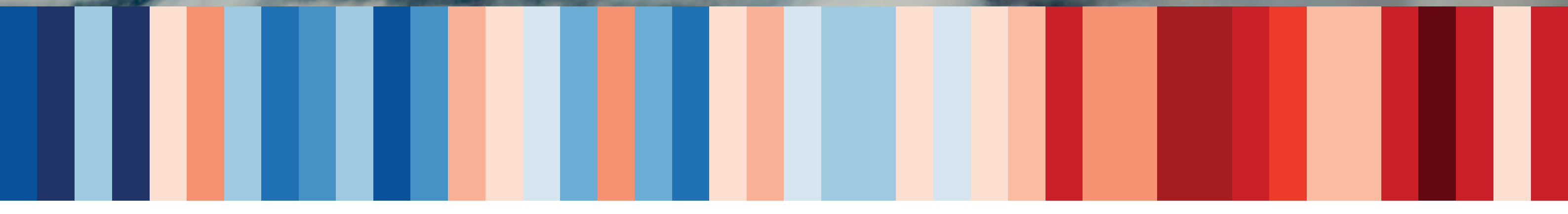
EASA
European Union Aviation Safety Agency

EUROPEAN AVIATION ENVIRONMENTAL REPORT 2022



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References

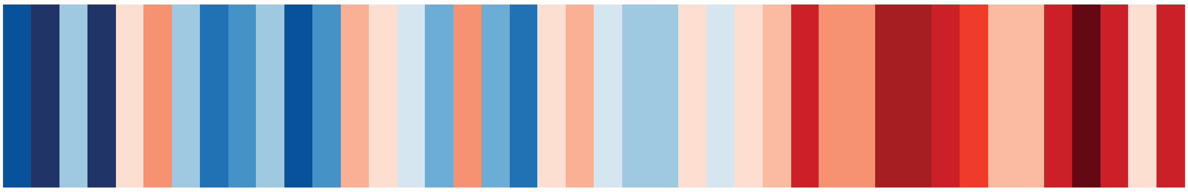
Information originating from work not performed as part of this report is referenced in square brackets and detailed in the List of Resources appendix along with other relevant sources.

Cover Pages

The aviation warming stripes were developed in collaboration with the University of Oxford, Manchester Metropolitan University, and the NERC National Centre for Earth Observation.

Aviation Warming Stripes

Based on a recent study that quantified aviation's contribution to global warming [Introduction, ref. 4], the below aviation 'warming stripes' have been developed with the aim of communicating a complex message in a visually simple and memorable way that people can relate to. Warming stripes typically communicate on the impact of global warming in terms of changes in average surface temperature over time at the global or national level [Introduction, ref. 5]. In comparison, the colours of the aviation warming stripes below represent the modelled % contribution of aviation emissions to overall global warming (temperature increase against a pre-industrial baseline) on an annual basis between 1980 (1.9% on left) and 2021 (3.7% on right).



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EUROPEAN AVIATION ENVIRONMENTAL REPORT 2022

WELCOME MESSAGES

Adina Vălean

European Commissioner
for Transport

Two years of COVID-19 pandemic have had a deep impact on air transport, as well as on connectivity and regional development across Europe.

As aviation recovers from this crisis it must also find ways to “build back better” more sustainably. There is today broad consensus that addressing aviation’s environmental footprint is a prerequisite for it to continue growing and fulfilling our current and future mobility needs.

The challenge is huge if we are to transform Europe into the first climate-neutral continent by 2050, which, in turn, requires cutting transport-related greenhouse gas emissions by 90% in the same timeframe. We need to drastically cut carbon dioxide emissions, reduce exposure to harmful noise levels, improve local air quality and address other non-CO_2 emissions that contribute to climate change.

To get there, the European Commission presented, at the end of 2019, our European Green Deal – aimed at transforming the EU into a modern, resource-efficient and competitive economy. When it comes to transport and aviation, this ambition has been translated into a Sustainable and Smart Mobility Strategy, which sets out a basket of measures to support aviation’s sustainable transformation. This includes supporting the development of new aviation technologies, making flying more efficient through the Single European Sky, gradually replacing fossil jet fuel with sustainable alternatives and making sure carbon emissions are cut in a cost-effective way through the EU Emissions Trading System, as well as driving forward global action.

Of course, achieving our climate ambitions will only be possible with the involvement and engagement of all stakeholders and the general public. The commitment of the European aviation eco-system to sustainability and net zero carbon emissions by 2050 for all flights within and departing from Europe, as expressed in the DESTINATION 2050 initiative of 2021, therefore provides a promising basis for future efforts.

If we are to help the European aviation sector to meet these challenges, we must also be able to base our actions and gauge our progress against accurate, up-to-date data and scientific evidence. That is why this report matters so much. It presents us with a factual and comprehensive analysis of the air transport sector, its impact on the environment, progress to date, and future challenges – also capturing some of the temporary or longer-lasting impacts of COVID-19.

This evidence is already feeding into meaningful policy developments, such as the recent proposal for a “ReFuelEU” Regulation to kickstart the production and use of sustainable aviation fuels. The European Commission and the European Union Aviation Safety Agency (EASA) are also working hand in hand, in cooperation with the aviation industry, to develop an environmental label in the aviation sector, so that passengers will be able to find reliable information on the environmental performance of aircraft, airlines and individual flights and compare between different options available on the market.

I am convinced that these initiatives will not only contribute to making aviation more sustainable, but also more resilient, helping us to maintain our European leadership position in this major global industry.

Patrick Ky

Executive Director

European Union Aviation
Safety Agency (EASA)

Safety is a core element of the culture within the aviation sector and this commitment is reflected at all levels. The set of beliefs, values and rules, both formal and unspoken, on aviation safety is shared by all stakeholders and considered an essential prerequisite for a successful and effective business. The European Green Deal means that these same principles now need to be applied to the strategic issue of environmental protection to ensure the long-term viability of the industry.

This is especially so for climate change where decisions and actions taken in this decade will be decisive in terms of delivering on Paris Agreement commitments and mitigating climate impacts during this century. The challenge of decarbonising the economy is tough, especially for the aviation sector, and coordination at the international level is critical to address this global issue, but we're up to it if we focus on what we gain, which is a sustainable aviation sector.

The aviation sector needs to harness its creativity and ability to innovate, and act as a leader in finding solutions to address environmental challenges, rather than being seen as a barrier to these objectives. Addressing these urgent issues now, and mitigating future risks, is in the sector's self-interest.

Future European and industry goals linked to the environmental performance of the aviation sector now need to be delivered, while maintaining connectivity. It is critical that this is done in a transparent manner to gain the confidence and trust of European citizens that measures in place will meet the agreed targets.

The European Aviation Environmental Report is a key element that supports this objective and informs these discussions. It provides objective, clear and accurate information on the past and future environmental performance of the European aviation sector and the actions being put in place to drive forward sustainability ambitions. It also contains recommendations on how the level of environmental protection in the area of civil aviation could be improved.

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ACKNOWLEDGEMENTS

This third European Aviation Environmental Report has been prepared by the European Union Aviation Safety Agency (EASA) with support from the European Environment Agency (EEA) and EUROCONTROL. Its development was coordinated by a Steering Group made up of representatives of these three organisations as well as the European Commission; the Austrian Federal Ministry for Climate Action, Environment, Energy, Mobility, Innovation and Technology; the Netherlands Ministry of Infrastructure and Environment; the Swiss Federal Office of Civil Aviation; the Clean Sky Aviation Joint Undertaking and the SESAR 3 Joint Undertaking who all separately contributed to the report.

The Steering Group gratefully acknowledges the support of the Advisory Group, whose representatives[1] provided valuable input and comments on the report. The latest information on actions being undertaken by all parts of the aviation sector is provided within the 'Stakeholder Actions' boxes. The continued collaboration with this diverse set of organisations ensures that the report provides a balanced perspective.

European Aviation Environmental Report website

For further information linked to the environmental performance of the aviation sector, we invite you to visit the EASA website (www.easa.europa.eu/eaer). This contains the previous European Aviation Environmental Reports, and the latest updated news and information. Questions associated with this report should be sent to EASA (eaer@easa.europa.eu).

