turbine engines, with a range of over 1 000 nautical miles (1 850 km), making it suitable for short-haul trips.
- A blended-wing body design (up to 200 passengers) in which the wings merge with the main body of the aircraft with a range similar to that of the turbofan concept. In this case, the wide fuselage opens up multiple options for hydrogen storage and distribution as well as for cabin layout.

Hydrogen with high purity characteristics can also be used in fuel cells to produce electricity and provide mechanical traction through an electric motor or provide energy to auxiliary power units (APU) for non-propulsion appliances such as heating, ventilation and air cooling, lighting and cabin pressurisation. The latter is an option that may be more relevant for the early application of fuel cells on aircraft (Safran, 2020).

Taxiing systems also present a mid-term opportunity for aircraft electrification without significant changes to flight propulsion. Safran, for example, has developed an electric-taxiing system in which an electric motor is mounted to the landing gear. This is more energy-efficient than using aircraft engines on the ground and makes aircraft autonomous from towing trucks, reducing delays at airports. The electric engine is operated with the APU and increases aircraft weight by 400 kg. For short-haul aircraft operating six or seven flights a day and spending a significant amount of time at airports, Safran estimates possible fuel savings of 4% per flight and per aircraft. Safran aimed to start offering this system on the A320 family to airlines in the near future (Safran, 2017b; Safran, 2017c), but the partners shelved the project in late 2019. The additional equipment weight makes electric taxiing attractive only for aircraft operating many short flights with long taxiing times, while recent industry trends are towards fewer, non-stop flights over longer distances per aircraft (Hepher and Chang, 2019).

Low-carbon fuels and other energy vectors

The high capital costs of new aircraft designs, slow fleet replacement times and lagging pace of infrastructural changes suggest switching to more efficient, electric and hybrid-electric aircraft will be affected by relatively long lead times. This is exacerbated by the fact that the technologies offering the largest energy savings tend to have lower technology readiness levels. In addition, technologies such as hybrid engines, all-electric and hydrogen-powered aircraft have a primary scope of applicability on short-range flights, whose share of fuel burn is proportionally far lower than the share of total flights (Schäfer et al., 2019). In this context, developing alternative energy vectors for aviation is key, especially in cases where they can be directly blended with conventional jet kerosene.

Sustainable Aviation Fuels (SAF), a category that essentially comprises biofuels and synthetic fuels,[27] can significantly reduce the life cycle GHG emissions of aviation fuels, provided that they can be sustainably produced at scale. In the initial phase of a progressive decline in the carbon intensity of aviation fuels, SAF may face competition from low-carbon aviation fuels (LCAF).[28] These are petroleum-based fuels with well-to-tank emissions that fall below the average benchmark of petroleum-based fuels (Box 8). Increases in LCAF production cost are likely lower than in the case of SAF. LCAF are also less likely to face major scalability limitations. Their main drawback lies in the limited GHG emission reduction potential due to their inherent reliance on fossil carbon.

Seven SAF pathways have been approved to date by the American Society for Testing and Materials (ASTM), the standardisation authority that is currently the global reference for SAF certification. They are included in the ASTM D7566 Standard Specification for Aviation Turbine Fuel Containing Synthesized Hydrocarbons. They essentially consist of synthetic paraffinic kerosene (SPK), approved for a maximum blending ratio of 50%, and synthetic iso-paraffinic kerosene (SIP), approved for blends of up to 10%.[29] In addition, the ASTM D1655 standard (which defines jet fuel specifications) also allows co-processing of up to 5% of lipidic feedstock (fats and oils), which may have biogenic origin, in refineries.

To maximise GHG emissions abatement benefits and minimise negative impacts on food prices and land-use change, SAF based on waste feedstock or crops with high biomass yields per hectare should be given preference (ICAO, 2019f), although waste feedstock is not exempt from environmental impacts. Emissions from all fuels should be analysed over their full life cycle, including feedstock production and indirect effects, such as indirect land-use change (ILUC). High-quality[30] fuel such as SPK also has a positive impact on aviation's non-CO_2 emissions as they can reduce contrail-inducing soot emissions (Burkhardt, Bock and Bier, 2018). Default life cycle CO_2 emission values for CORSIA-eligible fuels have been determined by ICAO (2021b) (Figure 5).[31]

Box 8. Low-carbon aviation fuels

Low-carbon aviation fuels (LCAF) are Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA)-eligible petroleum-based aviation fuels emitting at least 10% less net GHG emissions than the baseline life cycle emissions value of 89 g CO_2-eq/MJ (ICAO, 2019f and ICAO, 2019g). Using such fuels allows airlines to reduce CORSIA offsetting requirements. It also requires the establishment of effective instruments that account for the carbon intensity of different types of oil (and gas) extraction, e.g. to track issues such as methane leakage (IEA, 2021b) and other determinants of different performances (Masnadi et al., 2018).

LCAF benefit from lower well-to-tank emissions than conventional jet fuel due to the lower carbon intensity of oil extraction and better quality of the oil, which minimise GHG emissions from refining. Important measures that could further reduce GHG emissions include the adoption of conscious resource choices (e.g. prioritising the production of aviation fuels in refineries using light sweet crudes), improved extraction practices (no routine flaring, minimal fugitive and venting emissions), integrating renewables and low-carbon electricity into new oil developments, and using carbon capture and storage in oil extraction practices.

While some of these practices can reduce emissions, it is difficult to ascribe impacts to aviation or any other end-user of the fuel as most refineries produce a range of fuel products. Offering credits for lower-carbon petroleum also creates the risk of fuel shuffling, where preferential lower-carbon crude sources are assigned to aviation fuels, while higher carbon crudes are assigned to other fuels, leading to minimal, if any, change in net emissions. It is important that policies incentivising lower-carbon conventional fuel production reflect actual emissions reductions and that these are additional to the petroleum industry's standard practices.

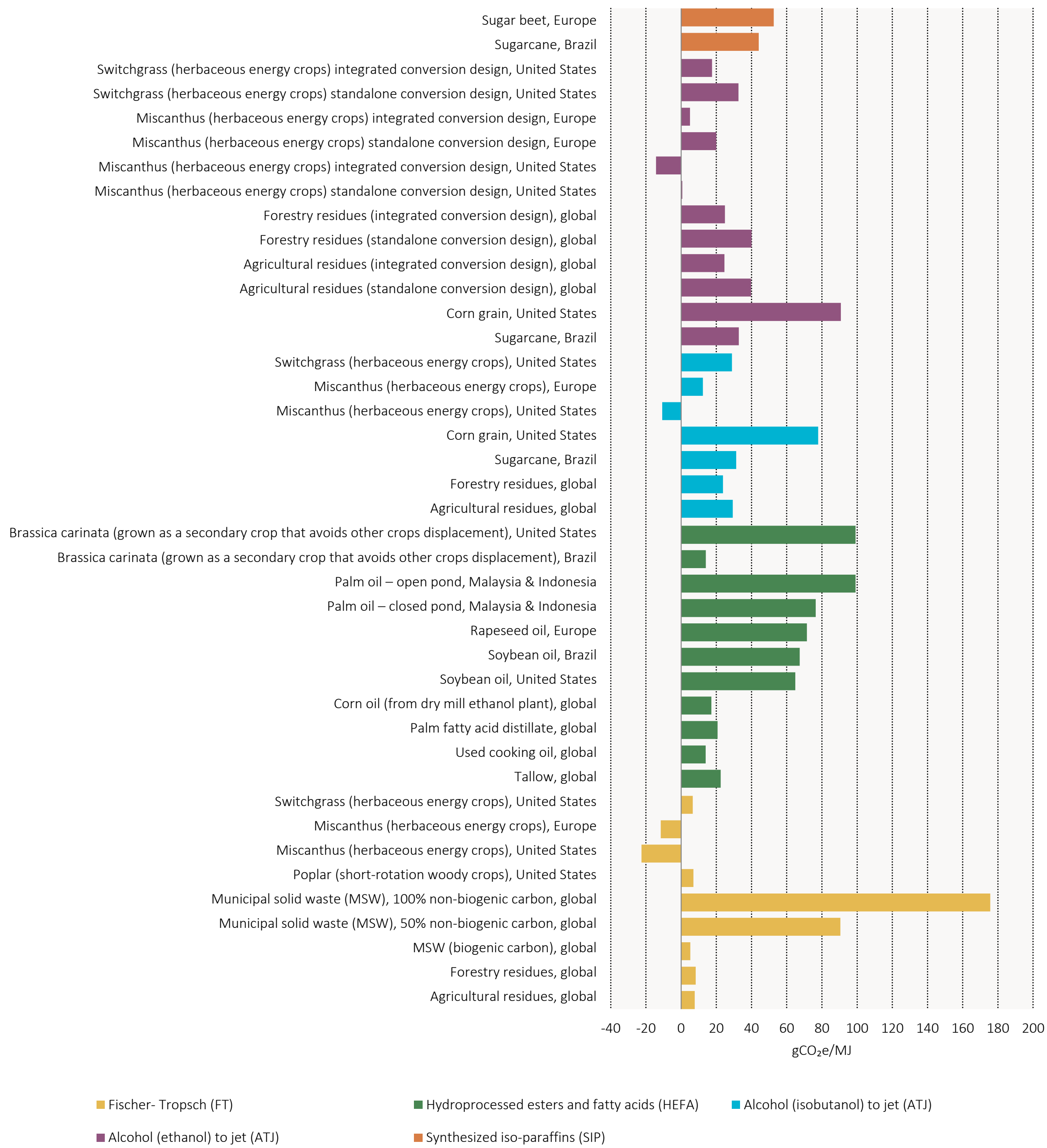
The lower production costs and higher potential availability of LCAF may also limit the uptake of other SAF by delaying investments to start deploying, scaling-up and developing technology improvements for biomass-based SAF. These were the focus of the Fuels Task Group's activities until the 2019 decision of the ICAO Council to accept LCAF as CORSIA-eligible fuels.

Without a supportive policy framework, the high production costs of SAF currently prevent them from commercially competing with petroleum-based fuels. In this context, promoting energy-efficient aircraft technologies remains crucial during the transition to SAF, as they can buffer against high fuel costs.

SAF production pathways can be grouped into three families of fuel production processes: oleochemical/lipid, biochemical and thermochemical pathways (IEA Bioenergy, 2019) (Figure 6). These will be the focus of the first part of the following section.

Complementary or alternative technologies allowing for CO_2 emission reductions in aviation include hydrogen and electrofuels. Hydrogen is needed for hydrogen-powered aircraft and also having a role as a feedstock for the production of fuels, possibly in combination with biogenic carbon from biomass. Electrofuels are synthetic fuels obtained from hydrogen and other sources of carbon (in particular atmospheric capture), requiring low-carbon electricity to deliver meaningful CO_2 emission reductions. They will be discussed in subsequent sections.

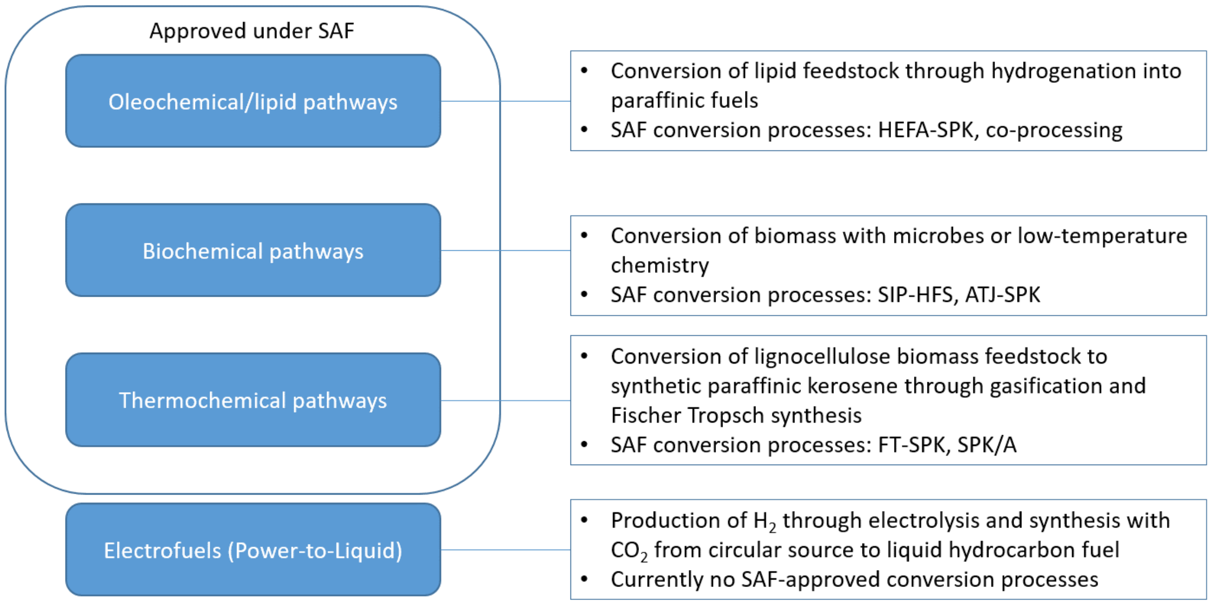
Figure 5. Default values for life cycle CO_2 emissions of CORSIA-eligible fuels



Note: MSW: Municipal solid waste; gCO_2-eq/MJ: grammes of CO_2 equivalent per mega joule. Negative values reflect cases where indirect land-use change affects more than offset positive emissions from feedstock production and conversion. They are provisionally allowed during the pilot phase of CORSIA (2021-23). A decision on whether to continue allowing negative values will be made by the end of the pilot phase (2023).

Source: Adapted from ICAO (2021b).

Figure 6. Production pathways of low-carbon, drop-in aviation fuels



Notes: SAF: sustainable aviation fuels; HEFA-SPK: hydro-processed esters and fatty acids synthetic paraffinic kerosene; SIP-HFS: synthetic iso paraffins from hydro-processed fermented sugars; ATJ-SPK: alcohol-to-jet; FT-SPK: Fischer Tropsch; SPK/A: synthetic paraffinic kerosene with aromatics; H_2: hydrogen.

The last part of the analysis in this section will look at carbon dioxide removal (CDR) technologies. These are emerging as an area of interest in aviation because of their relevance for offsets and their relevance for production of electrofuels. The assessment will conclude with a section assessing contributions that could become available from all these solutions, drawing on considerations related to costs, technology readiness, requirements needed to ensure an effective contribution to decarbonisation and the availability, at scale, of the different options.

Oleochemical and lipid pathways for sustainable aviation fuel

The oleochemical and lipid pathway converts lipid feedstock (e.g. vegetable oils, animal fat or used cooking oil) through hydrogenation into paraffinic fuels compatible for drop-in blending with conventional jet fuel, often integrated into the refining process.

The main ASTM-certified fuel in this family is hydro-processed esters and fatty acids to synthetic paraffinic kerosene (HEFA-SPK).[32] It is currently the main route for drop-in alternative fuel production in aviation (IEA Bioenergy, 2019). It is intended for fats, oils, and greases and from oilseed crops or algae (Holladay, Abdullah and Heyne, 2020).

HEFA production costs are largely dependent on feedstock costs. The availability and mobilisation of waste oils through efficient supply chains is crucial to lower costs. However, low-carbon HEFA development is limited by the low availability of waste oils, a feedstock capable of covering up 10% of the aviation fuel demand of 2019 (World Economic Forum, 2020). Other renewable fuels such as biodiesel are also competing for access to low-cost waste oils. If this is not already the case, cost reductions could also be achieved by integrating the supply chains of HEFA and hydro-treated vegetable oil (HVO), a broader production pathway for biofuels in the diesel pool whose production was expected to double between 2018 and 2024 (IEA, 2018b). Scale increase is another important cost-reducing opportunity.

The second ASTM-certified fuel in this family results from the co-processing of up to 5% of lipidic feedstock (fats and oils) in refineries[33] to yield jet fuel, among other refined products. Future developments in this pathway could include the co-processing of bio-based intermediates with higher oxygen content. In this case, refinery integration would need to take place through insertion points in specific refinery components, such as hydrotreaters or fluid catalytic crackers. This could widen the feedstock base for biomass-based SAF from refinery integration, but this technology is currently at a low-readiness level.