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[1] Aerospace and Defence Industries Association of Europe (ASD), Airports Council International Europe (ACI-E), Airlines for Europe (A4E), Airport Regions Council (ARC), Aviation Environment Federation (AEF), Bundesministerium für Digitales und Verkehr (BMVI), Carbon Market Watch, Civil Air Navigation Services Organisation (CANSO), Civil Aviation Authority Norway, Deutsche Energie Agentur (DENA), Deutsches Zentrum für Luft- und Raumfahrt (DLR), ENAV S.p.A., European Business Aviation Association (EBAA), European Express Association (EAA), European Passengers' Federation (EPF), European Regions Airline Association (ERAA), Fuels Europe, International Council for Clean Transportation (ICCT), HACAN, International Sustainability and Carbon Certification (ISCC), Manchester Metropolitan University (MMU), NESTE, Transport and Environment (T&E), SkyNRG, TOTAL, Transport Malta and Union Européenne Contre les Nuisances Aériennes (UECNA).

FOREWORD

If intelligent extra-terrestrial life were looking down from space at us humans today, they may think us mad, or stupid, or both.

We are fully aware of the rapidly rising concentration of CO_2 in our atmosphere, and the resulting existential risks. The WMO's recent State of the Climate report, and the latest IPCC reports could not be clearer. Climate risk is real, happening now and deadly. Record heatwaves in India and Pakistan during May 2022, which led to so much suffering and devastation, were made 30 times more likely by human-caused climate change. Yet still emissions continue their deadly ascent, and threaten human survival, economic stability and international security.

Over the past two decades, commercial air transport has contributed significantly with its emissions rising by 50%. The time to course correct is now, and some steps are already being taken. The EU has committed to being carbon neutral by 2050, and financial markets are factoring in environmental impacts. The aviation sector has also committed to achieve net zero emissions by 2050. I welcome these efforts.

Every action to move us forward matters, but we also have to ask ourselves whether these are enough. A high emissions footprint equals a high degree of responsibility in charting what more we can do now in terms of speed and scale. As the UN Secretary General has said: fossil fuels are a dead end - environmentally and economically. The aviation industry, which relies so heavily on those fuels, is going to have to be intentional, purpose driven, and frankly downright stubborn about making the necessary changes.

The atmosphere does not react to pledges for the future. It only reacts to real emission reductions and does so with delay. So, beyond commitments, pledges and good intentions we need to see proof of action every year. A clear emissions reduction pathway that is independently monitored to provide an objective oversight of progress is needed to ensure transparency, accountability and credibility.

We have to peak global emissions by 2025 and cut them by 50% in 2030 for any chance of staying below the 1.5°C temperature ceiling outlined in the Paris Agreement. At the same time, we need to contribute to nature-positive outcomes, by actively improving the abundance, diversity and resilience of species and ecosystems. This is especially relevant for biofuels, which must be fully assessed for their impact on nature – especially on land and freshwater. Free prior and informed consent and engagement with local communities, land stewards and indigenous peoples is imperative.

It will not be easy, but the ingenuity and capacity of human beings has no limits. We built aeroplanes so that we could make safe trips over continents and oceans. It is now time to transform the whole sector so that we can continue to fly but do so without putting ourselves, those continents and those oceans at risk.

Christiana Figueres

Executive Secretary of the United Nations Framework Convention on Climate Change (UNFCCC)

2010-2016

Co-host of climate podcast Outrage + Optimism

EXECUTIVE SUMMARY

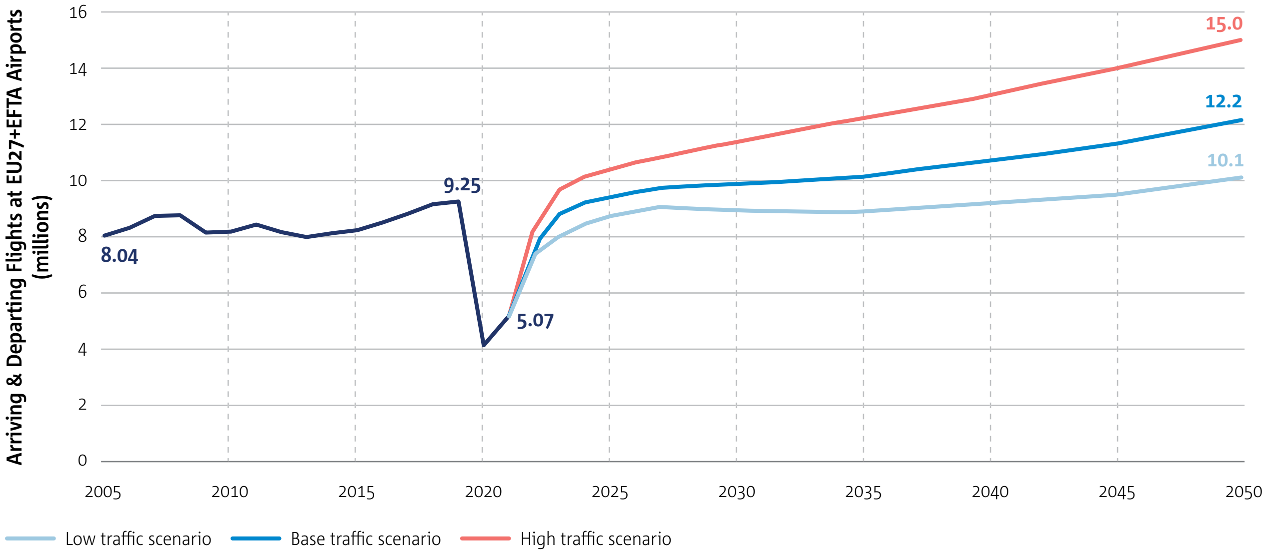
The last three years has seen a spotlight shone on the environmental performance of the aviation sector, and the future challenges that it faces to ensure a license to operate. The third European Aviation Environmental Report provides an objective overview of the significant developments that have taken place in response to this.

While the sector provides economic benefits, connectivity, and stimulates innovation, European citizens are becoming increasingly aware of the effect that aviation activities have on their quality of life through climate change, noise and air quality, and many are prepared to act on these concerns. This is especially so on climate change, which is considered by Europeans to be the single most serious problem facing the world. With these challenges also come opportunities for businesses to build their strategies and brand around this key priority of sustainability to reduce their environmental impact and attract a growing market share, talent and investment, as well as empower customers to join the fight against climate change in this decisive decade.

Scaled-up collaboration between public and private stakeholders will also be of the utmost importance to enhance existing measures, and identify new ones, that can deliver the European Green Deal objectives. This report provides a clear and accurate source of information to inform and inspire discussions and cooperation in Europe. The long-term future of the aviation sector will depend on the success of this effort.

EAER DASHBOARD

TRAFFIC



Indicator	Units	2005	2019	2020	2021
Number of flights[2]	million	8.04	9.25	4.12	5.07
Passenger kilometres[3]	billion	781	1484	389	509
Number of city pairs served most weeks by scheduled flights		5389	8161	N/A	6188

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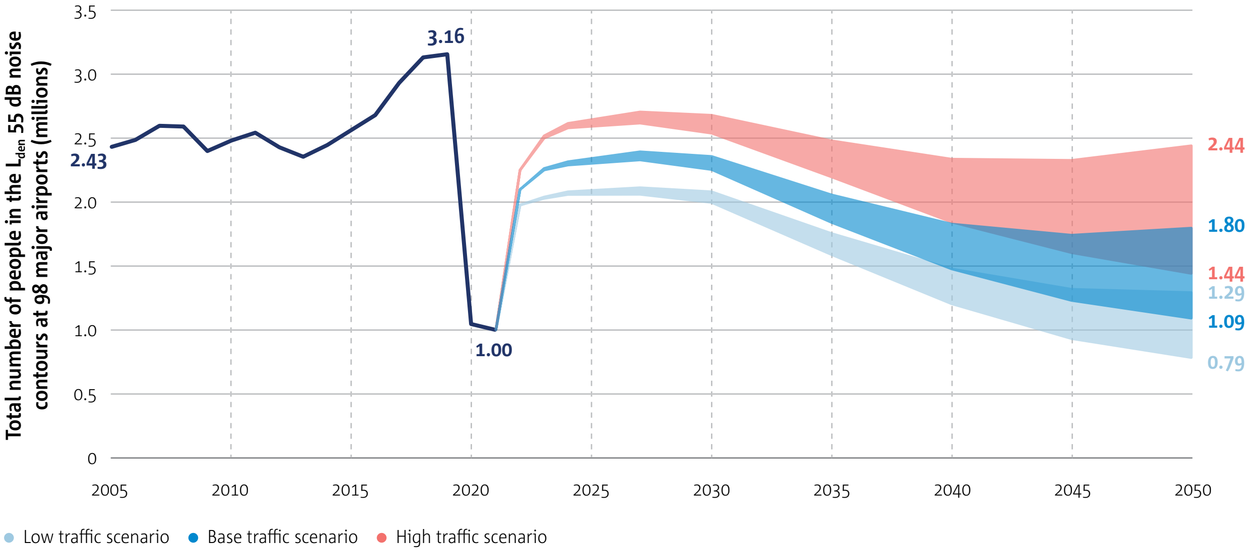
[2] All departures and arrivals in EU27+EFTA.

[3] All departures from EU27+EFTA.

NOISE

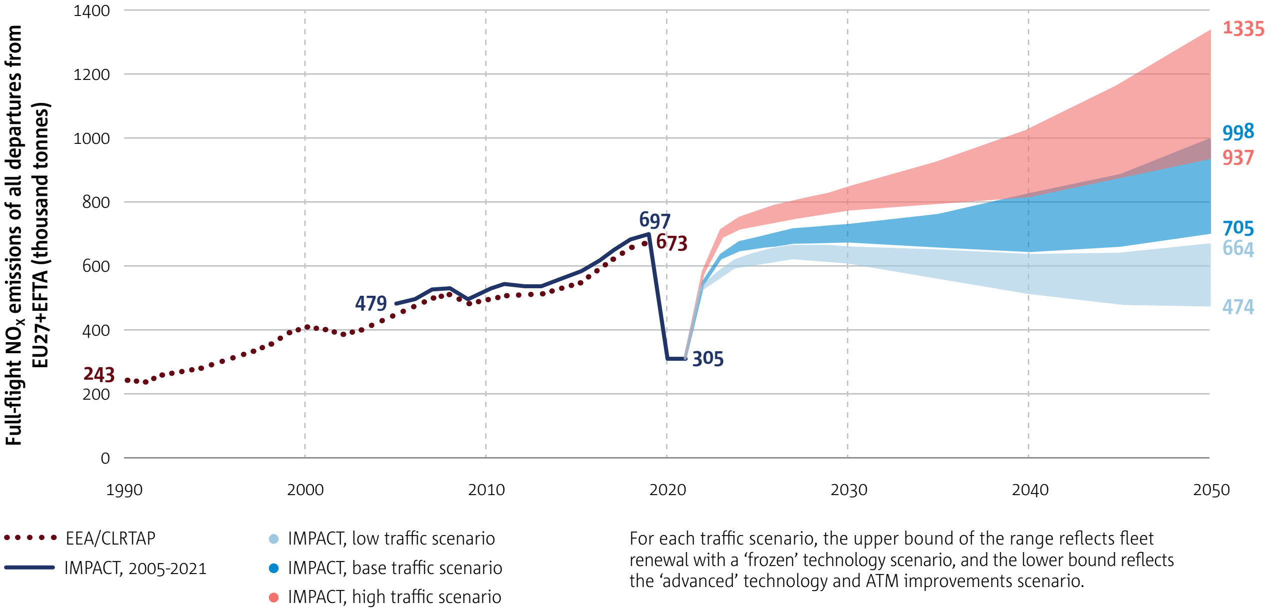


Assumptions:
- Infrastructure of each airport is unchanged (no new runway)
- Population distribution around airports is unchanged
- Local take-off & landing noise abatement procedures are not considered

For each traffic scenario, the upper bound of the range reflects fleet renewal with a 'frozen' technology scenario, and the lower bound reflects the 'advanced' technology scenario.

Indicator	Units	2005	2019	2020	2021
Number of people inside L_{den} 55 dB airport noise contours[4]	million	2.43	3.16	1.05	1.00
Average noise energy per flight[5]	10^9 Joules	1.22	1.30	1.21	1.15

EMISSIONS



For each traffic scenario, the upper bound of the range reflects fleet renewal with a 'frozen' technology scenario, and the lower bound reflects the 'advanced' technology and ATM improvements scenario.

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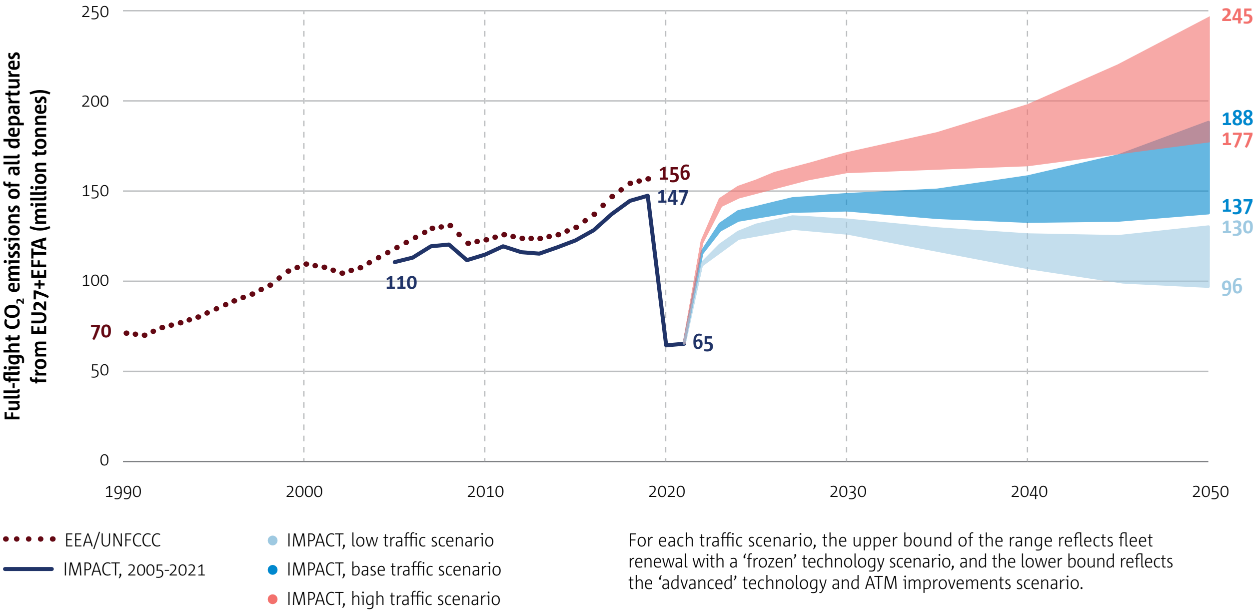
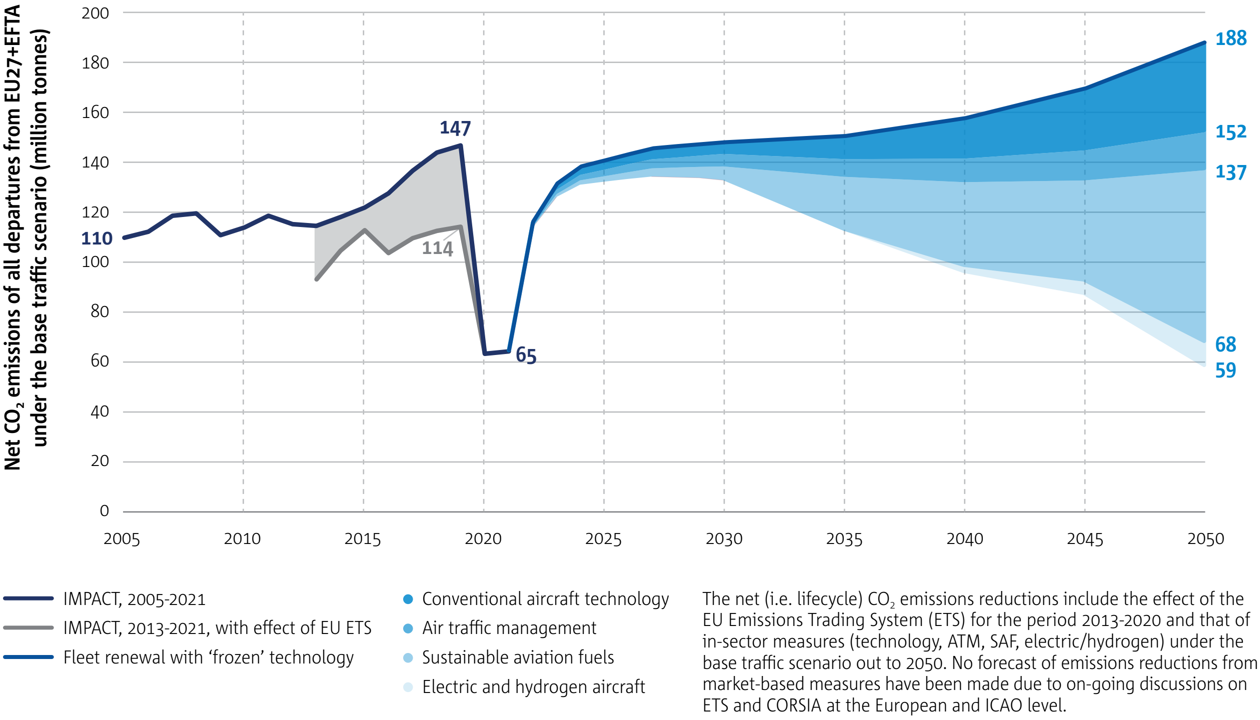
[4] 98 major European airports.