A third ASTM-certified fuel in this family consists of SPK from lipids from hydrocarbon-bearing algae (*Botryococcus braunii*) that have been subject to hydrocracking and hydroisomerisation to remove all oxygen and saturate double bonds (HC-HEFA) (Holladay, Abdullah and Heyne, 2020).[34] It was approved in 2020 as a 10% blend. A fourth pathway bridging the oleochemical and thermochemical families is the Applied Research Associates Catalytic Hydrothermolysis Jet (ARA CHJ). This uses a hydro-thermal process to produce aviation fuel from lipids. It was approved in 2020 as a 50% blend.[35]

Biochemical pathways for sustainable aviation fuel

Biochemical pathways convert biomass through biological processes, such as glucose fermented to ethanol for conventional biofuel production ("first-generation biofuels"), and enzymatic hydrolysis followed by biological sugar conversion. In advanced biocatalytic processes, the latter can yield drop-in fuel or fuel intermediates such as longer chain alcohols, including butanol and butanediol, isoprenoids and fatty acids (IEA Bioenergy, 2014).

Production costs for biochemical pathways are estimated to be higher than for HEFA (ICAO, 2018). Cost-related challenges for biochemical pathways initially led to a focus on higher-value markets for bio-based chemicals (IEA Bioenergy, 2014), but increasing interest in biojet fuel production has spurred interest in the development of ASTM certification for biochemical fuels (IEA Bioenergy, 2019). As of mid-2021 ASTM approval has been granted to hydro-processed fermented sugar (HFS-SIP)[36] by Gevo, which converts sugars into hydrocarbons using modified yeasts and alcohol-to-jet (ATJ-SPK)[37] by Lanzatech, which converts alcohols into hydrocarbons through dehydration, oligomerisation and hydroprocessing. Other biochemical pathways are currently in the ATSM approval process.

Similar to HEFA, efficient supply chains are crucial to lower the cost of biochemical fuels. One way to do this is to piggyback on existing ethanol facilities, taking advantage of the existing supply chain for conventional production (IEA Bioenergy, 2014). However, this could risk displacing bio-based fuels for road use with aviation fuels rather than displacing fossil fuels.

Thermochemical pathways for sustainable aviation fuel

Thermochemical pathways largely consist in the conversion of ligno-cellulosic feedstocks (including wood, energy crops, some forms of municipal solid waste and residues from agriculture and forestry) to synthetic paraffinic kerosene through biomass gasification (to syngas) and Fischer Tropsch (FT) synthesis, whereby carbon monoxide and hydrogen are converted into liquid hydrocarbons.

FT synthesis has large-scale commercial applications in South Africa, where energy company SASOL produces synthetic hydrocarbons using coal as feedstock (coal-to-liquids), and in five large-scale gas-to-liquid plants which convert natural gas into liquid fuels located in Malaysia, Nigeria, Qatar and South Africa (Nichols, 2017). FT-based fuel production from biomass has been used in demonstration plants in Europe and North America (ETIP Bioenergy, 2020a and 2020b). When biomass is the feedstock, this process is often called biomass-to-liquids (BtL).[38] The relevant certified aviation fuels issued by this pathway are FT

Synthetic Paraffinic Kerosene (FT-SPK[39]) and FT-SPK/A[40], a variation of FT-SPK including aromatic compounds.

The BtL pathway faces technical challenges due to the need to remove impurities such as small char particles, tar vapours and volatile nitrogen and sulphur compounds in intermediate steps of fuel production (IEA Bioenergy, 2019). Scaling-up BtL production is also challenging due to the inherent limitations from the physically sparse nature of the biomass feedstock, which is also an issue for other biofuel pathways, and the relatively low readiness of the technology. These issues have repercussions on costs, with the cost gap with oil-based fuels estimated to be higher than for HEFA. On the other hand, the reliance on ligno-cellulosic feedstocks of BtL pathways gives a major advantage to these pathways in terms of available and sustainable resource potential, much greater than the estimates identified for HEFA (IEA, 2010, Creutzig et al., 2015).

The yield of BtL fuels from biomass feedstocks can also be significantly improved by integrating syngas production from biomass gasification with additional hydrogen inputs (Hannula, 2016a). If low-carbon hydrogen is used, this can also help to maintain low-GHG emissions intensities and address other sustainability challenges, including land-use requirements. If cost challenges are overcome and technology readiness is increased, these enhanced processes – combining hydrogen from renewable electricity and biogenic carbon streams, referred to as power and biomass-to-liquids (PBtL) – gain a commercial advantage over non-enhanced designs when the average cost of low-carbon hydrogen falls below EUR 2.2 (USD 2.6) to EUR 2.8 (USD 3.3) per kg, depending on the process configuration (Hannula, 2016b).

Hydrogen

Hydrogen is an energy vector of growing interest in aviation and the wider transport sector. In particular, it could help to mitigate the geopolitical challenges of the clean energy transition, as it can be derived from a variety of primary energy sources. Currently, hydrogen is already produced at-scale for a range of industrial uses, mainly using fossil fuels, either by steam methane reformation (76%) or coal reformation (23%) (IEA, 2019c). Both of these production processes release large amounts of GHG emissions. These current conditions, combined with energy losses from liquefying hydrogen[41] and other energy losses needed to ensure the transport and distribution of hydrogen, would make hydrogen use in aviation far more intensive in terms of energy requirements and GHG emissions than the use of conventional jet fuel.

Low-carbon hydrogen production is, therefore, a strict condition to achieve meaningful reductions in GHG emissions for aviation. Low-carbon hydrogen can be produced through electrolysis powered with renewable or nuclear electricity and even with fossil fuels if hydrogen production takes place in processes that use effective measures to capture and avoid, or store, CO_2 emissions.

Producing hydrogen by electrolysis and using electricity from renewables has the potential to eliminate almost all GHG emissions from hydrogen production but requires significant volumes of water.[42] Hydrogen from electrolysis is already at a high level of technological maturity (IEA, 2020e) but currently faces higher costs than the main production methods in use.[43]

Two solutions to reduce emissions from hydrogen production from fossil fuels include applying carbon capture and storage (CCS) technologies to existing fossil production methods or methane pyrolysis. CCS could theoretically sequester up to 90% of the CO_2 emissions occurring from hydrogen production by fossil fuel reformation[44] and close to 100% if the process can combine water electrolysis for oxygen production (and hydrogen as a by-product) with power generation through the Allam cycle and CO_2 sequestration (Collins, 2021). However, carbon capture technology must be financially viable and effectively store carbon in a secure way for centuries.

Hydrogen production from methane pyrolysis involves anaerobically decomposing natural gas at high temperatures or in the presence of a catalyst, producing hydrogen and solid carbon. Because gaseous CO_2 is not produced in this process, hydrogen produced in this manner facilitates carbon storage. Methane pyrolysis is currently used to produce carbon black, a material used to reinforce vehicle tyres (Monolith Materials, 2020). However, as a method to produce hydrogen, it is currently at a relatively early level of technology readiness (IEA, 2020e). Methane pyrolysis could theoretically reduce the GHG intensity of hydrogen by approximately 90% compared to existing steam methane reformation methods, provided low-carbon sources are used for heat and the transport of natural gas. This pathway will also remain susceptible to fugitive methane emissions in supply chains which, unless effectively addressed, may significantly reduce its climate benefits (Weger, Abánades and Butler, 2017; Parkinson et al., 2019).

Electrofuels

The combination of hydrogen with carbon-monoxide building blocks can yield a range of different synthetic hydrocarbons, in gaseous (methane) or liquid (methanol, gasoline and diesel). SPK is one of the possible liquid outputs of these processes. BtL relies on biomass resources to synthesise these building blocks into fuels, but the same building blocks can be derived from other processes.

In this context, electrofuels are an option that has been gaining visibility recently and constitute a fourth possible pathway for SPK for aviation. This pathway combines hydrogen with renewable carbon from diluted or concentrated sources. To ensure that electrofuels lead to meaningful GHG emissions savings during fuel production, hydrogen must come from low-carbon pathways and carbon needs to be part of a circular loop. Low-carbon hydrogen can be produced from electrolysis using renewable electricity, but also synthesis from methane with carbon capture and storage.

A possible carbon source is biomass, as in PBtL, where the loop is closed by growing plants absorbing atmospheric carbon. In this case, the fuel classification can be seen as a hybrid between electrofuels and the biofuel production pathways previously discussed. This is because the use of low-carbon hydrogen from electrolysis can enhance the production of hydrocarbon electrofuels from the thermochemical conversion of biomass, increasing the yield of fuels from the carbon available in the biomass feedstock by increasing its hydrogen/carbon ratio.

Another option (aligned to the definition of electrofuels) is direct air capture (DAC) of CO_2, resulting from processes that separate atmospheric CO_2 to obtain carbon that is then used for the chemical synthesis of electrofuels. DAC is also pursued as a technology aiming to deliver carbon removals from the atmosphere. An option that is starting to be actively considered by aviation stakeholders and is discussed in the next section.

More concentrated CO_2 sources, e.g. from fugitive emissions in industry and/or combustion processes, are another possible source. These are not renewable unless obtained from the combustion of biomass and therefore linked to electrofuel production processes that fall within the scope of "carbon utilisation", rather than carbon capture.

Electrofuels produced through DAC can have a relatively low impact on land-use change compared to other SAF production pathways. However, significant thermodynamic losses – exceeding those in oleochemical, biochemical and thermochemical pathways – occur during the process and imply that producing electrofuels at a large scale would require significant amounts of energy. This leads to a strong dependency of net climate benefits of DAC to fuel processes on the energy source. It also underlines the fundamental importance of low-carbon energy inputs and ambient heat extraction through heat pumps to enable DAC to fuels to emit less than the direct use of fossil hydrocarbons (Deutz and Bardow, 2021).

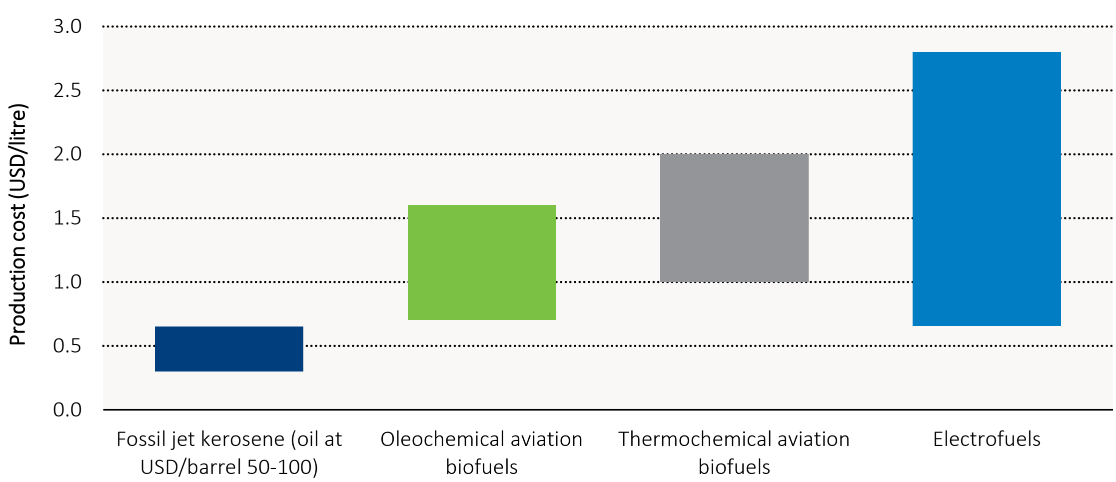
Additionally, climate benefits are lower for electrofuels reliant on carbon utilisation technologies other than those based on biomass combustion since the primary origin of the carbon has is not part of a circular loop originating in the atmosphere.

Thermodynamic losses are also an important limitation for DAC to fuel pathways. These have a low energy return on energy invested, leading to significant increases in primary energy consumption if compared with conventional fuels and other SAF production pathways. Replacing 20% of all aviation fuel with DAC-based electrofuels, reliant on low-carbon electricity, would increase global electricity production by almost 10%.[45] Primary energy requirements are lower for electrofuels reliant on carbon utilisation due to the more concentrated nature of CO_2 streams, along with opportunities with waste heat recovery. In this case, CO_2 savings are also lower. For electrofuels reliant on hydrogen from electrolysis, thermodynamic losses are also accompanied by increases in water requirements per unit of energy contained in the final fuel.

Costs of electrofuels from renewable electricity and DAC have been estimated around EUR 2.3 (USD 2.8) per litre for large scale production (Scheelhaase, Maertens and Grimme, 2019; Albrecht, Maier and Dietrich, 2017). Other estimates suggest that electrofuels were four- to six-times more expensive than petroleum-based jet kerosene in 2019 (IEA, 2020d). These cost estimates are higher than for other SAF pathways (e.g. for advanced aviation biofuels, as can be seen in Figure 7) and require reductions in both operating and capital expenses.

Nevertheless, the rapidly decreasing cost of renewable electricity production can be an opportunity for electrolysis and electrofuels more broadly as electricity generation is the largest cost of electrofuel production.[46] Using more optimistic assumptions on the levelised cost[47] of renewable electricity (USD 0.02/kwh) and overall thermodynamic efficiency of 36% for electrofuel production leads to operation cost estimates (including energy) as low as USD 0.6/L of synthetic kerosene. This magnitude is consistent with estimates indicating that electrofuel costs could decrease to 1.5 to 2 times the values of petroleum-based jet kerosene in the long term (IEA, 2020d).

Figure 7. Production cost ranges for fossil jet fuel and aviation biofuels



Source: Adapted from IEA (2018b); Scheelhaase, Maertens and Grimme (2019); Albrecht, Maier and Dietrichet (2017); IEA (2019c).

Carbon dioxide removal

Carbon dioxide (CO_2) removal (CDR) processes remove carbon dioxide from the atmosphere and sequester it. CDR can be enabled by natural processes, notably by planting trees or reducing deforestation, but ensuring the permanence of emission reductions over time is challenging (see Box 9). It is also possible by the capture, sequestration and geological storage of CO_2 from the atmosphere, with CO_2 removal from the air by direct air capture (DAC), a process requiring the reaction of CO_2 with other chemicals.

Geological storage can occur via mineralisation or injection of carbon dioxide into underground reservoirs. The former option, which transforms CO_2 into what is essentially a rock, is challenged by energy use, slow reaction rates and material handling but it is a highly verifiable storage method. Injection in underground reservoirs is already used at scale in the oil and gas industry for "enhanced oil recovery", whereby the CO_2 injection enables increased oil extraction in production wells by increasing overall pressure. Geological injection is also suitable to capture CO_2 from point sources (e.g. industrial facilities) and is also one of the enablers of biomass-based negative emission technologies (discussed in Box 9).

Box 9. Biomass Carbon Removal and Storage

Biomass Carbon Removal and Storage (BiCRS) groups a number of processes that use biomass to remove CO_2 from the atmosphere and store it underground or in long-life products.[48] The effectiveness of these processes to reduce GHG emissions in this respect depends, as in all other biomass-based approaches, on steps taking place across the whole life cycle of biomass production, harvesting, de-watering, transportation and conversion. BiCRS include bioenergy carbon capture and storage (BECCS), whereby biomass is first combusted to generate power and heat and the resulting CO_2 is captured. BiCRS also includes biomass conversion (through biochemical and/or thermochemical pathways) to produce liquid fuels and other products since these conversions also lead to CO_2 emissions that can also be subject to carbon capture. BiCRS also encompasses processes that remove carbon from the atmosphere without the production of energy. The inclusion of these processes is based on the value of using biomass for removing carbon from the atmosphere exceeding the value of using biomass for energy (Sandalow et al., 2021).

Direct bioliquid injection and disposal (DBID) is a specific BiCRS pathway using processes (in particular fast pyrolysis) that converts biomass into substances (bioliquids or bio-oils), potentially making it well-suited for disposal and storage in deep geological formations and avoids the downstream capital and operating costs associated with further conversion. As it does not include the use of biomass to produce energy, its economic viability is entirely reliant on the existence of a carbon price (Sandalow et al., 2021) or the availability of other financing channels. For example, profits from the extraction of fossil hydrocarbons, most relevant in cases where BiCRS would compensate emissions of fossil CO_2).

Once and if fossil energy requirements across their supply chains are minimised, BiCRS can be a source of carbon offsets.

BECCS technologies have been considered low-hanging fruit in the context of carbon capture and storage technologies. Through them, biogenic CO_2 can already be separated in concentrated or highly concentrated streams (Olsson et al., 2020). BECCS comes with the advantage of energy (and revenue) generation, but it cannot lead to negative emissions.