[5] All EU27+EFTA airports.



For each traffic scenario, the upper bound of the range reflects fleet renewal with a ‘frozen’ technology scenario, and the lower bound reflects the ‘advanced’ technology and ATM improvements scenario.



The net (i.e. lifecycle) CO_2 emissions reductions include the effect of the EU Emissions Trading System (ETS) for the period 2013-2020 and that of in-sector measures (technology, ATM, SAF, electric/hydrogen) under the base traffic scenario out to 2050. No forecast of emissions reductions from market-based measures have been made due to on-going discussions on ETS and CORSIA at the European and ICAO level.

Indicator[6]	Units	2005	2019	2020	2021
Full-flight CO_2 emissions	million tonnes	110	147	64	65
Full-flight ‘net’ CO_2 emissions with ETS reductions	million tonnes	110	114	64	65
Full-flight NO_X emissions	thousand tonnes	479	697	306	305
Average fuel consumption	litres fuel per 100 passenger kilometre	4.8	3.5	4.8	N/A

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[6] All departures from EU27+EFTA

KEY MESSAGES

Overview of Aviation Sector

- The number of flights at EU27+EFTA airports increased by 15% between 2005 and 2019 to 9.3 million, while passenger kilometres almost doubled (+90%). However, flights declined to just 5.1 million in 2021 due to the COVID-19 pandemic.

- At 98 major European airports during 2019, 3.2 million people were exposed to L_{den} 55 dB aircraft noise levels and 1.3 million people were exposed to more than 50 daily aircraft noise events above 70 dB. This is 30% and 71% more than in 2005 respectively.

- The top 10 airports in terms of L_{den} 55 dB population exposure in 2019 accounted for half of the total population exposure across the 98 major European airports.

- The CO_2 emissions of all flights departing from EU27+EFTA airports reached 147 million tonnes in 2019, which was 34% more than in 2005.

- Long-haul flights (above 4,000 km) represented approximately 6% of departures during 2019 and half of all CO_2 and NO_X emissions.

- Single-aisle jets had the larger share of flights and noise, but twin-aisle jets had the larger share of fuel burn and emissions.

- The average grams CO_2 emitted per passenger kilometre went down by an average 2.3% per annum to reach 89 grams in 2019, equivalent to 3.5 litres of fuel per 100 passenger kilometres.

- In 2020, due to the COVID-19 pandemic, emissions reduced by more than 50% and population exposure to noise fell by about 65%, while the average grams CO_2 emitted per passenger kilometre increased back to 2005 level.

- Fleet renewal could lead to reductions in total noise exposure at European airports as measured by the L_{den} and L_{night} indicators over the next twenty years.

- In 2050, it is predicted that in-sector measures could reduce CO_2 emissions by 69% to 59 million tonnes compared to a business-as-usual “technology freeze” scenario (19% from Technology/Design, 8% from ATM-Ops, 37% from SAF and 5% from electric/ hydrogen aircraft).

Aviation Environmental Impacts

- To mitigate adverse effects from aircraft noise on EU citizens' health, the World Health Organisation Europe recommends reducing aircraft noise levels below L_{den} 45 dB and L_{night} 40 dB.

- Air pollutant emissions from aviation have increased within the EU. Effective action requires better characterisation of aviation's specific contribution compared to other sources of emissions, especially on particulate matter.

- The growth in aviation CO_2 emissions was accelerating prior to COVID-19, with almost half of global CO_2 emissions between 1940 and 2019 having occurred since 2000.

- In 2018, the estimated Effective Radiative Forcing from non-CO_2 emissions accounted for more than half (66%) of the aviation net warming effect, although the level of uncertainty from the non-CO_2 effects is 8 times larger than that of CO_2.

- Environmental certification standards already exist for aircraft engine non-CO_2 emissions, including NO_X and nvPM, and further mitigation policy options are being considered.

- Where specific mitigation measures incur trade-offs between CO_2 and non-CO_2 emissions, a robust assessment methodology is essential to ensure an overall reduction in climate impact. In addition, 'win-win' options that reduce both simultaneously should be supported (e.g. appropriate sustainable aviation fuels).

- In 2022, the IPCC 6th Assessment Report noted that immediate, rapid and large-scale reductions in greenhouse gas emissions are needed to limit warming to 1.5°C and that the aviation sector is still in the earlier stages of adaptation to increased climate hazards.

Technology and Design

- New aircraft designs certified during the last 10 years (e.g. Airbus A320neo, A350 and Boeing 737MAX, 787) have a cumulative margin of 5 to 15 EPNdB below the latest Chapter 14 noise standard.

- While certification activities have recently reduced for conventional aircraft, they have increased in new market segments (e.g. Drones, Urban Air Mobility).

- EASA is developing dedicated noise certification standards for Drone and Urban Air Mobility aircraft that take into account their specific characteristics.

- In-production engine types were designed prior to the new non-volatile Particulate Matter (nvPM) standards and manufacturers are evaluating how to mitigate nvPM emissions in new engine designs.

- The engine NO_X/nvPM standards, and the aircraft noise/CO_2 standards, define the design space for products to simultaneously address noise, air quality and climate change issues.

- Pipistrel Velis Electro became the first fully electric general aviation aircraft to be certified by EASA in 2020 and is now being used by pilots to learn to fly.

- In 2021, the Airbus A330-900neo was the first aircraft to be approved worldwide against the new aeroplane CO_2 emissions standard, although certified aeroplane CO_2 data remains limited.

Sustainable Aviation Fuels

- Current SAF supply remains low at less than 0.05% of total EU aviation fuel use.

- The European Commission has proposed a SAF blending mandate for fuel supplied to EU airports, with minimum shares of SAF gradually increasing from 2% in 2025 to 63% in 2050, and a sub-mandate for Power-to-Liquid SAF.

- To achieve this mandate, approximately 2.3 million tonnes of SAF would be required by 2030, 14.8 million tonnes by 2040, and 28.6 million tonnes by 2050.

- Drop-in SAF will play a key part in decarbonising the aviation sector as they can be used within the existing global fleet and fuel supply infrastructure.

- Currently certified SAF are subject to a maximum blending ratio of 50% with fossil-based jet fuel depending on the feedstock-production pathway considered, but industry and fuel standard committees are looking into the future use of 100% SAF by 2030.

- SAF are certified by Sustainability Certification Schemes against criteria defined at EU level in the Renewable Energy Directive and at global level in the CORSIA framework.

- While SAF are currently more expensive than fossil-based jet fuel, cost savings are expected notably through future production economies of scale. SAF prices can vary depending on the production pathway, associated production costs and fluctuations in the energy market.

Air Traffic Management and Operations

- The European Green Deal requires a more ambitious, comprehensive and holistic approach involving all stakeholders to accelerate solutions to enable greener operations in the short term.

- In 2019, excess fuel burn on an average flight by flight basis within the Network Manager area was estimated to be between 8.6% (XFB10)[7] to 11.2% (XFB5), with excess fuel burn decreasing as the flight distance increases.

- The European ATM Master Plan, managed by SESAR 3 Joint Undertaking, defines a common vision and roadmap for ATM stakeholders to modernise and harmonise European ATM systems, including an aspirational goal to reduce average CO_2 emission per flight by 5-10% (0.8-1.6 tonnes) by 2035 through enhanced cooperation, compared to 2017.

- Single European Sky (SES) union-wide environment targets were not reached during the entire Reference Period 2 (RP2) (2015-2019), with performance worsening in the second part of RP2. In 2020, whilst performance did improve, several Member States still did not achieve their environment targets despite the dramatic drop in traffic due to the pandemic.

- The KPI reflecting the relationship between flight routing and environmental impact is considered inadequate and needs to be re-evaluated, taking into account environmental indicators based on actual CO_2 emissions.

- As traffic returns to pre-COVID levels, efficiency improvements observed in 2020 should be maintained through ‘green’ recovery principles such as dynamic use of airspace constraints that are only applied when justified and the use of optimised flight planning by aircraft operators.

- It was estimated that, in 2018, 21% of European Civil Aviation Conference (ECAC) flights performed fuel tankering, representing a net saving of €265 million per year for the airlines, but burning an unnecessary 286,000 tonnes of additional fuel (equivalent to 0.54% of ECAC jet fuel used).

Airports

- In 2020, EASA launched the Environmental Portal to facilitate sharing of Aircraft Noise Certificate information together with the ANP Database for sharing Aircraft Noise and Performance data.

- During 2020, approximately 50% of operations in Europe were by aircraft compliant with the latest Chapter 14 noise standard.

- There are significant delays in approving and implementing the Performance Based Navigation transition plans, which in turn delays the achievement of environmental benefits.

- As the aviation sector evolves to respond to environmental challenges, and new market segments are created, airport infrastructure also needs to adapt accordingly.

- By 2030, the European Green Deal’s Zero Pollution Action Plan aims to reduce the share of people chronically disturbed by transport noise by 30% and improve air

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[7] The 10th percentile (XFB10) reference means in effect that for a city pair / aircraft type combination 90% of flights burnt more fuel than the reference and 10% of flights burnt the equivalent or less fuel.

quality to reduce the number of premature deaths caused by air pollution by 55% (compared to 2017).

- In 2020, the Airport Carbon Accreditation Programme added Levels 4 (Transformation) and 4+ (Transition) to support airports in achieving net zero CO_2 emissions and to align it with the objectives of the Paris Agreement.

Market-Based Measures

- During 2013-2020, the EU Emissions Trading System led to a total reduction in aviation net CO_2 emissions of 159 Mt (approximately equivalent to the annual emissions of the Netherlands in 2018) through funding of emissions reductions in other sectors.

- Monitoring, reporting and verification of CO_2 emissions under the ICAO Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA) began in 2019. 88 States volunteered to participate in the CORSIA offsetting pilot phase from 2021, including all EU and EFTA States. This has increased to 107 States in 2022 and represents a majority of ICAO Member States.

- The environmental integrity of offsets depends on their ability to demonstrate that the emissions reductions would not have occurred in the absence of the market mechanism that funds the offset.

- At COP26 in 2021, accounting rules under the Paris Agreement were agreed for international transfers of carbon market units, including the avoidance of double-counting of emission reductions in respect of CORSIA and nationally determined contributions by countries under the Climate Change Convention.

- International cooperation is key in building capacity to address the global environmental and sustainability challenges facing the aviation sector. EU funded action has enhanced the relationship with partner States on implementing CORSIA and other areas of environmental protection.

- Other measures linked to carbon pricing initiatives that are relevant for the aviation sector are being discussed in Europe.

RECOMMENDATIONS

The following recommendations from EASA and EEA build on the information and analysis within the European Aviation Environmental Report (EAER) 2022. They aim to improve the level of environmental protection in the area of civil aviation and assist the European Union in ensuring that the aviation sector contributes to the objectives of the European Green Deal[8] through effective collaboration, commitment and verification.

Supporting the achievement of European environmental objectives

- To establish long-term noise and emissions reduction pathways and aspirational goals for European aviation in terms of in-sector (e.g. technology, operations, fuels) and out-of-sector (e.g. market-based) mitigation measures.
  - — Support the European Green Deal objectives:
    - At least 55% reduction in economy-wide net greenhouse gas emissions by 2030, compared to 1990 levels, and a goal of climate neutrality by 2050.
    - 90% reduction in transport-related greenhouse gas emissions by 2050 compared to 1990 levels.
    - 30% reduction in the share of people chronically disturbed by transport noise by 2030 compared to 2017.
    - Improvement in air quality to achieve a 55% reduction in the number of premature deaths caused by air pollution by 2030 compared to 2005, including near airports by tackling the emissions of pollutants from aeroplanes and airport operations.
  - — Strengthen the aviation sector's commitment in planning the necessary investments for the transition to a sustainable and climate-neutral economy.

- To enhance information underpinning the EAER and ensure a robust EU monitoring system on the environmental performance of the European aviation sector in support of the implementation of EU legislation and policy objectives, and to help verify the achievement of these objectives.
  - — Enhance datasets and analytical capabilities to provide an objective, comprehensive, transparent and accurate oversight of the historic and forecasted progress towards goals.

Integrating effective environmental measures into the European Air Traffic Management system

- To enhance implementation of the Single European Sky (SES) by the Network Manager, Air Navigation Service Providers (ANSPs), airports and other service providers[9], with a view to enable and incentivise airspace users to fly 'green' flight trajectories.
  - — Promote cross-border solutions and minimise network restrictions.

- To further explore economic incentives that encourage greater efficiency and improved environmental performance from airspace users, such as common unit rates and the modulation of Air Navigation Service charges.

- To develop environmental metrics that better reflect the environmental performance of ANSPs subject to the SES Performance Scheme, as well as other relevant stakeholders.

Scaling up the supply and use of Sustainable Aviation Fuels

- To explore the feasibility of putting in place a long-term coherent support structure to ensure the successful introduction of new SAF production pathways in Europe with high potential for emission reductions.
  - — Establish an EU Clearing House to support SAF producers through the fuel approval process and investigate an EU Fuel Standard to ensure robust certification processes that support environmental protection objectives.

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[8] The European Green Deal encompasses in particular the European Climate Law, the Sustainable and Smart Mobility Strategy and the Zero Pollution Action Plan.

[9] For example, Providers of Data Services (PDS), European Satellite Service Providers (ESSP), European aeronautical information services database (EAD).

  - Advance approvals of higher SAF blends up to 100%, based on a diverse mix of feedstocks. Different types of SAF may support different aviation market segments in the medium term.

- To consider the use of the EU ETS Innovation Fund to support higher-risk SAF production investments, and other mechanisms that incentivise the uptake of SAF.

Promote research and identify solutions to address environment and climate impacts as well as build climate change resilience

- To respond to the IPCC 6th Assessment Report which states that aviation sector is a key vulnerable economic sector that is only in the early stage of adaptation to climate change.
  - Coordinate and enhance understanding on the hazards and risks to the aviation sector from climate impacts and extreme weather events.
  - Integrate climate adaptation and resilience considerations into planning processes, future investments and criteria applicable to the design of products and critical infrastructure.

- To coordinate and perform further research on the overall climate impact of aviation, including non-CO_2 emissions and contrail-cirrus cloud formation, that reduces scientific uncertainties and informs cost-effective actions.
  - Identify and apply 'win-win' solutions that reduce both CO_2 and non-CO_2 emissions and, where necessary, assess trade-offs from mitigation measures using a robust assessment methodology to ensure an overall reduction in climate and air quality impacts from aviation (e.g. changes to fuel specifications such as lower aromatics and/or sulphur, 'green' flight trajectories and use of Sustainable Aviation Fuels).

- To accelerate the development and deployment of technological and ATM solutions, in collaboration with key partners, to improve the environmental performance of the European and global fleet.

Incentivise technological innovation through continued international cooperation on regulatory standards

- To assess the environmental impact from new market segments (e.g. drones, urban air mobility, supersonic), and develop certification standards that ensure a high and uniform level of environmental protection which facilitates their integration into the aviation system.

- To develop, based on latest data, more stringent regulatory limits for existing ICAO environmental certification standards that are technologically feasible, economically reasonable and environmentally beneficial.