The combined cost of using BiCRS and conventional oil-based fuels (which contain hydrogen) may also be lower than the production of fuels using the same biogenic carbon streams of BiCRS. This could be the case, for example, if the *sum of the costs* of sequestering biogenic carbon in products from pyrolysis, extracting fossil fuels and refining is *lower* than the cost of producing renewable hydrogen *and* converting biogenic carbon from pyrolysis products into fuels combined.

Sufficient availability of sustainably produced biomass is the limiting factor for all BiCRS processes and other biomass-based solutions. Large-scale deployment could affect food security (linked to direct and indirect land-use change), clean energy development, biodiversity, water resources and other services of value to society (Sandalow et al., 2021). Other limiting factors may be associated with the effectiveness of long-term geological carbon storage and/or the effect of storing it in durable products.

This confirms the importance of developing and effectively enforcing sustainability criteria for biomass production, including careful monitoring of land use/land cover. It applies to all decarbonisation options relying on biomass as a primary resource.

In the case of geological injection for enhanced oil recovery, if the carbon content of CO_2 injection exceeds the amount recovered in oil extraction, this technically leads to net CO_2 sequestration (McGlade, 2019). For geological storage, it is estimated that 78% to 98% of injected CO_2 can remain underground for centuries (Wang et al., 2020).

Ensuring the integrity of CO_2 storage is a critical requirement in any application requiring carbon storage. This does not only require advances in leak detection technology (Bui et al., 2018) but also raises questions related to financial and long-term liability, similar to nuclear waste, given the need for very long-term monitoring and the ability to ensure remediation interventions if necessary.

The recent pledge of United Airlines to reach net-zero greenhouse gas (GHG) emissions by 2050, including a commitment to significant investment in DAC (United Airlines, 2020), is notable and likely aimed at potential longer-term benefits. Indeed, DAC is currently unlikely to lead to economic advantage in comparison with alternative and more concentrated CO_2 sources.[49] This also aims to improve the understanding of DAC's potential to become cheaper, if and once it has been scaled-up, than other forms of abatement in aviation, possibly also helping to reduce costs of aviation fuels that require DAC to provide renewable carbon inputs.[50] The idea of DAC being possibly cheaper than other options also aligns with the results outlined in scenarios that account for the availability of DAC at costs in the range of USD 125 to USD 325 per t CO_2 (Friedmann et al., 2020), and therefore substantially lower than what has been assessed in peer-reviewed research to date.[51]

The announcement also clarifies that the captured CO_2 will be permanently, safely and securely stored with a process certified by independent third parties. Although this is commendable, it is unclear whether the investment, developed in partnership with Occidental Petroleum, is intended for EOR and therefore, capable of leading to a net-climate benefit (Wang and Malaki, 2020).

More broadly, although DAC appears as a relevant solution for air transport, it is still currently far from being easily applicable at a large scale for CDR. Important reasons include:

- The highly diluted nature of atmospheric CO_2, likely to be directly paired with high costs, is estimated to be most likely in the range of USD 600 – 1 000 per t CO_2 (adding USD 1.6 to USD 2.6 per litre of jet kerosene) and possibly as low as USD 300 per t CO_2 (i.e. adding USD 0.8 per litre of jet kerosene) (Bui et al., 2018).[52]
- The requirement of substantial amounts of electricity and heat from low-carbon sources for chemical CO_2 absorption or adsorption and injection (Bui et al., 2018). This places upward pressure on the already challenging need to ensure that energy is supplied from low-carbon sources, at scale and in a reliable manner.

- Ensuring that both electricity and heat are available at low costs, and the need for systems capable of operating at high-capacity factors, thus restricting the scope for suitable locations of DAC plants (Bui et al., 2018).
- The time needed to achieve meaningful CO_2 removal, considering the limitations of optimal DAC siting (DAC plants would need to be near the source of energy they use), limiting the number of DAC plants to be built per year (Bui et al., 2018).
- Remaining questions on long-term financial viability and aspects related to liability. The CO_2 storage needs to be secured over a very long period of time (Bui et al., 2018).
- DAC to fuels (and therefore carbon capture and use, rather than storage, resulting in avoidance, not removal) is the only viable business model in the absence of a carbon price or a carbon value for offsets (e.g. from financing based on profits of the extraction of fossil hydrocarbons, whose emissions could be compensated by DAC) (Bui and Mac Dowell, 2018).

An additional important consideration of DAC to fuels relates to DAC being able to deliver net benefits in terms of GHG emissions. First, DAC needs to rely on low-carbon energy inputs and integrate heat pumps to deliver net removals (Deutz and Bardow, 2021). In addition, emission reductions from DAC powered by renewable electricity also need to be considered against GHG and pollutant emission benefits derived from the direct use of renewable electricity in the rest of the energy system. For example, using solar and wind electricity to displace coal without capturing carbon substantially reduces CO_2, air pollution, and total social cost (Jacobson, 2019).

For CDR solutions, such as DAC, to become more widely available and actively pursued as a decarbonisation strategy, clear and transparent conditions under which CDR is acceptable at scale will also be crucial (Wang et al., 2020). In the case of aviation and the solutions discussed here, this would be especially important to mitigate investment risks in technologies with higher costs.

Technological decarbonisation measures: Where do we stand?

In the near term, biomass-based fuels from oleochemical pathways are likely to be the most attractive options available for the reduction of the carbon intensity of aviation fuels. They are currently the most cost-effective and technologically ready. Their effectiveness to deliver net reductions in CO_2 emissions and meet other sustainability requirements (in particular on land use) requires a laser focus on waste oils as a feedstock, and this limits their availability at scale.

The use of low-carbon hydrogen in refining processes to reduce the carbon intensity of fuels can complement sustainable oleochemical pathways for the production of SAF, and this can be followed by the integration of biogenic carbon feedstock in chemical processes. Fuels derived from biogenic carbon and renewable hydrogen are further away from being technologically ready, but they could contribute to the SAF mix if there is sufficient technological progress. Thermochemical processes like BtL are also well suited for integration with low-carbon hydrogen to enhance fuel yields from biogenic carbon. Low-carbon hydrogen could potentially contribute to the decarbonisation of the fuel pool in aviation, though significant engineering challenges in the short- to medium-term prevent aircraft capable of storing and using it from being available soon.

The combination of negative emissions from BiCRS and fossil-fuel extraction could also emerge as a solution that can reduce GHG emissions in aviation. To be viable at scale, this requires the successful development of carbon capture and storage technologies and may need a carbon price. In the absence of a carbon price, the value for carbon capture would need to be funded from profits made with the extraction of fossil hydrocarbons. Like all other options relying on biogenic carbon, BiCRS is highly dependent on the availability of sustainably produced biomass and the establishment of effective supply chains that manage costs effectively. With carbon capture and storage technologies available at scale, DAC combined with geological storage could hypothetically be a relevant complement to BiCRS to offset the impacts of hard-to-abate sectors like aviation, though it would also be highly dependent on exceptionally high availability of low-carbon energy available at very low cost. This is a major challenge in terms of feasibility, especially once investment risks are taken into consideration. In addition, the timeframe for DAC to play an essential role is hampered by its low technology readiness.

Electrofuels relying on DAC face even greater barriers to make a meaningful contribution to decarbonisation. Their requirements for abundant and cheap sources of very low-carbon energy are even higher than in using DAC combined with geological storage to offset the continued use of jet fuel. For this reason, electrofuels using carbon sourced with DAC and hydrogen from renewable electricity require the successful roll-out, at extremely large-scale and at low-costs of production, of very low-carbon electricity generation. This would need to come from highly available renewable energy resources in specific global areas, such as solar and wind, and also integrate the extraction of ambient heat from heat pumps in DAC processes. Using fossil energy with CCS would further exacerbate thermodynamic losses and require very high rates of CO_2 storage. Differences of scale would make the achievement of this an even greater challenge in terms of feasibility than for DAC and may artificially inflate CO_2 storage requirements in cases where carbon is subject to a pricing mechanism.

Improving operational efficiency of aviation

Improving the efficiency of airspace management and airport operations can reduce CO_2 emissions per flight. 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, ANSPs, airlines and other aviation stakeholders are already taking co-ordinated action to make air transport operations as efficient as possible as well as mitigate indirect emissions linked to airport operations and surface access. Similar optimisation efforts, primarily due to economic drivers, are undertaken by airlines to maximise the share of available seats on board each aircraft.

However, as reduced operating costs can stimulate increased demand, also driving up the air transport demand, energy-efficiency savings from improvements in operational efficiency tend to be lower than what would be attainable without cost variations. This is known as the rebound effect (Box 10).

Load factors rose from 75% in 2005 to 82% in 2019 (ICAO, 2019a and Statista, 2020), which resulted in non-negligible reductions in the direct CO_2 emissions per unit of air transport activity shown in Figure 1. 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 activity imputable to air traffic management (ATM) improvements may be similar. The IPCC (1999) 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. On the ground, emissions under airport control account for around 5% of total aviation CO_2 (ACI, 2017).

The following sections provide an overview of different measures that can be implemented in the air and on the ground to optimise operational efficiency. A more detailed review of individual measures to reduce operational fuel burn can be found in ICAO's report on operational opportunities to reduce fuel burn and emissions (ICAO, 2014).

Box 10. The rebound effect in air transport

The rebound effect occurs when energy efficiency improvements do not translate directly into energy savings since the lower operating costs enabled by efficiency also stimulate increased demand. The rebound effect was first theorised by Jevons (1865) and quantified by Khazzoom (1980) for household appliances. Subsequent studies focused on residential fuel consumption and automobile transport, but not many studies have focussed on the rebound effect in air transport.

In one such study, Evans and Schäfer (2013) found an average rebound effect of 19% for US domestic flights in an air traffic network, including 22 of the country's busiest airports serving 14 of the highest origin-destination city pairs. This means that 19% of the full potential of aircraft efficiency improvements goes unexploited: for every 1% reduction in aircraft energy use, the resulting decrease in system energy use is 0.81%. Lower operating costs achieved through the use of more efficient aircraft in the highly competitive domestic network of the United States meant airlines offered lower fares, which increases demand. The main outcomes are increased flight frequencies and network delays, which offset a portion of the emissions mitigation achieved with more efficient aircraft. Evans and Schäfer also estimated that all else being equal, a fuel tax equivalent of 72% of the fuel price would be necessary to avoid the 19% rebound effect, as fuel accounted for around 32% of total operating costs.

The rebound effect is expected to be significantly higher in lower-income countries due to higher airfare elasticities: greater demand response to the same variation in price per passenger (Evans and Schäfer, 2013). For the same reason, the global rebound effect in air transport is expected to decline over time as income grows, especially in mature air transport markets.

The rebound effect highlights that a share of CO_2 savings from load factor increases and that aircraft fuel efficiency improvements can be offset by increased demand for air transport in the absence of economic incentives. Efficiency improvements in operations can also lead to a rebound effect. Sector-wide programmes aiming to increase operational efficiency, such as the EU's Single European Sky, have simultaneous objectives of accommodating more capacity and reducing emissions. Programmes that improve operations efficiency, in particular, reduce CO_2 emissions per flight and reduce delays but may also increase capacity at otherwise congested airports. In the absence of ATM caps, this can lead to further growth in total air transport emissions as more flights can be accommodated at congested airport sites.

Management of airspace

Inefficiencies in airspace management affect aircraft operations during departure, climb, cruise, descent, and approach phases, excluding taxiing, take-off, and landing. Some causes of inefficiency, such as weather events, avoidance of military airspace and minimum distance between aircraft, are unavoidable. Controllable inefficiencies essentially arise from sub-optimal air traffic control (ATC) systems and fragmented airspace governance, causing airlines to fly inefficient routes and burn excess fuel. Eliminating these causes of inefficiency could reduce fuel consumption by 8% to 12% per flight (World Bank, 2012; IATA, n.d.).

Both technological and governance changes are crucial to achieving a harmonised, interoperable ATM system and improving the efficiency of aircraft operations in airspace. They require strong collaboration between all aviation stakeholders, including governments, civil aviation authorities, airlines, ANSPs and airports.

On the technological side, automated ATC would be more efficient and precise than the current system, which has not changed much since the 1950s, but significant barriers to its implementation exist. ATC is very labour-intensive and unionised, and unions could deter governments from carrying out modernisation projects which would put jobs at risk. The labour-intensiveness of ATC makes changes relatively difficult and costly to implement. Buying and implementing new technology and equipment is expensive and time-consuming. Globally, ATC is far from being automated on a large scale, despite national and international airspace modernisation programmes. In the future, drones and remote towers may create disruptions to ATC, although their impact on environmental performance is uncertain at this stage.

International co-operation and governance are crucial to enable harmonised and interoperable ATM systems. Fragmented national airspaces with different rules and charges lead to inefficient flight routing by airlines and ANSPs, and there are significant political and organisational barriers to implementing changes across such a wide, complex and interconnected system (Spinardi, 2015). Many governments may have the perception of giving up sovereignty. Path dependency also explains that technologies tend to get "locked-in" once they are adopted: the more technologies are widely used, the more experience is gained with them and the more they can be improved, increasing returns and network externalities (Arthur, 1989). Geopolitical factors such as conflicts can also significantly affect flight paths due to airspace avoidance by airlines.

Investments in internationally harmonised and interoperable ATM systems are generally cost-effective as they reduce delays, increase capacity, and lead to fuel savings on each flight. In many cases, most of the costs are borne by governments and ANSPs, while a large share of the benefits accrues to airports, airlines and passengers.

Any potential reform that would involve flightpath changes will have to consider its possible noise impacts on local communities living around airports. Many flight paths result in relatively higher CO_2 emissions per flight because they avoid noise-sensitive areas. Airlines may also deliberately fly sub-optimal routes to optimise costs and minimise delays, as different countries apply different airspace charges. Airlines can also contribute to reducing CO_2 emissions by training and incentivising their pilots to fly in a more CO_2-efficient way as well as by other means (Box 11).

Box 11. Airline-related measures to improve efficiency

Airlines can put in place efficiency-improving measures that do not require co-ordination with other aviation stakeholders. Aside from buying and operating more fuel-efficient aircraft and increasing load factors (discussed earlier), airlines can take action to make existing assets more efficient, for example by (Aviation Benefits, n.d.):

- retrofitting winglets on older aircraft, reducing lift-induced drag and improving overall fuel efficiency
- washing aircraft and engines to reduce drag and improve engine efficiency
- implementing single-engine taxiing, which reduces the energy intensity of taxiing
- introducing environmental training for pilots, as pilot flying practices affect fuel consumption (e.g. optimal cruising speed)
- reducing the weight of cabin items (e.g. seats, catering equipment and water) and of the fuel tank by avoiding fuel tankering (see Box 13).

Air traffic management harmonisation programmes

ICAO ASBUs serve as a roadmap for ANSPs developing their own programmes aiming at a global interoperable aviation system (CANSO, n.d.). They are a framework that houses a number of national and international programmes for harmonising electronic systems in aviation, ATM ground infrastructure and automation. Currently, the most advanced of these ATM modernisation programmes are the EU Single European Sky (SES) and the US NextGen.

Initiated in 1999, the SES aims to improve ATM and air navigation service (ANS) performance through European airspace integration in order to increase capacity, reduce delays and improve fuel efficiency (Coito, 2019). It features binding performance targets in areas including safety and the environment and the introduction of functional airspace blocks to reduce European airspace fragmentation. Its technological pillar, the Single European Sky ATM Research (SESAR) Joint Undertaking, is responsible for the deployment of the new European ATM system. In Europe, the contribution of improved ATM to the decarbonisation of air transport is limited to 5% to 10% by 2035 (SESAR Joint Undertaking, 2020).

The SES framework has separated regulatory functions from service provision, allowing greater flexibility in the use of civil and military airspace, created better interoperability of equipment and a common charging scheme for ANS. Upon completion in 2030-35, it could triple airspace capacity, halve ATM costs and "reduce the environmental impact of aviation by 10% compared to 2004" (Coito, 2019, p. 1). Delays decreased, and cost-efficiency increased in Europe between 2008 and 2016, but these improvements can partly be explained by relatively low traffic levels following the economic downturn from 2008.

Similarly driven by commercial considerations, NextGen in the United States modernises communication and navigation infrastructure to improve position and information time and hence increase efficiency, reduce delays and improve safety. Implemented in 2007, NextGen is about halfway through an investment and implementation plan expected to be completed around 2025-30 (FAA, n.d.). Over 1 billion litres of fuel were saved between 2010 and 2017, and an estimated USD 6 billion in economic benefits through 2018 were achieved. The programme's next phase aims to shift from current 3D control to 4D control of US airspace.