Fostering green airport operations and infrastructure

- To keep Performance-Based Navigation (PBN) transition plans up-to-date and fully implement them in line with the applicability dates of EU Regulation 2018/1048 on airspace usage requirements and operating procedures.
  - Assess and optimise the environmental benefits (noise and emissions) from PBN implementation when preparing transition plans.

- To incentivise and enable the development and implementation of necessary green airport infrastructure and operations (e.g. standards on supply of SAF / hydrogen / electrification).

- To promote Airport Noise Action Plans that mitigate adverse effects from aircraft noise on citizens' health by moving towards aircraft noise levels recommended by the World Health Organisation for the European Region.

Promoting investments and Market Based Measures to enhance the sustainability of aviation

- To ensure the environmental credibility of voluntary and compliance-based carbon credits used in offsetting or reducing emissions within the aviation sector.

- To continue the progressive inclusion of the costs from aviation environmental and climate impacts within market prices.

- To encourage the use of the EU Taxonomy system to incentivise sustainable investment within the aviation sector.

INTRODUCTION

Welcome to the third European Aviation Environmental Report (EAER)! The core aim of this report is to provide an objective, clear and accurate source of information on the environmental performance of the aviation sector at the European level every three years.

Europe's aviation sector is strategically important and provides significant benefits through connectivity, employment and the wider economy. However, this license to operate is dependent on its ability to address the negative effects (noise, air quality and climate change) of its business on the health and quality of life for European citizens. This is especially so on climate change, which is considered by Europeans to be the single most serious problem facing the world [1, 2, 3]. Consequently, environmental protection is a key strategic priority for the aviation sector, where the future of the industry will depend on how it reacts to the climate crisis during this decisive decade.

What is the environmental performance of the European aviation sector?

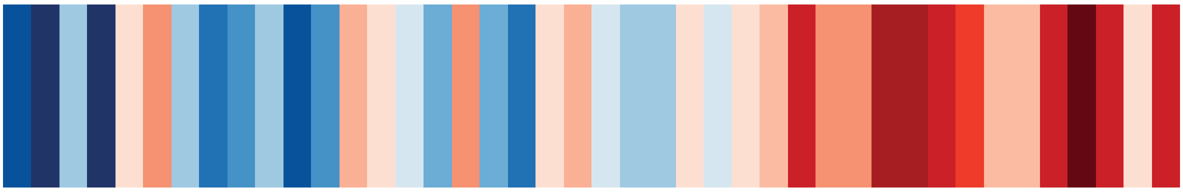
How might the sector's performance evolve in the future?

What measures are reducing climate change, noise and air quality impacts?

How can the sector further improve its level of environmental protection?

Aviation Warming Stripes

Based on a recent study that quantified aviation's contribution to global warming [4], the below aviation 'warming stripes' have been developed with the aim of communicating a complex message in a visually simple and memorable way that people can relate to. Warming stripes typically communicate on the impact of global warming in terms of changes in average surface temperature over time at the global or national level [5]. In comparison, the colours of the aviation warming stripes below represent the modelled % contribution of aviation emissions to overall global warming (temperature increase against a pre-industrial baseline) on an annual basis between 1980 (1.9% on left) and 2021 (3.7% on right).



The race to net zero aviation CO_2 emissions through a recent multitude of State and Industry commitments underlines the urgency [6, 7, 20, 21, 22], and these emissions reductions now need to be delivered to ensure the Paris Agreement target of limiting the temperature increase to 1.5°C remains a possibility. Harnessing public and private finance to put into action this shared vision and goal is imperative.

The EAER acts as a reference document by monitoring past performance and forecasted future developments to inform strategic discussions on progress towards agreed goals and how the environmental performance of the aviation sector can be improved. This supports the prioritisation of future work and resources (policy, legislative, operational, research) to effectively coordinate a comprehensive approach across different initiatives and address the issue of sustainability, which is the defining challenge for aviation in the 21st Century.

Innovative and smart solutions on environmental sustainability have historically been driven by Europe, both at a regional and global level. The changes resulting from the green transition will include some turbulent times, but it is also an opportunity for the European aviation sector to position itself such that it increases its competitiveness in this new green economy. Continued active engagement will also be required to attract the next generation of highly skilled personnel needed to develop and implement these solutions to the environmental challenges. The status in this on-going transition is summarised in the various Chapters of this report.

European policy on noise and air quality

In 2021, the European Union (EU) adopted the Zero Pollution Action Plan [8] that set out a vision to reduce air, water and soil pollution to levels no longer considered harmful to health and natural ecosystems by 2050. Key intermediate 2030 targets, compared to 2017 levels, have also been identified to: (1) reduce pollution at source, including the reduction of the share of people chronically disturbed by transport noise by 30% and (2) improve air quality to reduce the number of premature deaths caused by air pollution by 55%.

The Environmental Noise Directive [9] and the Balanced Approach Regulation [10] are the EU legislation under which environmental noise is monitored, communicated to the public and actions subsequently taken by Member States to reduce noise exposure in cities and near major transport infrastructure. EU air pollution legislation is implemented through both air quality standards [11, 12] and source-based mitigation controls (e.g. engine emissions and fuel quality standards). Binding national limits for emissions of the most important pollutants have also been established in the EU, but not all aviation activities are included [13].

European policy on climate change

In 2019, the European Commission presented the European Green Deal [14], which aims at improving the well-being of people and making Europe climate-neutral by 2050. The 2021 European Climate Law [15] incorporated this goal into legislation, such that EU institutions and Member States are bound to take the necessary measures at EU and national level to meet the target, taking into account the importance of promoting fairness and solidarity among Member States. The Climate Law includes:

- a legal objective for the Union to reach climate neutrality by 2050; and
- an ambitious 2030 climate target of at least 55% reduction of net emissions of greenhouse gases as compared to 1990, with clarity on the contribution of emission reductions and removals.

The Green Deal includes a goal to reduce emissions from the transport sector by 90% in 2050 compared to 1990 levels. In 2020, specific objectives on mobility and transport were subsequently presented in the Sustainable and Smart Mobility Strategy [16] together with an Action Plan of 82 initiatives that will guide its work. This strategy lays the foundation for how a smart, competitive, safe, accessible and affordable EU transport system can achieve its green and digital transformation and become more resilient to future crises. All transport modes need to become more sustainable, with concrete milestones to keep the green transition on track.

In 2021, the ‘Fit for 55’ legislative proposals [17] were published setting out the ways in which the Commission will reach its updated 2030 target in real terms (see previous page). It covers a wide range of policy areas, some of which effect the aviation industry (e.g. revision of the EU Emission Trading System Directive concerning aviation, ReFuelEU Aviation Initiative, revision to the Renewable Energy Directive and revision to the Energy Taxation Directive).

UN Sustainable Development Goals

In 2015, the United Nations agreed on the Agenda for Sustainable Development, with 17 overarching Sustainable Development Goals (SDGs) at its core [18]. The SDGs are a blueprint to achieve a better and more sustainable future for all people and the world by 2030, with priorities such as good health and well-being, and climate action. These goals are taken as important guidelines for public policy and industry strategy across the world, including within the EU [19].