Many other air navigation improvement programmes at varying stages of implementation exist, for example, CARATS in Japan, SIRIUS in Brazil, and FIANS in India. Programmes are also in place in Australia, Canada, China and Russia (CANSO, n.d.). Generally, these programmes aim to improve safety, capacity and fuel efficiency, and by extension, reduce CO_2 emissions per flight.

Further improvement of load factors

Profit maximisation and the need to recover cost from expensive capital outlays needed to purchase and maintain aircraft have been important drivers of load factor increases that characterised aviation in the past decade.

Achieving this is a complex task that requires the development and increased use of automated, integrated software platforms aiming to optimise revenue and requiring collaborative effort for all stakeholders involved in the operational networks of each airline. Such systems rely on real-time data to dynamically adjust prices and have direct implications for load factors. Changes in loads that are determined through these systems may take into account the mode and time of purchase. To shift reservations towards flights with lower load factors, revenue management systems use instruments such as nested fare classes. Additional tools may also take the form of targeted campaigns and integrate overbooking and/or origin and destination control strategies (Agili, 2019).

Airlines can also reallocate capacity such as aircraft type, cabin configuration, crew, and other resources for profit maximisation purposes. These choices also have impacts on load factors. Additional profitability elements with impacts on the evolution of load factors include accuracy in the determination of expected demand developments (facilitated by instruments such as reservation analytics) and the capacity of automated systems to factor in expenditures that are dependent on aircraft loads (such as fuel use). These same systems can also integrate aspects such as crew management, aircraft maintenance schedules and information related to ground operations (Agili, 2019).

Achieving major improvements in loads is likely to face inherent limitations. These are due to the already high values attained in the late 2010s (before the Covid-19 crisis) and diminishing margins of improvements beyond them, given that the main optimisation goal is profit maximisation and not full load capacity. Selling all the seats might not result in the highest revenue or profits possible since profits also depend on the price of reservations. Even if stronger asset utilisation is a key to maintaining lower costs, challenges for its achievement include persistent elements of the seasonality of demand and variability across different weekdays. Other aspects, such as the use of open seats for positioning employees throughout the system and unforeseen events (even if not as disruptive as the Covid-19 pandemic) also matter in this respect (Stalnaker et al., 2018; Three points aviation services, 2015).

Management of airports

Direct airport emissions and those under airport control represent only about 5% of all aviation emissions, but airport operators have been making sustained efforts to reduce their CO_2 emissions and those of aircraft operations on the ground. While decarbonising airports is arguably easier than decarbonising aircraft operations, airport operators have an important part to play in driving industry-wide climate action as they act as an interface between different stakeholders, including passengers, airlines, and fuel suppliers.

Airports can take measures to improve efficiency and reduce CO_2 emissions. These include

- collaborating with ANSPs and airlines to improve the efficiency of aircraft operations under airport control
- electrifying ground services
- incentivising the use of cleaner aircraft and fuels by airlines through differentiated charging and infrastructure provision
- incentivising more sustainable surface access for passengers and staff.

These measures and others are further detailed in ACI Europe's Sustainability Strategy (ACI EUROPE, 2019b).

Airport measures for improving operational efficiency

An important source of CO_2 emissions under airport control comes from airport congestion, which can result in delays during take-off and landing and lead to aircraft burning excess fuel. Aircraft stacking, whereby aircraft wait to land in airspace surrounding the airport, is a common problem at congested airports. Stacking leads to excess fuel burn close to the ground, generating excess CO_2 emissions, but also noise and air pollution in neighbouring communities. Government policy generally determines how much capacity airports can build and operate and how capacity is allocated, particularly at congested airports, although airports have some degree of flexibility with respect to accommodating aircraft within the government-imposed constraints.

A crucial measure airports can implement to minimise congestion is Airport Collaborative Decision-Making (A-CDM). By sharing operational data among aviation stakeholders (ANSPs, airlines, etc.) and linking airports with the ATM network, A-CDM aligns flight schedules better with available runway and airspace capacity (ITF, 2017a). This tool has proven to be very cost-effective, with a return on investment reached after 18 months and a cost-benefit ratio of seven over a ten-year period, accounting just for tactical cost savings to airlines and not for the financial benefits to other stakeholders (EUROCONTROL, 2016). However, while most of the costs are borne by airports and ANSPs, the lion's share of the benefits is enjoyed by airlines and passengers. Co-ordinated Arrival Departure Management (CADM), time-based separation (TBS), and the application of simulation modelling for better airside co-ordination can also help aviation stakeholders improve operational efficiency and minimise excess fuel burn (ITF, 2017a).

Airport measures for reducing CO_2 emissions

Aside from improving the efficiency of existing infrastructure and buildings, airport operators can electrify operations on the ground, such as ground-handling services. Airport operators can also electrify ground operations, for example, by providing aircraft with fixed electrical ground power and pre-conditioned air. Sourcing this energy from renewables can significantly reduce airport emissions. This is the case at Schiphol Royal Group airports, which fully rely on Dutch wind power for electric operations.

Airport operators also play an important role in incentivising SAF and the deployment of hybrid-electric and electric aircraft. Some airport operators have started to provide SAF regularly through existing fuel infrastructure (e.g. Avinor and Swedavia), while others have created partnerships, provided expertise and support for SAF production (e.g. Schiphol and Zurich Airport). Airport operators can create commercial incentives for the deployment of electric aircraft: Heathrow Airport Ltd, for example, has announced a one-year waiver on landing charges for the first commercially operated hybrid-electric or electric aircraft.

Inadequate surface access to airports and congestion also contributes to CO_2 emissions on the ground, as well as noise and air pollution for neighbouring communities. Airport operators can implement incentives for passengers and staff to use public or low-emissions transport, for instance, by increasing parking fees. Revenues can be recycled to fund projects that help reduce car use and emissions, as is the case at Heathrow Airport (Heathrow Airport Limited, 2018). Amsterdam Schiphol Airport, where 47% of passengers arrive by public transport, plans to invest in charging facilities for EVs and incentivise the use of bicycles for employees.

In partnership with relevant authorities and stakeholders, airports can also incentivise more sustainable surface access by building or improving existing multimodal infrastructure, such as light-rail links or buses. Airports with existing integrated rail stations can work with relevant stakeholders and authorities to increase the frequency of rail services and make this form of surface access more attractive to passengers.

Policy instruments to decarbonise air transport

Policy instruments are necessary to ensure that fuel-saving solutions and low-carbon fuels can be adopted resiliently in the coming decades. This section of the report elaborates on policies that can be adopted to help decarbonise the air transport sector. It covers:

- Measures that price CO_2 emissions directly, via carbon taxes, or indirectly, by setting CO_2 emission-reduction requirements in combination with emission trading schemes (ETS). Such measures can be cross-sectoral or specific to the air transport sector.
- Low-carbon fuel standards (LCFS) with trading to incentivise the deployment of low-carbon fuels.
- Regulatory measures specific to air transport, including fuel-blending mandates and aircraft fuel efficiency standards.
- Support for fuel-saving and fuel switching technology development.
- Taxes levied on tickets.
- Policy instruments for the decarbonisation of airports.
- Policies that can encourage a shift to other, less carbon intensive, transport modes.

Carbon pricing, carbon taxation, and emissions trading schemes

Carbon taxation or an ETS, also known as a cap-and-trade system, place a prince on CO_2 emissions. Applied to jet fuel burn, both instruments equate to levying a fuel tax. These measures are already employed at the national or regional level in some jurisdictions, but there are obstacles to their application to international flights.

Carbon taxes and other taxes levied on fuel and energy use are widespread outside of the aviation sector. Fuel excise duty (fuel tax) is levied per unit of fuel purchased, while carbon taxes are levied on the CO_2 emissions produced by the combustion of the fuel. Excise taxes are designed primarily to raise revenue to fund general or specific expenditure, so one form of taxation does not exclude the other, and many countries apply both. A fuel tax can also be intended to address other negative externalities (e.g. air pollution) and concerns (e.g. energy security). The economic steering effect of taxation depends on the tax rates and the extent of their application. Thus, an excise tax introduced initially to raise revenues does not need to be increased to stimulate decarbonisation if it is already above the estimated shadow price of CO_2 emissions (see Box 12). Public finance, as well as other externalities and concerns, may nevertheless warrant higher rates than would be justified from a climate perspective alone.

Box 12. Putting a price on carbon

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 exist (Wang et al., 2019) and this approach is of limited assistance to policy makers in defining actual carbon prices. 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, 2016; Kaufman et al., 2020).

The low-end estimate of the climate damage costs of carbon is EUR 30 (USD 35) per tCO_2-eq. In most countries, effective carbon rates from all forms of fuel taxation and trading systems[53] are lower than that (OECD, 2018a). Wherever the EUR 30 (USD 35) threshold is reached, it is mostly applied to emissions from road transport.

The "carbon pricing gap", measuring the difference between this EUR 30 (USD 35) benchmark and effective carbon prices, was estimated in 2018 (for 2015) at 76.5% in all 42 OECD and G20 countries. The gap further widens when considering the estimated carbon prices required to achieve Paris Agreement targets: USD 40-80 by 2020 and USD 50-100 by 2030 per tonne of CO_2, as estimated by the High-Level Commission on Carbon Prices (CPLC, 2017).

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. Regulators allocated a share of permits freely to limit carbon leakage in industries with strong international competition and, as in the case of the "Fit for 55" policy package recently proposed in Europe, have also proposed alternative approaches – namely a carbon border adjustment mechanism – to progressively phase out free allocations (European Commission, 2021a). This seeks to address the risk of carbon leakage by ensuring that imported products are subject to equivalent carbon pricing as domestic products, but it does not give credit for non-tax measures (such as technical regulatory requirements on safety and environmental impacts).[54]

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 an administrative market for carbon credits.

Carbon taxation and emissions trading use different mechanisms to price carbon emissions, but both are cost-effective decarbonisation instruments.[55] Carbon pricing incentivises emitters to introduce the abatement measures that can be implemented at a cost below the carbon price. On the supply side in the aviation sector, 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 ticket costs, and it limits the rebound effect of efficiency improvements. Increasing the price of jet fuel provides an incentive to improve aircraft efficiency, operational efficiency and fuel efficiency.

Both instruments are ultimately driven by political decisions. Whether on the tax rate or the emissions target, these decisions also have a significant role in the determination of the CO_2 price that policy choices imply. However, an ETS means that more parameters are subject to political arbitration, making decisions less transparent. Early experience with the EU ETS saw prices fall to levels too low to spur investment as a result. Under an ETS, volatile prices can increase capital costs and provide insufficient certainty to invest in abatement. Designing carbon-pricing programmes adequately and implementing mechanisms supporting price stability are crucial for long-term effectiveness.

Sufficiently high and stable carbon prices are even more important for sectors with relatively costly abatement options, such as aviation. At insufficiently high carbon price levels and in the presence of cheaper abatement options in other sectors, airlines will likely simply pay the carbon price and pass the cost on to passengers. Higher prices would be especially important to support sufficient investments in alternative lower-carbon fuels, given their relatively high marginal abatement costs (especially in the early phase of their deployment and adoption).

The design of a carbon pricing instrument 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 taxation should be avoided).

In cases where carbon pricing also applies to CO_2 removal technologies, it needs to pay attention to differences in scale associated with different energy end-use technologies. This is because technologies that have greater fossil energy requirements per unit of service delivered than competing alternatives are inherently associated with much higher carbon capture and storage requirements. For example, fossil-fuel extraction and combustion require far greater amounts of carbon capture compared to direct electrification and use of renewables. Such considerations would help to avoid perverse effects, such as the generation of windfall profits for companies involved in both fossil-fuel extraction and geological storage of CO_2 (by scaling-up volumes of CO_2 that need to be sequestered), at the detriment of options that are likely to have a far better profile in terms of resource efficiency and could prove more effective to reduce costs once scaled-up. The extent to which this matters for aviation depends on how direct electrification technologies can be part of the decarbonisation pathway for the sector.

Both carbon taxes and ETS have specific advantages and shortcomings which should be considered by regulators. Either's effectiveness will ultimately depend on the policy design and safeguards implemented to mitigate risks. Carbon taxation is cheaper and more straightforward to administer than an ETS, particularly if the carbon tax is integrated within the existing excise regimes (OECD, 2018a). As an instrument, it is less prone to distortion and political arbitration than an ETS. Carbon taxation rates also tend to be more stable than carbon prices under an ETS, providing more certainty for investment in abatement technologies. ETS can better adapt to the economic context without regulatory intervention, as permit prices vary with economic growth rates. Both carbon taxation and ETS can be applied domestically, internationally or in specific global regions agreeing to use them. A single international approach is better suited to avoid economic distortions, but it would also require a feasible international agreement.

Theoretically, an ETS can achieve emissions targets with more certainty than a carbon tax. This is important because scientific estimates demonstrate that there is greater certainty as to the carbon budget that the atmosphere can accommodate to limit temperature than on the marginal damage cost estimate, which is used to set carbon taxes. In practice, though, political factors often play a significant role in setting targets, with the risk of generating carbon prices that are too low and volatile. Emission reduction targets that are too low can lead to an oversupply of credits. Prices may fall beyond what can spur investment in emissions abatement. This risk can be mitigated by enhancing the certainty of carbon prices through measures based on quantity (e.g. allowance reserves and cancellation mechanisms), price (e.g. an allowance price ceiling and/or floor), regulatory parameters (e.g. intensity-based allocation), and time flexibility (e.g. banking and borrowing allowances) (IEA, 2020c). Carbon taxes can also be implemented in parallel to an ETS and act as a floor price, as is the case in the United Kingdom.

Table 4. Risks and safeguards for the implementation of carbon pricing

Measure	Risks	Safeguards
Carbon pricing	• Failure to account for life-cycle emissions can favour unsustainable alternative fuels • Low prices fail to stimulate sufficient investment in aviation abatement measures with relatively higher cost • Can lead to windfall profits for companies involved in both fossil fuel extraction and geological storage of CO_2 if applicable to carbon removals and if applied in sectors where cost effective decarbonisation is possible through energy and resource efficient alternatives.	• Implement a low-carbon fuel standard in parallel or ban the sale of fuels with higher life cycle emissions than conventional fuel • Increase carbon prices; implement a low carbon fuel standard with higher credit prices in parallel • Ensure that carbon pricing incorporates mechanisms that account for differences in energy and resource efficiency of different low-carbon technology end-use choices
Carbon tax	• Tax rates can fail to reflect damage cost estimates	• Employ a methodology based on abatement costs
Emissions trading scheme (ETS)	• Low and/or volatile prices	• Set sufficiently high emission-reduction targets to limit oversupply of credits; integrate quantity or price-based measures (e.g. allowance reserves, cancellation mechanisms and allowance price ceiling and/or floor), regulatory parameters (e.g. intensity-based allocation, change of a cap trajectory), and time flexibility (e.g. banking and borrowing allowances).

There are no legal obstacles to pricing carbon emissions from jet fuel used on domestic flights. In the EU, international (intra-EU) aviation is included in the ETS and therefore subject to carbon pricing. Outside of the EU ETS, pricing carbon emissions from jet fuel used on international flights face the same legal obstacles as any international aviation fuel tax. Most bilateral ASAs between countries contain a specific non-taxation provision, meaning the implementation of international fuel taxes on aviation would require amendments to such agreements. Currently, carbon pricing for international aviation at the global scale can only occur through the relatively weak signals provided by ICAO’s CORSIA. Changing this will require further progress in international negotiations.

Carbon taxes on jet fuel for international flights would be possible in single markets created by regional tax treaties in the same way that intra-EEA flights are included in the EU ETS. Creating sufficiently large single markets, such as the EU’s, could limit carbon leakage (Box 5) and fuel tankering (Box 13) risks.

Box 13. Fuel tankering

Airlines may choose to carry excess fuel on flights to benefit from fuel price differences. This is in addition to the amount of contingency fuel required to deal with potential diversions or delays resulting from congestion at airports or other disruptions. This increases the aircraft's total weight, resulting in excess fuel burn and CO_2 emissions. This practice, known as fuel tankering, is mainly employed on medium-haul flights to reduce overall fuel costs.