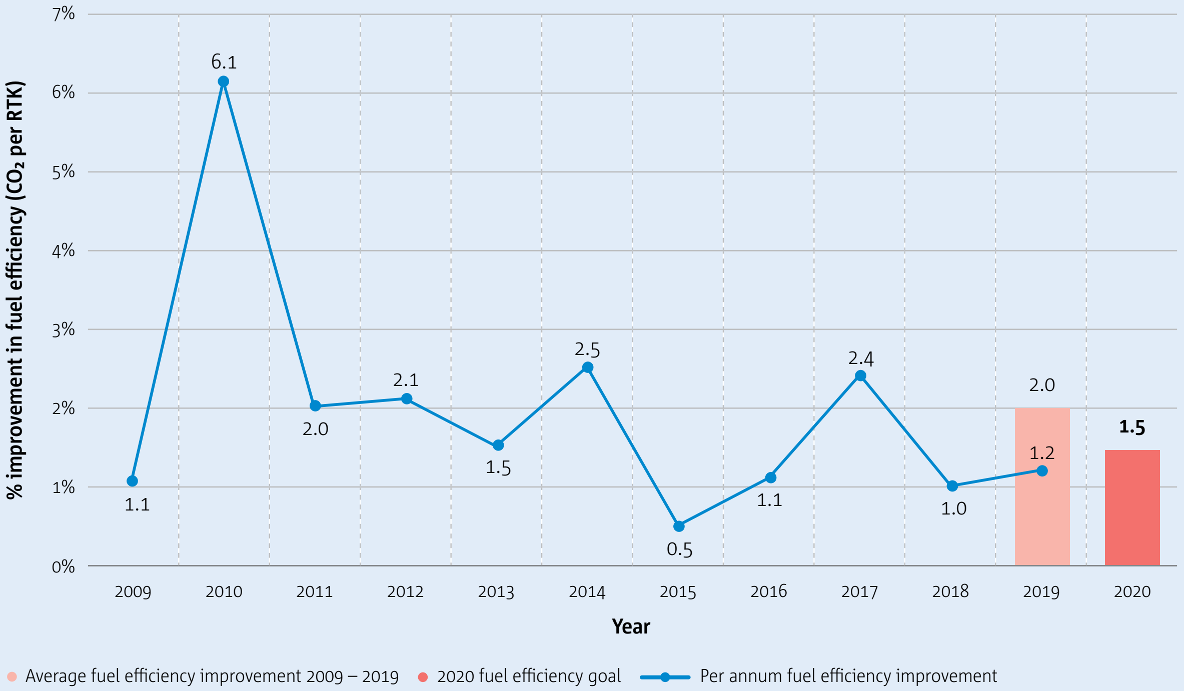
STAKEHOLDER ACTIONS

Industry goals on climate change 2009-2020

In 2008 the global stakeholder associations of the aviation industry (ACI, CANSO, IATA, ICCAIA), committed to addressing the global challenge of climate change and adopted a set of targets to mitigate CO_2 emissions from air transport:

- A cap on net aviation CO_2 emissions from 2020 (carbon-neutral growth)
- A reduction in net aviation CO_2 emissions of 50% by 2050, relative to 2005 levels
- An average improvement in fuel efficiency (CO_2 per Revenue Tonne Kilometre) of 1.5% per year from 2009 to 2020.

The figure below provides an overview of the progress towards the goal on fuel efficiency with an average improvement of 2.0% per year during 2009-2019 compared to a goal of 1.5% (source: IATA).



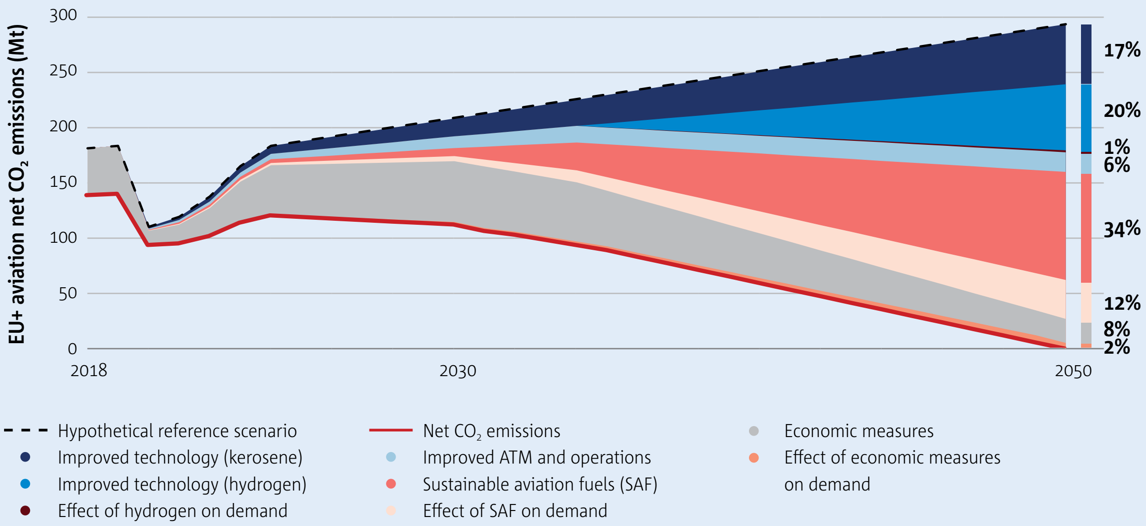
Destination 2050 – A route to net zero European aviation

In the spring of 2021, five European associations representing airlines, manufacturers, airports, and air service navigation providers published the Destination 2050 report [20]. It outlines a roadmap for the aviation sector, in collaboration with regulators, to decarbonise significantly by 2030 and reach net zero CO_2 emissions by 2050, and has committed the sector to:

DESTINATION 2050

- Assessing the feasibility of making 2019 the peak year for absolute CO_2 emissions from flights within and departing from the EU.
- Reducing net CO_2 emissions from all flights within and departing from the EU by 45% in 2030 compared to the hypothetical reference scenario.
- Reaching net zero CO_2 emissions by 2050 from all flights within and departing from the EU.

As illustrated in the figure below, these commitments can be achieved via a combination of measures. Impacts on demand due to the cost implications of the measures and the related CO_2 emissions reductions were also considered.



Results are presented for all flights within and departing from the the EU region (EU27+UK+EFTA). Improving aircraft and engine technology, ATM and aircraft operations, SAF and economic measures all hold decarbonisation potential. Modelled for 2030 and 2050, the impacts are linearly interpolated. The base year for this study is 2018.

Aircraft and engine technology improvements are expected to include hydrogen-powered aircraft on intra-EU routes from 2035 onwards; a step-change in energy efficiency from new aircraft types in the next ten years; and optimised range and capacity of hybrid-electric aircraft. This will require a high level of technology readiness by 2027–2030, new certification procedures for disruptive technologies, and accelerated fleet renewal.

Improvements in air traffic management and aircraft operations could be realised by 2035 through the implementation of the Single European Sky that moves towards a network-centric and digital ATM system, accelerated innovation and rapid decarbonisation of ground operations.

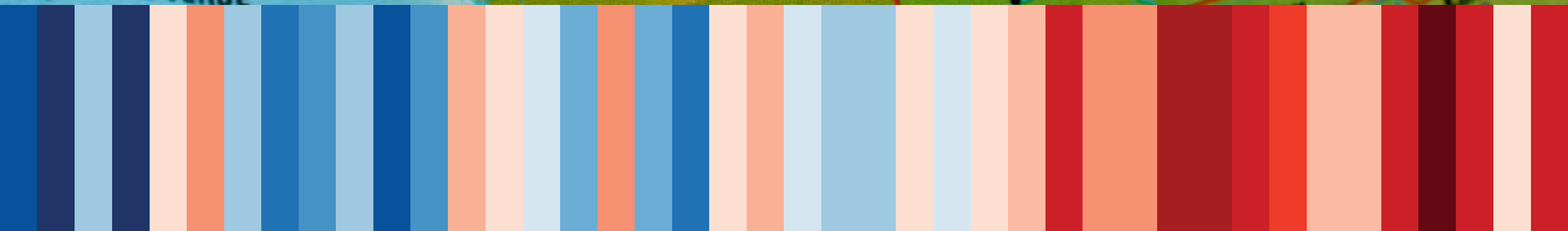
The supply of sustainable aviation fuel (SAF) is expected to account for 83% of the total fuel consumption in 2050. However, to make this a reality, SAF production and deployment must be scaled up whilst ensuring robust and transparent sustainability criteria and a diversified and sustainable feedstock base. An increase in the maximum blending ratio from 50 to 100% is also required.

Finally, market-based measures (MBMs) are crucial in the short term (e.g. EU ETS, ICAO CORSIA). By 2030, MBMs could be responsible for 27% of CO_2 reductions, while by 2050, as the sector relies more on in-sector reductions, MBMs could be responsible for 8% of CO_2 reductions. Until then, the EU ETS should be strengthened to be in line with the Paris Agreement targets and carbon credits under CORSIA must be of the highest quality.

Similar commitments by the aviation sector at the global level have also been made in the ATAG Waypoint 2050 report [21, 22].