In the European Civil Aviation Conference (ECAC) airspace, carrying fuel to avoid or reduce refuelling at destination airports with more expensive fuel leads to an estimated net saving of EUR 265 million (USD 312 million) per annum for airlines, despite the extra cost of carrying excess weight (EUROCONTROL, 2019). On average, fuel tankering leads to 136 kg of excess fuel burn and 428 kg of additional CO_2 per flight concerned (around 20% of ECAC flights), with a net saving of EUR 126 (USD 148) per flight concerned due to fuel price differences. Fuel tankering in ECAC airspace results in 286 000 tonnes of excess fuel consumption and 0.9 million tonnes of additional CO_2 annually.

In the domestic market of the United States, around 1% of fuel consumed on an average flight comes from carrying contingency fuel in excess of a reasonable buffer, which is determined by the Federal Aviation Administration (FAA) and Air navigation service provider (ANSPs) (Ryerson et al., 2015). Based on data obtained from a major US airline and applied to all carriers operating US domestic flights, it is estimated that eliminating excess contingency fuel would save 1.1 million tCO_2 annually.

A number of measures to limit fuel tankering have been suggested, including airlines fully hedging fuel at a single price at airports of operation (EUROCONTROL, 2019). Policy makers could also increase the cost of CO_2 allowances for aviation in the EU ETS to "dissuasive" levels or equalise fuel tax rates. In the United States, it has been estimated that changes in flight dispatching could reduce tankering and save 169 000 tonnes of CO_2 (Ryerson et al., 2015).

Low-carbon fuel standards with emissions trading: A hybrid measure

A low carbon fuel standard (LCFS) sets an emission intensity target for fuel that can incorporate trading. This hybrid economic and regulatory measure[56] could be employed as a complement to carbon taxation or economy-wide emissions trading.

An LCFS sets a standard for the life-cycle[57] carbon intensity of fuel that is set to tighten over time. A set of rules for trading carbon credits to facilitate compliance is established and regulated entities to trade with one another to meet the target. Fuels with a carbon intensity below the standard generate credits, while those above generate deficits. The trading of credits establishes a prevailing market price affected by a variety of factors, including the supply of credits relative to expected emissions, the cost of abatement, underlying economic conditions, perceptions of political or market risk, and in some cases, the effect of speculative investors. Regulated entities are generally fuel suppliers or other entities that produce, import, distribute or sell transportation fuels.

Abatement effort in fuel production is more efficient in an LCFS than a non-tradable standard because it allows marginal cost equalisation across technologies and firms (Yeh et al., 2020). A regulatory focus on the carbon intensity of fuels, rather than on shares or quotas of alternative fuels, allows the market to determine the best technology to meet policy requirements. Establishing and regulating a credit-trading market entails additional transaction costs, but the prevalence of private-party credit transactions mitigates this and displaces much of the cost from the government to private entities.

An LCFS provides decentralised incentives for investments in low-carbon fuel production technologies by rewarding fuels that outperform the standard and penalising those below the standard. Because the lowest-carbon fuels generate the most credits, an LCFS supports the development of fuel production technologies delivering significant emissions savings. Since the target declines over time, fuels must either reduce their carbon intensity at the same rate as the target or see the incentive decline. This creates an incentive for continuous innovation and ensures that fuels offering only small emissions benefits have a finite and predictable amount of time before they no longer receive an incentive.

An LCFS tends to provide stronger support for alternative fuel deployment than carbon pricing. This is because revenue directly provided to alternative fuel producers are at typically higher credit prices than carbon prices under a tax or ETS. LCFS systems also tend to retain revenue within the transportation system since credit transactions occur between fuel distributors. However, as an LCFS sets an emissions intensity target and not an emissions cap, it does not provide an incentive to reduce output to the same extent as a carbon emission cap (Yeh et al., 2020). An LCFS complements the price signal sent by an ETS or a carbon tax by incentivising investment in lower-carbon fuel options. Both tools can be employed as complements with additive benefits.

A well-designed LCFS can be a sharp and targeted decarbonisation instrument if environmental and administrative safeguards are in place. Adequate sustainability criteria are key to ensure that fuels are sustainable and have lower life cycle emissions than conventional fuel options. The biodiversity loss associated with many biofuel feedstocks, including through indirect land-use change, means that many will not qualify under adequately strict sustainability criteria. Feasibility studies are also required to ensure that carbon intensity targets are realistic and achievable. Similar to an ETS, mechanisms aiming to reduce the probability of credit shortfalls and price spikes, and increase market certainty regarding maximum compliance costs, can also be used under an LCFS. In this case, crucial solutions include the possibility of banking credits and using credit price caps (CARB, 2020).

Aviation fuel can be brought into LCFS programmes that cover road fuels or kept separate with their own targets and credit market, narrowing the cost gap between fossil and low-carbon aviation fuels and supporting investments in low-carbon fuel supply (Argus, 2018; CAAFI, 2019). Adding aviation to larger LCFS programmes maximises liquidity in credit markets and the number of compliance options but may result in little investment in SAF if alternatives are more economically attractive. Fewer alternative fuels are available to aircraft than surface transport vehicles. Therefore aviation may not be able to maintain the same pace of decarbonisation as the transport sector as a whole. This can lead to higher charges on aviation fuel and revenue flowing to non-aviation alternatives. Separating aviation fuel into its own LCFS allows a better match between target reductions for aviation and the available alternative fuels. This comes with the advantage of focusing action on low carbon fuels on a transport mode that faces greater challenges in achieving the same decarbonisation results from other solutions (e.g. direct electrification), but it also comes with the cost of smaller, less liquid markets.

Carbon leakage (Box 5) and fuel shuffling can potentially reduce the effectiveness of an LCFS. This is the case if regulated entities choose to sell cleaner products in the regulated area and more carbon-intensive products elsewhere. Policy solutions include international co-ordination and co-operation, carbon border adjustments, protections for trade-exposed industries, special treatment of imported products and expanding regional coverage (Yeh et al., 2020).

Regulatory measures on fuels and energy efficiency of aircraft

Regulatory measures specific to air transport can complement cross-sectoral economic policies to help the air transport sector meet its CO_2 emission reduction targets and stimulate the development, deployment and scale-up of innovations. Lower uncertainty from market dynamics means that regulations can also be crucial to stimulating technological progress beyond what pricing signals alone can achieve. While regulatory requirements cover both safety and environmental aspects, the analysis developed in this section focuses specifically on regulations that have direct relevance for fuel use and CO_2 emissions.

Fuel-blending mandates

Similar to an LCFS, a fuel-blending mandate aims to reduce the carbon intensity of fuel by promoting investment in lower-carbon fuel production. It prescribes the blending of specific quotas of alternative fuel with conventional fuel, either as a blending share or in absolute quantity, over given periods of time. Depending on policy design details, the responsibility for blending with SAF can lie with different regulated entities. In current applications (Norway) and proposals (e.g. in the context of the ReFuel EU Regulation of the European Commission, part of the “Fit for 55” package), regulated entities considered with priority are fuel suppliers and airlines.

Blending mandates can incentivise investment in the most sustainable fuel production technologies. They can differentiate between types of SAF, for instance, taking into account their capacity to deliver net CO_2 emission savings on a life-cycle basis and set GHG emission abatement requirements rather than blending shares. This is indeed the case for the proposed ReFuel EU Regulation. Setting highly accountable penalties for non-compliance can make blending mandates more akin to an LCFS. Especially if penalties are higher for advanced and low-carbon SAF, creating a stronger incentive to invest in fuels that have high CO_2 emission saving capacity, even when they are still at low technology readiness levels. The proposed ReFuel EU Regulation, for example, includes non-compliance fines that are at least double the price difference between synthetic and conventional aviation fuels. The strength of the incentive to invest in advanced fuels depends on the certainty around non-compliance penalties and their value. A sufficiently high carbon tax on jet fuel could also act as a floor price for a fuel-blending mandate, creating more certainty for investment in lower-carbon fuel production. Government action plans supporting the increased availability of sustainable feedstocks for SAF are also important to help increase investor confidence and ensure sufficient SAF supply.

Fuel-blending mandates can provide a simpler alternative to an LCFS. They are easier and less costly to design, implement and administer, as they do not require a market for trading. The absence of a credit market limits transaction costs, but it may be less effective for the equalisation of abatement costs between technologies and regulated entities. Setting serious penalties for non-compliance can make the mandate akin to an LCFS, as these penalties act as a high carbon price in non-compliance cases. The combination of blending mandates with carbon taxes can also help reduce investment risks by establishing a floor price. However, like other regulatory instruments, a fuel-blending mandate remains subject to the risk of changes in regulatory requirements, e.g. due to calls to weaken the standard and avoid penalties.

Both blending mandates and LCFS reduce the carbon intensity of fuel and bring important co-benefits, such as improving energy security by diversifying fuel supply (Sims et al., 2014), as long as production capacities match regulated requirements and affordability for end-users is ensured. Technological spillovers from the fuel and energy sectors can also benefit other economic sectors such as battery production. Airlines and other transport businesses also benefit from reduced exposure to oil price volatility through the use of alternative fuels. However, higher fuel prices resulting from blending mandates and LCFS can also lead to fuel tankering and carbon leakage.

As with an LCFS, feasibility studies and strict environmental sustainability safeguards relating to life cycle GHG emissions and land-use change, as well as water, soil, and air, among other criteria, are required to ensure the environmental integrity of alternative fuels. A robust set of sustainability criteria is crucial to ensure that investments will be mobilised for SAF pathways that make the most sense to meet multiple sustainability goals. These criteria, considered crucial by a broad range of stakeholders, spanning from airlines to non-governmental, are orienting SAF towards those made from agriculture waste and forest residues, along with electrofuels (Taylor, 2021), and may require the phase-out of certain types of biofuels such as those based on palm oil.

Table 5. Risks and safeguards for the implementation of low carbon fuel standards and fuel-blending mandates

Measure	Risks	Safeguards
Low carbon fuel standard (LCFS)	• Low and/or volatile prices • Insufficient effect on output • Unrealistic or insufficiently ambitious carbon intensity targets • Promotion of unsustainable fuels • Carbon leakage and fuel tankering	• Allow regulated entities to bank credits and implement credit price caps • Implement alongside a broad-based carbon tax or emissions trading system • Carry out feasibility studies prior to implementation • Design and implement adequate sustainability criteria • Expand regional coverage of the policy
Fuel-blending mandate	• Penalty price uncertainty • Unrealistic or insufficiently ambitious blending targets • Promotion of unsustainable fuels • Carbon leakage and fuel tankering	• Allow certificate carry-over between periods; implement a floor price or use a broad-based carbon price to act as one • Carry out feasibility studies prior to implementation • Design strong sustainability criteria based on the life-cycle impact and differentiate between different types of fuels • Expand regional coverage of the policy

Aircraft fuel efficiency standards

Aircraft fuel efficiency standards mandate fuel efficiency thresholds below which aircraft cannot operate or be sold from a given year. Currently, ICAO member states must adopt standards at least as stringent as those defined by the ICAO Council to sell aircraft internationally (Box 14).

Box 14. International Civil Aviation Organization aircraft standards

In 2017, the International Civil Aviation Organization (ICAO) Council adopted a CO_2 design certification standard for aircraft as part of its basket of measures to mitigate CO_2 emissions growth from international aviation (ICAO, 2017). This followed a 2012 agreement on a CO_2 metric to measure aircraft fuel-burn performance and approximate CO_2 emissions produced by aircraft (ICAO, 2012). The standard applies to new aircraft designs from 2020 and to aircraft designs already in production as of 2023.

ICAO’s design certification standard contains anti-backsliding provisions requiring that new types certified after 2020 are at least as efficient as most of those certified between 2011 and 2019. On average, it will require a 4% reduction in cruise fuel consumption in 2028 compared to 2015, but actual reductions will range from 0% to 11% in function of the maximum take-off mass of the aircraft (ICCT, 2017). The standard provides a framework that where additional improvements can be implemented in the future.

The almost-worldwide application of ICAO standards helps to harmonise the global aircraft market, avoiding a patchwork of different national standards and avoids interference with international competition between aircraft manufacturers. However, ICAO standards are technology-following rather than technology-forcing (ICCT, 2020a). This is due to imperative proofing in relation to the operational safety of new technologies, which takes time. The main goal of the regulation is to ensure new aircraft incorporate the best technology available rather than pushing the limits of decarbonisation potential. In practice, new aircraft delivered in 2016 already met the efficiency requirements of ICAO’s fuel efficiency standard for new aircraft in 2020 (ICCT, 2020b). Advanced new aircraft types today surpass the standard by 10% to 20%.

Increased fuel efficiency of aircraft fleets is important for the long-term resilience and competitiveness of the aviation industry, especially in the presence of increases in fuel costs. To take action on this while fostering decarbonisation in aviation, national governments[58] can consider the enforcement of stricter standards and negotiate more ambitious standards within ICAO. Fleet-wide national fuel efficiency standards could be effective to accelerate efficiency improvements without compromising safety by encouraging fleet renewals and retrofits to increase energy efficiency for aircraft in the current fleet. Technology-forcing aircraft standards are not favoured by regulators and the industry due to such safety concerns. Significant differences in fuel efficiency and carbon intensity across carriers and flights (ICCT, 2020a) support the argument for fleet-wide standards, even if the sector is already striving to maximise fuel efficiency, given that fuel accounts for 25-30% of an aircraft operator cost.[59] Fleet-wide fuel efficiency standards could take the form of one of:

- a pass/fail phase-out for individual in-service aircraft, essentially targeting the worse performing ones
- a tiered standards for airline fleets, which would require airlines to have an increasing share of their aircraft meet higher standards over time
- a declining fleet average GHG standard (ICCT, 2020a).

The Covid-19 pandemic has already started to contribute to the retirement of the least efficient aircraft due to the reduction in demand. Therefore, fleet-wide fuel efficiency standards could also be considered in conjunction with economic incentives. Alternatively (or as a complement), fleet-wide fuel efficiency requirements could accompany supporting mechanisms for operators that have been induced by Covid-19. One way to achieve this could be the use of conditionality clauses that make organisational-level support contingent on fuel-efficiency improvements. These policy instruments could also help to reduce the tendency to postpone investments in more energy efficient aircrafts that could be induced by financial constraints.

Table 6. Options for regulating airline fuel efficiency

Approach	Target	Means of compliance	Potential improvement (%/year)	Advantages	Disadvantages
Pass/fail phase-out	In-service aircraft	Aircraft retirement	<1.1%	Easy to implement; best matched to current type certification (i.e. the documentation of airworthiness of the approved design – or type – of an aircraft)	Inflexible; higher cost; static; cannot credit early action
Tiered standards for fleets	Airlines via in-service aircraft	Aircraft purchase	<2%	Easy to implement; dynamic, medium flexibility and compliance cost; can credit early action; can be matched with fines	Medium complexity; requires multiple stringency levels
Declining fleet average GHG standard	Airlines	Aircraft purchase; operational improvements; alternative fuels	<2.5% + alternative jet fuels	Highly flexible; lowest cost of all the approaches; dynamic and easily tightened over time; can credit early action; can be matched with fines	Added complexity; requires initial benchmarking of airlines

Source: adapted from ICCT (2020a).

Support for fuel-saving and fuel-switching technology development

Governments can use revenues from economic decarbonisation measures to support the decarbonisation of the air transport sector. Policy makers can use a broad range of instruments to mitigate risk in the development, production and uptake of cleaner aircraft and fuels. Financial support can be provided regularly (e.g. subsidies and tax exemptions) or be delivered as a lump sum on a project basis.

When providing financial support, governments may focus on the investment initiatives that are furthest from commercialisation and likely not to be undertaken without it. For instance, aircraft manufacturers will very likely carry out incremental aircraft efficiency improvements without government financial support. Governments can therefore limit their role to channelling resources towards riskier projects that may not have taken place without government support.

Direct subsidies or tax exemptions (including VAT) can be directed to incentivise the development, production and widespread uptake of cleaner aircraft and fuels. Direct and indirect subsidies to the aviation sector are already significant (Gössling, Fichert and Forsyth, 2017) and tend to increase activity and emissions from the sector. Subsidies in other sectors (e.g. direct and indirect subsidies to fossil fuels) also negatively affect the decarbonisation of the aviation sector. Subsidies and tax exemptions should be redirected towards products and services contributing to decarbonisation. For example, R&D inputs and outputs can be given preferential tax treatment. One example is income from licensing or asset disposal attributable to R&D or patents. Subsidies can also be made conditional to the achievement of determined environmental outcomes for public procurement and public service obligations (PSOs).

In road transport, differentiated taxes (or feebate mechanisms, such as the French bonus/malus on vehicle excise duty[60]) have been widely used to promote vehicles with the best energy efficiency and energy diversification performances. The mechanism is also technically suitable for aircraft but harder to apply due to the smaller number of "vehicle models" and the implications of these policies for market shares, given the duopolistic nature of the commercial aircraft market.

Many financial instruments employed by governments can help lower capital costs and limit the risk of investment in cleaner aircraft and fuel technologies for the private sector. These include:

- Debt service reserves, where governments keep cash deposits to make interest and principal payments in case a private borrower fails to make scheduled payments.
- Government-held subordinated debt, where a public agency agrees to take on a lower priority position for debt repayment than senior debt holders, allowing senior debt holders to be repaid fully before other debt holders. This eases the borrower's access to private capital.
- Credit insurance products for bond financing, i.e. government insurance agreeing to make bond payments in case the issuer defaults.
- Public loans and loan guarantees, including export credits for technology, where governments can lend directly to the private sector, or act as a guarantor for the private sector to obtain a market loan with a lower interest rate.
- Grants to partially or fully cover interest payments on private loans, or grants partially or fully covering specific project expenses.
- Co-investment, which helps to share commercial risk between the public sector and private partners.
- Advance market commitments, in which governments guarantee the purchase of a number of aircraft or an amount of fuel that meets specified emissions characteristics. In the case of fuels, these include offtake agreements – i.e. arrangements between a producer and a buyer to purchase or sell the (low-carbon) energy that will be produced.[61]
- Contracts-for-difference, which commit the government to paying part or all of the cost difference between conventional fuels or aircraft, and lower-emission versions, to airlines.

The case of advanced market commitments is not only relevant for governments, where it effectively resembles a form of public procurement, but also viable between private sector actors, as shown by their successful application to the low-carbon electricity sector, in the form of power purchase agreements for wind and solar projects.

In addition, the bond market is increasingly being used by policy makers and financiers as a source of low-cost financing or refinancing for projects and economic activities meeting a range of sustainability requirements (green bonds). Especially (but not only) when they are paired with tax exemptions or advantages for investors, green bonds can provide revenues for investors that are similar to standard bonds while also allowing bond issuers to be subject to lower interest rates than those that could typically be obtained from alternative sources of funding, along with the potential to raise more capital (e.g. through co-financing) and increased flexibility in the use of capital.

Box 15 details how a number of these instruments applied in the case of the production of low-carbon fuels from waste through a thermochemical conversion process.

Box 15. An example of financial instruments being used to foster the production of low-carbon fuels

Fulcrum Bioenergy relies on biomass gasification technology combined with a Fischer-Tropsch fuel process for the production of a synthetic crude that can be then upgraded to jet fuel and diesel. The construction of its first production plant benefited from a grant awarded upon the achievement of specific milestones by the United States Department of Defense in the framework of the Defense Production Act. This Act allows the Department of Defense to invest in building production capacity for a wide range of military materials (Biofuels Digest, 2014).

The grant attracted other financiers, as it demonstrated that the project had complied with robust due diligence. Additionally, as the grant comes in the form of equity financing, it was also instrumental for the company to raise complementary debt financing. Fulcrum was also a potential beneficiary of a loan guarantee. This was subject to the construction of a demonstration plant, its operation for a certain amount of time and the availability of a commercial loan. Political risks and the availability of alternative options at better financial conditions meant that the loan guarantee was not the option pursued by the company.

The alternative consisted of the combination of green bonds and a debt service reserve provided by an insurance company on a commercial basis. Green bonds were enabled by the low-carbon characteristics of the fuel-production pathway and were crucial for the availability of better financial conditions for the loan. The guarantee for debt service payment came from the insurer confidence that the approach selected by the company for the development of the production plan, integrating commercially purchased components with proprietary technologies, was sound.

The European Union is the global market that, as of July 2021, has made the most progress in terms of defining instruments (such as green bonds) to direct investments towards sustainable projects and activities, as already highlighted in the chapter on the current policy framework.

Taxes levied on tickets

Ticket taxes are levied on passengers departing from some national airports. The primary aim of these taxes is to raise revenue from air transport, although some more recently implemented taxes have stated environmental objectives. Transfer passengers and passengers on domestic routes are often exempt from taxation.

There are no bilateral restrictions on such taxes between countries enshrined in ASAs, therefore few barriers to implementing a ticket tax on international flights, which may explain the measure’s popularity with policy makers.

Ticket taxes are different to airport charges, which are levied by airport operators to cover infrastructure and operating costs. Airlines are responsible for collecting and paying ticket taxes to the government. They are usually applied as a share of the airfare or as a fixed amount per trip.

Ticket taxes and other government measures that can increase ticket prices are generally met with concern from the industry, which claims that revenue-generating taxes on international aviation have a disproportionate effect on low-income travellers (IATA and ACI, 2013). However, most flights are taken by a small and relatively wealthy segment of the global population: it is estimated that 1% of most frequent flyers accounts for over half of passenger air transport CO_2 emissions (Gössling and Humpe, 2020). Ticket taxes can also be designed and implemented in a way that does not disproportionately burden low-income or other categories of individuals. The tax rate can also be differentiated by class of travel and distance travelled, as well as specific age groups (e.g. children and the elderly).

Overall, ticket taxes are not ideally suited to decarbonising air transport. They have a primary impact on demand volumes[62] , and they do not directly target carbon emissions from the sector. In particular, they are less effective and stimulate a smaller range of responses than cross-sectoral economic instruments such as a broad-based carbon tax, an ETS or an LCFS. However, their ease of implementation relative to these instruments is an advantage for policy makers. Ensuring that the effect of ticket taxes on decarbonisation is improved requires a differentiation accounting for energy efficiency and/or fuel decarbonisation properties. Sweden is currently discussing such plans (AFP, 2021). Linking revenues from ticket taxes with funding mechanisms aimed to stimulate technological change and/or operational improvements can also help. Ticket taxes also have the advantage of avoiding fuel tankering issues inherent to measures that increase fuel prices, as well as allowing for some demand mitigation.

As ticket taxes are usually applied on departing flights and cannot be levied on the entire route network, they may have a distortive impact on consumer decisions that can translate into network inefficiencies, which may in turn drive up overall CO_2 emissions.[63] Such potential impacts need to be taken into account by policy makers. Moreover, policy makers considering the use of ticket taxes to promote decarbonisation should also take into account connectivity challenges resulting from increased ticket prices, particularly regarding regions that rely on aviation for essential connections.

Decarbonising air transport through government policy towards airports

Three main levers can help to reduce excess fuel burn by aircraft at airports, while also addressing congestion issues.

- measures aiming to optimise capacity
- slot co-ordination
- differentiating airport charges based on environmental impacts.

Caps on air traffic movements can also ensure that CO_2 emissions from aviation do not go beyond a certain level, provided they are explicitly linked to the amount of overall aircraft emissions and can be applied to other airports in a system.

Building new and optimising existing capacity at congested airports can reduce delays and excess fuel burn on a per-flight basis. In the appraisal framework, all environmental costs, including CO_2, should be considered before expanding or building new airport capacity (ITF, 2017b). The level of carbon pricing assumed in the assessments will influence the result of the analysis; without carbon pricing, the benefits and costs are vastly under or overestimated. The benefits of reducing delays are underestimated. The demand and hence the benefits are overestimated and the costs are underestimated. In many cases, expanding or building new airport capacity may seem more attractive as not all social costs are accounted for. When necessary infrastructure is approved, policy makers should ensure that CO_2 targets will be achieved through adequate policy measures and that design features minimise any potential excess fuel burn.

In all congested European airports and some other congested airports around the world, an independent slot co-ordinator administratively allocates slots to airlines based on administrative principles outlined by IATA's Worldwide Slot Guidelines (ITF, 2017a). This is not the case in the United States, where carriers schedule flights as they wish, in co-ordination with airport operators, at all bar three congested airports (John F. Kennedy International Airport, La Guardia Airport and Ronald Reagan Washington National Airport). Slot auctions have been experimented with (e.g. in China) but remain uncommon due to their high cost to airlines and passengers (IATA, 2017). As administrative slot allocation is based on granting slots to airlines (and not specific routes or aircraft types), the slot co-ordinators cannot explicitly drive reductions in CO_2 emissions through their decision-making.

Differentiated landing charges to limit congestion, noise, and other environmental impacts are already applied at some airports such as Heathrow, but these charges are generally not efficient as outcomes are below the social costs of noise and other environmental impacts.[64] Airport operators can incentivise airlines to fly more efficient aircraft by imposing relatively lower airport charges on those aircraft types that emit less CO_2 per passenger. The primary objective of airport charges, however, is to recover the costs of airport infrastructure that airlines use. Using airport charges as an instrument to reduce CO_2 emissions will play a limited and secondary role, particularly when compared to taxing carbon.

Caps on air traffic movements are usually implemented at the airport level to limit the adverse impacts of aviation activity on local communities, notably noise and air pollution. Such caps are in place at airports such as London Heathrow and Amsterdam Schiphol, and although no CO_2 emissions-motivated caps have been put in place yet[65], they could be applied to target a certain level of CO_2 emissions at a given airport or group of airports. Although a cap does not incur direct additional costs to governments, it constrains the number of flights that can take place, pushing up ticket prices and reducing aviation connectivity. Caps may result in traffic spill-overs to other airports and end up being ineffective if passengers have other alternatives.

Substitutes and alternatives to air transport

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-km (pkm) 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. However, to offset the CO_2 emissions from the construction of HSR infrastructure, significant traffic volumes of around ten million annual passengers per route are needed, and most of the traffic diverted to HSR must come from air transport (Westin and Kågeson, 2012). The overall net impact of building an HSR line on GHG emissions needs to be considered before the investment is made. The result will depend on such factors as the GHG emissions during the construction phase, GHG emissions from operations, expected travel volumes, and replacement potential for other transport modes.

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 km. The opening of an HSR corridor on some routes of this length has more-than-halved air transport's modal share (e.g. Paris-Lyon, Madrid-Seville, Brussels-London and Wuhan-Guangzhou (IEA and UIC, 2017)). In Japan, the Shinkansen's market share is always higher than that of air transport on routes under 965 km (Albalate and Bel, 2012).

A large share of air transport emissions could theoretically be mitigated through modal shift: 60% of flights corresponding to 18% of air passenger CO_2 emissions are from flights under 1 000 km (ICCT, 2019). In practice, the effect on emissions will be limited, as air-rail substitution is restricted to corridors with sufficiently high travel demand to justify rail infrastructure's high environmental footprint[66] and costs, especially when the construction of bridges and tunnels are needed (IEA, 2019b).[67] In the United States, replacing one-third of short-haul flights in ten designated HSR corridors in 2030 would result in just a 1% decrease in domestic air transport CO_2 emissions (Jamin et al., 2004).

Globally, there is potential for shifting some short-haul air travel towards HSR. Flights between airport pairs of over 1 million passengers a year where an HSR connection would shorten door-to-door travel times represent 14% of all flights and 3% of seat-kilometres on average (IEA, 2019b). This result excludes routes on terrains that would require extensive tunnel works. The share of replaceable flights exceeds 20% (5% of seat-km) in North America, where there currently is no HSR network. The potential to substitute air travel is smaller in regions with an existing HSR network or where travel demand is comparably low.[68]

Indeed, in densely populated parts of Europe with HSR networks, the potential for further emission reductions from air-HSR substitution is limited. At Amsterdam Schiphol Airport, 12 000 to 25 000 flights under 800 km could be replaced by HSR in 2030 (Savelberg and de Lange, 2018), but even the high end of this estimate accounts for just 5.2% of scheduled passenger aircraft movements (477 096) at the airport in 2019 (Royal Schiphol Group, 2019). At the European level, however, 6% to 11% of intra-European aviation CO_2 emissions could be avoided through a modal shift to rail for city pairs up to 1 000 km apart, excluding those with one or both cities on islands, as it is hard for railways to reach islands and also offer a competitive service to aviation – both in travel time (ferries needed) and costs (Bleijenberg, 2020). Achieving this would require faster rail services and a 50% increase in night trains, in combination with policies incentivising a shift to greener transport modes.

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. Strategies to decarbonise short-haul flights could eventually combine investment in both aircraft using low-carbon hydrogen or electricity and HSR networks, as both modes of transport will compete over similar distances if and when these low-carbon aircraft enter into service.

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 Railway (UIC) signed in early 2020 is expected to further strengthen air-rail partnerships, in particular through integrated ticketing (UIC, 2020). Government action in this area can target the removal of commercial, technological, regulatory, awareness and behavioural barriers (North Star and Atkins, 2018). However, rail as a feeder service for longer-haul flights could lead to a rise in air transport emissions, as slots for short-haul flights freed up due to rail substitution could be replaced by longer-haul flights. Carbon pricing would help counter any such rebound effect.

Decarbonisation pathways for aviation

Air transport can quickly move goods and people over large distances generating economic growth, creating jobs, and facilitating international trade and tourism. It also provides connectivity that often has no substitute. However, fossil-fuel combustion in jet engines emits greenhouse gases and air pollutants that have environmental and health impacts. Global air transport emissions were increasing steadily pre-Covid-19. They are projected to account for 4% to 15% of the cumulative CO_2 budget available between 2016 and 2100 under scenarios to limit global temperature rise to under 2°C above the pre-industrial levels (Lee, 2018a). Government and industry action is needed to ensure externalities are accounted for and that the sector meets Paris Agreement targets while preserving aviation connectivity that benefits our economies and societies.

This section charts a possible way forward to achieve decarbonisation of air transport. It draws from the policy review included in the earlier chapter. It takes policy developments to-date into account and considers technology options that could support CO_2 emission cuts. Starting from general considerations on carbon pricing, it moves progressively towards solutions that have specific relevance for the aviation sector, keeping a focus on solutions that are compatible with continued economic and social development supported by the aviation sector.

The case for a cross-sectoral and global carbon price

Cross-sectoral carbon pricing is an effective way of reducing CO_2 emissions across the economy. Putting a sufficiently high price on CO_2 emissions can internalise part or the entire cost of negative externalities. It can also incentivise the development, production and uptake of energy-efficient technology and low-carbon fuels.[69] As it helps to shift the tax burden from labour towards resource use, cross-sectoral carbon pricing can also contribute to rebalancing labour and resource taxes across the economy.[70]

Fuels used in international (and often also domestic) air transport and shipping receive preferential tax treatment relative to other transport modes (ITF, 2019b). Ensuring that the entire aviation sector is subject to a single carbon price globally could be an effective move towards a solution attempting to approximate the optimum represented by a cross-sectoral carbon price. To meet this objective, differences in carbon taxation across global regions would also need to be evened out. In concrete terms, though, ensuring that the global economy is subject to a global carbon pricing mechanism proved to be, so far, a very challenging, if not impossible, undertaking.

The case for an aviation-specific global carbon price

In the absence of a practically feasible way to apply a cross-sectoral carbon pricing scheme, policy makers have been considering mechanisms for the application of a carbon pricing scheme limited to the aviation sector alone.

The CORSIA framework provides the opportunity to achieve this, but it requires increased participation and ambition. As of July 2020, 88 states representing over 77% of international aviation activity agreed to take part in CORSIA's pilot phase (2021-23). The Covid-19 crisis resulted in a significant reduction of flights. Subsequently, the baseline year for carbon-neutral growth was changed from 2020 to 2019. On the one hand, the change in the base year gave the heavily affected airline industry room to regrow its operations. On the other, airlines are now likely to start offsetting their emissions after CORSIA's pilot phase. Furthermore, ICAO's second aspirational goal of achieving 2% fuel efficiency improvements per annum is not on track to be achieved, according to ICAO's own projections (ICAO, 2019b).

ICAO recognises that CORSIA does not align with the Paris Agreement and is analysing the feasibility of a long-term aspirational goal for international aviation, which could be adopted at its next General Assembly in 2022. A number of air transport decarbonisation targets have also been announced by the aviation industry. More may be added to this, following increasing global mobilisation to achieve net-zero emissions by mid-century. Table 7 lays out international targets for mitigating CO_2 emissions from aviation as of 2021.

Table 7. International air transport decarbonisation targets

Organisation or government	Target
International Civil Aviation Organisation (ICAO)	• Carbon-neutral growth from 2020 (revised post-Covid-19 to 2019) to 2035 • 2% annual fuel efficiency improvement through to 2050
Air Transport Action Group (ATAG)	Net CO_2 emission reduction of 50% by 2050 compared to 2005, i.e. to around 325 $MtCO_2$
ACI Europe	Net-zero CO_2 emissions from airport operations within airport control
Nationally determined contributions (NDCs) under the Paris Agreement	Domestic aviation emissions (from national flights, airports, and aircraft manufacturing) are included in NDCs. The Paris Agreement does not explicitly exclude or include international aviation and shipping (IAS) emissions in NDCs. The European Union includes international aviation (outgoing flights) in its NDC. A few countries, including the United Kingdom, are considering the formal inclusion of IAS emissions in national carbon budgets. Switzerland is also favourable to the inclusion of IAS emissions on the basis of future internationally agreed rules applicable to all Parties but does not currently include these emissions in its NDC. The French High Council on Climate has formally advised the French government to include IAS emissions in its NDC.

Note: ATAG comprises International Air Transport Association (IATA), Airports Council International (ACI), Civil Air Navigation Services Organization (CANSO), International Business Aviation Council (IBAC) and the aircraft and engine manufacturers.

Sources: ICAO (2010); ATAG (2008); ACI Europe (2019a); European Commission (2019a); Department for Transport (2020); Switzerland (n.d.); Haut Conseil pour le Climat (2019).

Recent industry projections also suggest that net-zero aviation could be feasible globally by 2060 or 2065 (with some regions and individual companies reaching this point sooner) but would require extensive government support without carbon pricing beyond what is currently planned within CORSIA (ATAG, 2020). Governments should therefore work together at ICAO to ensure that international aviation is subject to a global and meaningful carbon price, i.e. high enough to significantly stimulate the decarbonisation of the sector. In parallel, they should also take additional action at the regional or national level. This will be necessary to mitigate GHG emissions from domestic and regional aviation. It could also support the development of an international agreement providing an effective carbon price signal.

The case for national and regional carbon pricing

The scale of the climate emergency and the long lead times for reaching international agreements creates an urgent gap for short- to medium-term solutions. Regional carbon pricing initiatives are one area where the aviation sectors can contribute to the Paris Agreement targets within this timeframe. Regional initiatives such as the EU ETS can limit the fuel tankering and carbon leakage risks that result from non-universal schemes and serve to drive ambition for a global Paris-aligned carbon pricing scheme for international aviation. Fuel taxes on jet fuel used on international flights can also be enabled by amending ASAs between the countries wishing to do so.

Significant emissions reduction also need to be achieved through decarbonising domestic aviation, which accounted for 40% of the global sector's pre-Covid-19 CO_2 emissions (ICCT, 2019). National governments are inherently best placed on defining a clear long-term vision and targets for decarbonising their domestic air transport, alongside short and medium-term targets.

A wide range of policy instruments can be implemented to support the achievement of these targets, starting from the application of carbon prices. There are no legal obstacles to taxing domestic aviation fuels, which are already taxed in over forty countries, including some with significant domestic aviation markets, such as Brazil, Canada, India, Japan and the United States. In China and the United States, the world's largest air transport markets, 69% of air transport CO_2 emissions came from domestic operations before the Covid-19 crisis. Mitigating domestic air transport emissions can, therefore, significantly contribute to reducing the global carbon footprint of air transport.

Ticket taxes may complement national action on carbon pricing, provided that their design accounts for energy efficiency and/or fuel decarbonisation properties. Due to their primary impact on demand volumes, their application needs to be considerate of disproportionate burdens for specific categories of individuals and the importance to ensure affordable connectivity.

Pricing carbon emissions from international air transport is also possible, but it would require, in most cases, amending ASAs bilaterally. This could potentially grow to regional carbon pricing schemes and further drive ambition for a global carbon pricing mechanism. The latter can be developed under the auspices of ICAO.

In addition (or as a complement) to carbon pricing and taxation measures, other policies can help accelerate the decarbonisation of aviation while also allowing for economic development. These include policies supporting clean fuel technologies, energy-efficient aircraft and other policies geared towards the acceleration of technological developments.

Policies supporting clean fuel technologies

Policies supporting the development, deployment and uptake of low-carbon aviation fuels, such as low carbon fuel standards and fuel-blending mandates, can either be implemented on their own or as complementary measures to carbon pricing. They need to be deployed in conjunction with instruments that mitigate risk for low-carbon fuel supply and can complement other instruments aiming to stimulate innovation, further discussed in the next section. Their importance lies in the necessity to ensure that costs of low-carbon fuels can be effectively brought down, thanks to increasing scale and other technology learning processes.

A low-carbon fuel standard (LCFS) can effectively support measures to accelerate the development of low-carbon fuels in aviation. By design, it reduces the carbon intensity of fuel sold while providing a greater incentive than a carbon tax to invest in the cleanest fuel production technologies. It does this through the possibility to earn bankable credits and thus obtain long-term economic support. By providing larger incentives for the lowest-carbon fuels, an LCFS can stimulate the deployment of novel fuel technologies and production systems. In turn, this accumulates operational experience and improves cost-efficiency before more ambitious targets demand full-scale commercialisation.

Although LCFS are not as cost-effective in the short term as a carbon tax or ETS for abating CO_2 emissions, they provide greater marginal incentives for upstream innovation and ensure that reductions are made in critical sectors and applications, not just those with the lowest abatement cost. Generally, incentives from both policies are additive and can be combined without reducing the efficiency of carbon pricing. Evidence from the United States shows that meeting LCFS targets helps to meet ETS targets and that an LCFS combined with an ETS can strengthen the price signal of standalone trading schemes, which generally have lower credit prices than an LCFS (Yeh et al., 2020).

Fuel-blending mandates that account for life cycle GHG emissions intensities can also regulate the carbon intensity of fuel. By defining differentiated penalties for non-compliance according to the sustainability profile of fuels and implementing a floor price for penalties, mandates could partially mimic the LCFS to incentivise the development and deployment of best-performing fuel production technologies. Other measures aiming to de-risk investments are well suited to complement mandates to stimulate supply. Offtake agreements and contracts-for-difference are the most relevant for low-carbon fuels.

The absence of a market for exchanging credits makes mandates easier and cheaper to implement than an LCFS, but could adversely make it less cost-effective. The technology-neutral framework of an LCFS is also better suited for dealing with novel fuels which do not fit cleanly into existing categories of a blending mandate. In markets regulated by an LCFS or a blending mandate, carbon prices can also provide a floor price for investments in low-carbon fuels. The combination of an LCFS with a carbon tax or an ETS thus enables sustained and significant CO_2 emission reductions.

An LCFS could be implemented as a standalone policy within ICAO to support the development of SAF for international aviation, with all revenue being recycled within the sector. Globally benchmarked life cycle emissions profiles for different SAF would eliminate the risk of fuel swapping, as well as the risk of carbon leakage, by removing their root cause: the difference between regional carbon prices.

Regional initiatives supporting the development of SAF could also be implemented separately or complementary to carbon pricing. Widening the geographical scope of these measures can help limit carbon leakage and fuel tankering. At a regional level, an LCFS or a blending mandate can be easier to put in place as they do not face the same legal obstacles as pricing the carbon content of fuel used on international flights.

National governments implementing or extending existing carbon prices to domestic aviation fuel can provide further support to the development and uptake of cleaner fuels by implementing an LCFS or a blending mandate with ecological safeguards or implement them as standalone policies.

Policies supporting energy efficiency improvements

Regulations on aircraft fuel efficiency can accelerate the development, production, and widespread uptake of the most fuel-efficient aircraft.[71] ICAO's work on aircraft standards is important to ensure harmonised regulations apply to the international aircraft market. Countries with large aviation sector manufacturing industries can build on the ICAO framework to take the lead in negotiating more ambitious, fleet-wide aircraft standards. These standards can be applied to airlines to stimulate the demand for the lowest-carbon aircraft technologies and increase the value that is attributed by manufacturers to their development.

Fuel efficiency improvements can be further strengthened by government funds to indemnify and de-risk investment in fuel-saving technologies, such as those needed for engine hybridisation, boundary-layer ingestion propulsion and novel airframe developments. Financial instruments, including debt service reserves, government-held subordinated debt and loan guarantees and co-investment, amongst others, can also help lower capital costs on fuel-saving aircraft technologies.

Other innovative measures for the decarbonisation of air transport

Other policy instruments that can help decarbonise the sector include measures to help foster greener technologies and innovations for the sector. These can be deployed in conjunction with carbon pricing, economic incentives and regulatory instruments discussed earlier. They can be broadly categorised in two groups of instruments: market pull and technology push.

Market pull measures support the deployment and scale-up of technologies closer to commercial deployment than technologies targeted by technology push measures. Economic incentives "pulling" technologies towards the market can combine taxes, rebates, and specific regulatory requirements, including those discussed in the previous section. Fleet renewal schemes with specific requirements on energy efficiency (or a "green incentive") are an example that can combine economic and regulatory aspects and has a direct impact on decarbonisation. Fuel-efficiency standards and LCFS also combine market pull and technology push features, since they bring technologies to the market that would struggle to compete economically in the absence of the policy. They also ensure that decarbonisation remains a core driver of policy action.

Technology push measures have a greater scope to accelerate research, development and deployment of technologies at lower readiness levels. China, for example, has deployed electric vehicle subsidies on vehicle range, energy efficiency and battery pack energy density which are subject to tightening thresholds over time, to stimulate innovation and consolidation in the battery manufacturing industry. A similar logic, rewarding the best-performing technologies, could be applied to the allocation of public funds and resources to the aviation sector, including those that governments are mobilising for the post-Covid-19 recovery. To stimulate low-carbon technology development and deployment, support programmes provided by governments should include clear decarbonisation requirements for the recipients and make aviation both financially as well as environmentally sustainable over the longer term.

Disruptive technologies enabling greater energy efficiency, alternative propulsion systems and advanced low-carbon fuels are all well-suited candidates for technology push measures. Financial instruments like green bonds can also ease access to capital to finance the development of this type of technology, including zero-emission aircraft.

Aviation is a sector where there is scope for mission-oriented research and innovation due to its strategic position for defence and its close ties with aerospace. These missions consist of bold programmes using a defined amount of public resources to solve a pressing societal challenge. They co-ordinate many stakeholders and ensure the consistency and complementarity of public and private investments to drive a systemic change through impact-driven but realistic goals within a certain timeframe and budget (European Commission, 2019c). They have the advantage of clearly spelling out the value and goal of investments in research and innovation. Such an approach is followed in Horizon Europe, the European research and innovation framework programme and is well-inscribed in a long-lasting tradition of ambitious research projects developed in the United States.

Prime institutional examples include the Defence Advanced Research Projects Agency (DARPA), the National Aeronautics and Space Administration (NASA) and programmes of the United States Department of Defense and Energy that provide funding for the network of National Laboratories and Research Centers, including its Advanced Research Projects Agency-Energy (ARPA-E). The deep decarbonisation of air transport is well suited to frame a mission-oriented research programme. Its global relevance and the significant challenges to achieve net-zero flights with minimal environmental impacts, using a life cycle and a circular economy perspective, not to mention the involvement required from other transport sectors, make it an obvious choice for further study and attention.

Governments can also support technological progress, increased economic competitiveness and industrial development by taking actions that are not exclusively focused on aviation but remain relevant to make progress in the decarbonisation of air transport. The use of low-carbon electricity and/or hydrogen as energy vectors (or feedstock for electrofuels) are clear examples of ideas that would be relevant in this context. In the case of electrification, one example of indirect intervention is the support for the development of the capacity to recycle raw materials for battery production. In the case of hydrogen, which is subject to a range of technical storage and transport challenges, similar examples could be related to the development of affordable and recyclable storage tanks. Indirect support can also be provided through capacity building and training for the workforce, given that these major changes in the energy sector are likely to require the development of a range of new skills.

Conclusions

Decarbonising air transport will require a multi-layered approach by governments. It must combine carbon-pricing instruments, development of sustainability criteria and fuel efficiency standards, as well as incentivising development and deployment of new technological solutions to decarbonise the sector. It is important that governments work together with the industry and other aviation stakeholders to enable the transition.

A global carbon pricing scheme for international aviation that is consistent with the ambition of the Paris Agreement would be economically efficient and reduce the risks of market distortion, carbon leakage and fuel tankering. The urgency of the climate challenge and the long period it will likely take to reach such an international agreement suggests that cross-sectoral or aviation-specific carbon pricing initiatives should also be implemented, at least initially, at the regional and national level. Despite risks due to a lack of global harmonisation, this would raise international decarbonisation ambition and enable cost-effective abatement options for the air transport sector and the transport sector in general.

Complementary aviation-specific measures are required to combat the strong price signals needed to effectively unlock progress for low-carbon aviation technologies. An LCFS or a blending mandate with ecological safeguards, in particular, will be necessary to support the development and uptake of cleaner aviation fuels. Complemented or supported by government schemes to de-risk private investments, namely offtake agreements and contracts-for-difference, they can provide decentralised investment incentives and direct financial support to those investing in aviation fuels that have long-lasting capacity to deliver low-carbon emissions.

Regulatory policies such as aircraft standards could also speed up aircraft efficiency improvements beyond the pace of current efficiency increases and beyond the rate enabled by carbon pricing. Deploying aircraft with strong fuel efficiency improvements is not only better from a decarbonisation perspective but is also a way to maintain competitiveness in terms of costs for aviation, as they would be especially important to help mitigate higher fuel costs due to carbon pricing and/or low-carbon fuel requirements. Countries can also choose to implement fleet-wide standards at the national or supra-national level.

Following the highly disruptive period caused by Covid-19 for the sector, it is crucial that aviation can effectively move towards a model that is both economically and environmentally sustainable. Many governments provided the sector with support to ensure that it continues to provide air connectivity to the users of aviation and deliver benefits of connectivity to our economies and societies. The funds that governments mobilised to help the sector recover from the Covid-19 crisis can be deployed to encourage and accelerate research, development, and deployment of cleaner technologies and fuels. This is particularly important in the context of innovative solutions that are not yet market-ready.

Finally, non-CO_2 greenhouse gas emissions from air transport have a significant climate forcing impact and need to be mitigated. As these impacts are not yet fully quantified, governments should support further research in this area and consider how to mitigate non-CO_2 emissions from aviation alongside the decarbonisation targets. This can comprise policy actions supporting the deployment of already available technologies and mitigation means such as sustainable aviation fuels, conventional fuel quality improvements, and optimised flight routings to avoid ice-supersaturated areas that are melting.

Notes

1 Average trip distances in the air are approximately double those of surface transport modes, according to the ITF Outlook model.

2 The fuel efficiency improvement target is expressed in terms of fuel per revenue tonne kilometres (RTK), or revenue passenger kilometres (RPK). ICAO defines one RTK as 0.1 RPK, as 100kg is the default value assumed for the mass of one passenger, including checked bags (ICAO, 2013a).

3 Some uncertainty remains regarding the inclusion of IAS in nationally determined contributions (NDCs) (Murphy, A., 2020; Lyle, 2018).

4 The IMO initial strategy also aims to reduce average carbon intensity by at least 40% compared to 2008 by 2030, pursuing efforts to reach 70% by 2050 (IMO, 2018a; IMO, 2018b). IMO's GHG strategy differs from ICAO's in its inclusion of a long-term, absolute emission reduction target.

5 In addition, the European Union currently includes CO_2 emissions from international aviation (outgoing flights) in its NDC (European Commission, 2019a). Some countries, such as the United Kingdom, are also considering the inclusion of IAS emissions in their national carbon budgets (Department for Transport, 2020). The French High Council on Climate (HCC), an independent advisory body to the French government on climate change policy, also recommends this practice (HCC, 2019). Switzerland would also favour this practice if agreed internationally with the framework of the Paris Agreement (UNFCCC, n.d.).

6 The basket of measures was defined and adopted by ICAO's 39th Assembly in 2016.

7 Acknowledging that technological improvements and SAF would not be enough to achieve the carbon-neutral growth goal, a GMBM scheme was recognised by ICAO member states and the industry as being more effective than a patchwork of national and regional measures, which could potentially "cause inefficiencies without guaranteeing environmental benefits" (ICAO, 2013b; ICAO, n.d.).

8 CORSIA-eligible fuels include sustainable aviation fuels (SAF) and lower carbon aviation fuels (LCAF). LCAF are fuels with at least 10% lower life cycle CO_2 emissions than Jet A-1, which has a benchmark value of 89 gCO_2/MJ (ICAO, 2019f and ICAO, 2019g).

9 Eighty-eight states representing 77% of international aviation activity have volunteered for CORSIA's first two phases (2021-23 and 2024-27) as of December 2020 (Aviation Benefits, 2020). CORSIA's second phase (2027-35) will apply to all member states with a certain level of aviation activity and exclude Least Developed Countries (LDCs), Small Island Developing States (SIDS) and Landlocked Developing Countries (LLDCs) (ICAO, 2019b).

10 The double counting of emission reductions occurs when both selling and purchasing sides of the emissions reduction unit count an emissions reduction. At COP25, parties failed to reach an agreement on the rules of Article 6 of the Paris Agreement governing carbon markets. The absence of rules leaves these market-based measures vulnerable to double counting (Evans and Gabbatiss, 2019).

11 The two sustainability criteria for CEF stipulate that:

- CEF should achieve net GHG emissions savings of at least 10% compared to conventional jet fuel on a life cycle basis, and
- CEF should not be made from biomass obtained from land with a high carbon stock. This is considered as land converted after 1 January 2008 that was primary forest, wetlands or peat lands, and/or biomass that contributes to the degradation of carbon stock in primary forest, wetlands or peat lands. For land converted after 1 January 2008, as defined based on IPCC land categories, direct land-use change (DLUC) emissions are calculated: if DLUC GHG emissions exceed the default induced land-use change (ILUC) value, the DLUC value replaces the default ILUC value (ICAO, 2019e).

12 The full list is as follows: American Carbon Registry (ACR), Architecture for REDD+ Transactions (ART), China GHG Voluntary Emission Reduction Program, Clean Development Mechanism (CDM), Climate Action Reserve (CAR), Global Carbon Council (GCC), The Gold Standard (GS) and Verified Carbon Standard (VCS) (ICAO, 2021a).

13 ICAO emissions unit eligibility criteria require that, in addition of not doing net harm, emissions reduction, avoidance or sequestration credits (ICAO, 2019g):

1. Are additional. Emissions reduction projects should be additional, i.e. they should not have happened without offsetting programme revenues.
2. Are based on a realistic and credible baseline. The baseline is the level of emissions that would have occurred under a business as usual scenario.
3. Are quantified, monitored, reported, and verified.
4. Have a clear and transparent chain of custody. This implies that offset units should have an identification number allowing tracking.

5. Represent permanent emission reductions. Emission reduction, avoidance or carbon sequestration projects must be permanent, and have mitigation measures in place in case of risk of a reversal of emission reductions.
6. Assess and mitigate against potential increase in emissions elsewhere. This refers to carbon leakage, whereby emission reductions projects in one place lead to increased emissions elsewhere.
7. Are only counted once towards a mitigation obligation. This refers to the potential for double-counting of emission reductions whereby emission reductions sold by one country to another can be counted towards both countries' NDCs.

14 Eighty-eight ICAO member states accounting for 77% of international aviation activity currently volunteer for CORSIA, but analysis from May 2020 suggested that flights between the (then) 83 states accounted for less-than-half of international aviation emissions (Climate Action Tracker, 2020). Collectively, the 83 states accounted for 75% of international aviation activity.

15 The proposal concerns emissions from intra-EU voyages, half of the emissions from extra-EU voyages and emissions occurring at berth in an EU port.

16 Ticket taxes must be differentiated from airport charges. Airport charges are collected by airports or governments to cover the cost of infrastructure and/or operating costs.

17 A number of countries in the EEA also started to consider to take action on SAF mandates. In the case of Norway, jet fuel suppliers must blend 0.5% of advanced biofuels in jet fuel in 2020 and 2021, with the aim of scaling-up to 30% by 2030 (Government of Norway, 2019). Sweden also announced greenhouse gas reduction mandate for aviation fuel sold in Sweden in 2021 (Neste, 2021).

18 For electricity (and heat), they include (a) generation from renewable solar, wind, hydro, geothermal energy, and gaseous and liquid fuels leading to less than 100 g CO_2-eq/kWh and (b) biomass fulfilling the sustainability criteria defined in the recast of the Renewable Energy Directive (European Commission, 2021c). Economic activities included in the draft formulation also include (a) electricity transmission and distribution infrastructure – for cases where newly connected generation capacity is primarily serving generation capacity below the threshold value of 100 g CO_2-eq/kWh measured on a life cycle basis – and (b) electricity storage in closed-loop pumped hydropower storage (European Commission, 2021c). For hydrogen, they include construction of hydrogen storage facilities, development of transmission and distribution networks, manufacturing of technologies for producing hydrogen and hydrogen-based synthetic fuels, as well as production of hydrogen and hydrogen-based synthetic fuels, provided that they have life cycle GHG emissions savings requirement of 73.4% for hydrogen and 70% for hydrogen-based synthetic fuels, relative to a fossil fuel benchmark of 94 g CO_2-eq/MJ (European Commission, 2021c).

19 This report was published in March 2020, at the start of the Covid-19 crisis in Europe.

20 The bypass ratio is the ratio between the mass flow rate of the bypass stream and the mass flow rate entering the engine core.

21 The larger engine size and the need to integrate it on an aircraft not initially designed to host such a large engine is an issue that has been recently emerging prominently with the case of the Boeing 737 MAX and may raise the bar of safety related limitations in the future.

22 The 2020 EIA Annual Energy Outlook does not account for impacts of the Covid-19 crisis on energy prices. For instance, the listed 2020 price for jet fuel is USD 1.95 per gallon, while prices collapsed well below USD 0.5 per gallon during May 2020 (EIA, 2015, 2020; IATA, 2020). The development of fuel prices in the coming years may alter the economics of the presented technology options.

23 Aircraft engines are designed to operate optimally in cruising conditions. This is known as the "efficiency sweet spot". Fuel efficiency is lower during take-off, climb, and descent.

24 Current Li-Ion batteries are 250 Wh/kg at cell level, 40 times less than the energy density of jet fuel.

25 Power-oriented batteries generally come with trade-offs, as they store less energy per unit weight and may lead to additional weight increases.

26 Hydrogen compressed to 700 bar has an energy content of about 4 MJ/m3. Cryogenic liquid hydrogen at ambient pressure has an energy density of 10 MJ/m3. These compare to nearly 37 MJ/m3 for jet kerosene.

27 These consist of synthetic liquid hydrocarbon fuel produced from carbon and hydrogen.

28 LCAF are currently the subject of regulatory developments by the Fuel Task Group (FTG) of ICAO's Committee for Aviation and Environmental Protection (CAEP).

29 Jet fuel specifications are defined in ASTM D1655, Standard Specification for Aviation Turbine Fuels. ASTM has defined the steps for qualification and approval of new aviation turbine fuels in ASTM Sustainable Aviation Fuel: Review of Technical Pathways D4054, Standard Practice for Evaluation and Approval of New Aviation Turbine Fuels and Fuel Additives. Finally, there is a specification for SAF, ASTM D7566, Standard Specification for Aviation Turbine Fuels Containing Synthesized Hydrocarbons. The ASTM D7566 approval process begins upon completion of the D4054 tests (Holladay et al., 2020).

30 In this context, "high quality" refers to fuels having a consistent molecular shape allowing combustion with low non-CO_2 pollutant emissions.

31 ICAO also published methodological document for calculating actual life cycle emissions values (ICAO, 2021c).

32 Annex A2 of the ASTM D7566 Standard, approved in 2011.

33 This is allowed in the ASTM 1655 standard.

34 Annex A7 of the ASTM D7566 Standard, approved in 2020. From IHI Corporation.

35 Annex A6 of the ASTM D7566 Standard, approved in 2020.

36 Annex A3 of the ASTM D7566 Standard, approved in 2014.

37 Annex A5 of the ASTM D7566 Standard, first approved in 2016 for isobutanol feedstock and updated in 2018 for ethanol feedstock.

38 Other thermochemical pathways for fuel production, still at lower technology readiness than BTL (i.e. still at the pilot/small demo scale) and not discussed in the workshop, include fast pyrolysis and hydro-thermal upgrade.

39 Annex A1 of the D7566 Standard, approved in 2009.

40 Annex A4 of the D7566 Standard, approved in 2015.

41 The liquefaction of hydrogen is necessary to increase its energy storage density, and leads to losses equivalent to approximately 30% of its final energy content.

42 Aside from those resulting from the manufacturing of renewable capacity and the electrolysers, unless the production of materials is also decarbonised.

43 Hydrogen production from electrolysis could be competitive with natural gas with carbon capture and storage if electricity production costs are below 25 USD/MWh, a value that is already a reality for wind and solar electricity in highly endowed areas of the world, such as Morocco or Chile (IEA, 2019c; Armijo and Philibert, 2020).

44 Unless upstream fugitive emissions associated with the extraction of fossil fuels are also addressed, applying CCS technologies to hydrogen production from fossil fuel reformation would only reduce the life cycle GHG emissions intensity by 60-70% (Parkinson et al., 2019; The Royal Society, 2020).

45 This estimation is based on 7 million barrels a day of fuel consumption in aviation, representative of the global fuel use in aviation before Covid-19 related impacts (IEA, 2020a), and a 36% thermodynamic efficiency for DAC to fuel production (Blanco et al. 2018).

46 Hydrogen production from electrolysis was estimated to be competitive with natural gas (with prices pre-dating the Covid-19 related shock) with carbon capture and storage with electricity production costs below 25 USD/MWh, a value that is already a reality for wind and solar electricity in highly endowed areas of the world, such as Morocco or Chile.

47 It is a measure of the average net present cost of electricity generation.

48 Examples of biomass use in long-lived products include addition of biomass fibers or bio-char (i.e. charcoal created from pyrolysis of biomass at high temperatures) as a filler to cement and concrete. Other examples include wood products used for construction purposes, particularly in buildings, and plastics, such as polyethylene.

49 More concentrated options of sourcing CO_2 are still currently widely available around EOR operations. These would make CO_2 available at a lower cost than DAC, but would not enable the development of technology leaning on DAC itself.

50 This may be consistent with analyses indicating that CDR technologies – including DAC – are essential for meeting ambitious net-zero pledges (Climate Change Committee,2020). Nevertheless, it is important to bear in mind that the reliance on these technologies will be minimised if in-sector emissions reductions are prioritised.

51 This could reflect an optimistic context where DAC can be scaled-up and costs are reduced thanks to competition, economies of scale, mass production, and learning-by-doing (Larsen et al., 2019).

52 According to Bui et al. (2018), costs for unique designs have been estimated as low as USD 300-600 per tCO_2 (i.e. adding USD 0.8 to USD 1.6 per litre of jet kerosene). Bui et al. also point out that lower costs are likely to be significantly lower in cases where CO_2 is available in concentrated streams, while they found strong evidence that the cost of CO_2 capture rises with increasing initial dilution. Larsen et al. (2019) also mention that DAC costs are still uncertain given the early stage of the technology. They cite estimates in line with Bui et al. (2018), along with lower values, based on National Academies of Sciences, Engineering, and Medicine (2019). However, lower estimates in National Academies of Sciences, Engineering, and Medicine (2019) refer to novel configurations that will require further testing and demonstration to realise the lower price points or cases that considered operating costs. National Academies of Sciences, Engineering, and Medicine (2019) also warns about the need to ensure that comparable systems are considered in assessing costs.

53 Effective carbon rates reflect “the total price that applies to CO_2 emissions from energy use as a result of market-based policy instruments” (OECD, 2018a). They are the sum of taxes and the price of tradable emissions permits, and have three components: emission permit price, carbon tax and specific tax on energy use.

54 Critiques of the carbon border adjustment mechanism point to challenges due to its complexity (especially for complex products) and the possibility for companies to adopt measures that would not lead to increase adoption of lower-carbon technologies for the global market, but rather towards the creation of a low-carbon island or separate trade blocs (Tsafos, 2020; Liebreich, 2021). They also point to greater benefits, for climate change mitigation and global wealth increase through economic growth, likely to result from global low-carbon product standards and a carbon tracking system developed in a global free trade framework, calling for greater global engagement towards it (Liebreich, 2021).

55 OECD (2018a) provides a detailed explanation of why carbon pricing is cost-effective. a) The marginal abatement cost is equalised across emitters, ensuring economy-wide cost-effectiveness, because emitters are incentivised to reduce emissions when reducing emissions is cheaper than paying the carbon price. b) It enables the market instead of governments to determine which emissions should be reduced using which technologies, overcoming the asymmetry of information between governments and emitters. c) They promote innovation in abatement technology by providing a permanent incentive to reduce emissions.

56 ETS and LCFS are treated as economic measures for ease of reading in this report, but as hybrid economic and regulatory measures, they pertain to both the economic and regulatory categories in the ITF's TCAD (see www.itf-oecd.org/tcad).

57 Average life cycle GHG emissions are taken into account. The life cycle assessment considers GHG emissions associated with producing, transporting, and using the fuel, as well as direct and indirect emissions associated with changes in land use.

58 EU Regulation 2018/1139 states that aircraft must comply with the ICAO standard.

59 This magnitude corresponds with indications provided by IATA during the review of this draft.

60 For more information, see ICCT (2018).

61 They help the selling company to access capital for production facilities by de-risking investments through the promise of future income and proof of existing demand for the low-carbon fuel.

62 At slot congested airports, a ticket tax is likely to have no impact on demand as supply of flights exceeds the demand, so ticket taxes can be absorbed by the airline in the ticket price.

63 For example, a price-sensitive passenger may choose to fly from a European country that levies the ticket tax to the United States indirectly (through another European country), instead of directly – to avoid paying a higher rate of ticket tax, as the tax is levied only on the departing flight.

64 In addition, a carbon or ticket tax or ETS imposed on the airlines will have no effect on reducing the output when slots are constraining it. The price that the airlines sell to their passengers will be unaffected by the tax as the airlines will be forced to absorb the tax through a reduction in their economic rents.

65 The only exception so far is Arlanda Airport in Stockholm. Arlanda is the only airport in the world that has a cap on CO_2 emissions in its environmental permit, which stipulated that emissions from aircraft taking off and landing, from vehicular traffic to and from the airport, from internal vehicular traffic and from the heating of buildings may not exceed the level produced in 1990.

66 In the United States, GHG emissions from the building of infrastructure amounts to 5-9 gCO_2-eq/pkm for air transport and 3-11 gCO_2-eq/pkm for rail (Sims et al., 2014).

67 A new HSR route in Europe is estimated to cost EUR 25 – EUR 40 million (USD 30 – USD 47 million) per km, and EUR 145 million (USD 170 million) per km of tunnelling (ECA, 2018).

68 See Box 3.1 of IEA (2019b).

69 Cross-sectoral carbon pricing can also contribute to energy conservation and security provided that, where it applies to carbon dioxide removals, it accounts only for net reductions in atmospheric CO_2 and it is capped to maintain a focus on cases where alternative GHG emission mitigation options are not feasible. For more details on this point, see Preston Aragonès and Wang (2021).

70 There is a growing consensus that shifting the tax burden from labour towards resource use, particularly through taxes on GHG emissions, air pollution, and other externalities such as congestion, would stimulate employment, growth and competitiveness (Heine, Norregaard and Parry, 2012). This is particularly the case in OECD countries, where over half of tax revenue was based on labour in 2015 (ACCA, 2018). Reducing labour taxes in many advanced economies would reduce distortions and improve labour supply (IMF, 2015), while taxes on pollution and resource use could distort the economy less than taxes on labour and income (ACCA, 2018). OECD (2018a) identifies shifting the tax burden from direct sources such as labour to indirect sources such as consumption or pollution as a priority for ensuring long-term growth.

71 Regulations supporting demand for cleaner vehicles (aircraft) and fuels can form part of a single framework aiming to minimise CO_2 emissions and maximise energy efficiency across the life cycle of aviation services. In practice, they are implemented with different instruments, focusing on aircraft and fuel separately. This stems from the need to identify which entities should be regulated to achieve the highest emission reductions. Under a fuel-blending mandate, for instance, regulated entities can be airlines or, in most cases, fuel manufacturers or suppliers. Regulations can also target the demand side, by mandating eco-labels or the inclusion of environmental information for passengers.

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International Transport Forum

Decarbonising Air Transport

This report provides an overview of technological, operational and policy measures that can accelerate the decarbonisation of aviation. Its goal is to support governments and aviation stakeholders looking to introduce aviation decarbonisation measures regionally, nationally and internationally. All measures are discussed in light of their cost-effectiveness and the potential barriers to their implementation. The report summarises the conclusions from an expert workshop held in February 2020 as part of the International Transport Forum's Decarbonising Transport initiative.

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