1


Danimarka
Reykjavik
İZLANDA
Norveç Denizi
Föroyar Adl. (Dan.)
Torshavn
Shetland Adl.
Orkney Adl.
NORVEÇ
İSVEÇ
Oslo
Stokholm
Göteborg
Baltık Denizi
Tallinn
ESTONYA
Riga
LETONYA
LİTVANYA
Vilnius
Minsk
BELARUS
Kaliningrad
Rus Fed.
Kuzey Denizi
Edinburgh
Kopenhag
DANİMARKA
Varşova
POLONYA
Belfast
İNGİLTERE
HOL.
Amsterdam
Berlin
İRLANDA
ALMANYA
ÇEK CUM.
Prag
SLOVAKYA
Bratislava
Budapeşte
MAC.
Londra
Brüksel
BELÇİKA
LÜKS.
Lüks.
LIECH.
Vaduz
Viyana
AVUS.
Lübliyana
Zagreb
Belgrad
SIRB.
İngiliz Kanalı
Paris
Seine N.
İSVİÇRE
Bern
Alp Dağları
SLOV.
HIRV.
Saraybosna
B.H.
KAR.
Podgorica
FRANSA
Cenevre
MON.
Monte Carlo
Adriyatik Denizi
Roma
İTALYA
Bilbao
Pireneler
AND.
Andorra la Vella
Korsika Ad.
Tiren Denizi
Palermo
Sicilya Ad.
Sardinya Ad.
Madrid
Barcelona
Balearea Adl.
A K D E
İSPANYA
Annaba
Tunus
Valletta
MALTA
Miguel Ad.
Ponta Delgada
Santa Maria Ad.
Sevilla
Oran
Cezayir
Constantine
Cerid G.
Gabes
Trablus
TUNUS
Cebelitarık (İng.)
Cebelitarık Bğ.
Rabat
Fes
Touggourt
Ghadamis
MADEİRA (Por.)
Funchal
Casablanca
Yukarı Atlaslar
Kanarya Adl. (İsp.)
FAS
Marrakeş
Tademait Platosu
La Palma Ad.
Tenerife Ad.
Gran Canaria Ad.
Tindouf
İn Salah
Hoggar
Laayoune
Oğlak Dönencesi
BATI SAHRA
Büyük Sahra
Tenere
Fderik
Tessalit
Agadez
Beyaz Br.
MORİTANYA
MALİ
Gao
Tahoua
Zinder
CAPE VERDE

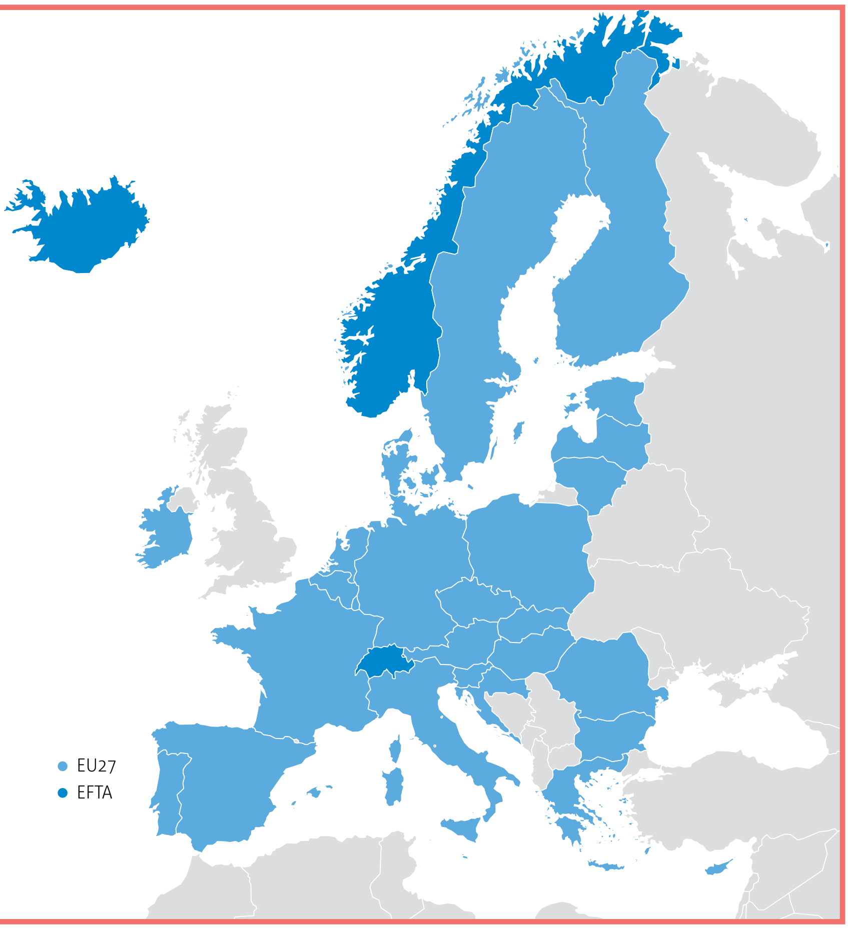


OVERVIEW OF AVIATION SECTOR

- The number of flights at EU27+EFTA airports increased by 15% between 2005 and 2019 to 9.3 million, while passenger kilometres almost doubled (+90%). However, flights declined to just 5.1 million in 2021 due to the COVID-19 pandemic.
- At 98 major European airports during 2019, 3.2 million people were exposed to L_{den} 55 dB aircraft noise levels and 1.3 million people were exposed to more than 50 daily aircraft noise events above 70 dB. This is 30% and 71% more than in 2005 respectively.
- The top 10 airports in terms of L_{den} 55 dB population exposure in 2019 accounted for half of the total population exposure across the 98 major European airports.
- The CO_2 emissions of all flights departing from EU27+EFTA airports reached 147 million tonnes in 2019, which was 34% more than in 2005.
- Long-haul flights (above 4,000 km) represented approximately 6% of departures during 2019 and half of all CO_2 and NO_X emissions.
- Single-aisle jets had the larger share of flights and noise, but twin-aisle jets had the larger share of fuel burn and emissions.
- The average grams CO_2 emitted per passenger kilometre went down by an average 2.3% per annum to reach 89 grams in 2019, equivalent to 3.5 litres of fuel per 100 passenger kilometres.
- In 2020, due to the COVID-19 pandemic, emissions reduced by more than 50% and population exposure to noise fell by about 65%, while the average grams CO_2 emitted per passenger kilometre increased back to 2005 level.
- Fleet renewal could lead to reductions in total noise exposure at European airports as measured by the L_{den} and L_{night} indicators over the next twenty years.
- In 2050, it is predicted that in-sector measures could reduce CO_2 emissions by 69% to 59 million tonnes compared to a business-as-usual “technology freeze” scenario (19% from Technology/Design, 8% from ATM-Ops, 37% from SAF and 5% from electric/hydrogen aircraft).

Analysis scope and assumptions

Historical air traffic data in this section comes from Eurostat and EUROCONTROL. The coverage is all flights from or to airports in the European Union (EU27)[10] and European Free Trade Association (EFTA). The forecast of European flights comes from the EUROCONTROL Aviation Outlook[11] (EAO) [9]. For more details on models, analysis methods, forecasts, supporting data sources and assumptions used in this section, please refer to Appendix C.



1.1 AIR TRAFFIC

Flights peaked in 2019 prior to COVID-19, and recovered to just 55% of that peak in 2021

Continuing the trend reported in the last report, the recovery after the 2008 financial crisis led to a new record high of 9.25 million flights in 2019 at EU27+EFTA airports (Figure 1.1). Passenger numbers also peaked in 2019, with more than 800 million passengers flying from EU27+EFTA airports. This passenger growth was driven by increased flights, the use of larger aircraft and a record load factor of 83.3%. The combination of these factors led to the number of passengers per flight increasing by 51% in 2019 compared to 2005. In addition, with longer-distance flying continuing to grow more quickly than short-distance, the passenger kilometres flown nearly doubled. The volume of cargo transported from EU27+EFTA airports increased by 60% between 2005 and 2019, which was less than the increase in passengers (Figure 1.7).

Passenger travel came almost to a halt in early 2020 as COVID-19 spread around the world and restrictions were put in place curtailing travel and grounding flights. The number of daily flights in Europe fell to just 12% of 2019 volumes in April 2020 (Figure 1.2). A recovery was short-lived during the summer of 2020 as further waves of the pandemic arrived leading to more lockdowns. With the roll-out of vaccination programmes, Europe saw a rapid recovery of tourism and travel during the summer of 2021, which was consistent with high forecasts, though still with relatively little medium- to long-haul traffic. The recovery was unbalanced with some Mediterranean countries exceeding 2019 flight counts, while some northern countries remained at 50-60% of 2019 levels. Late 2021 saw another traffic downturn, triggered by the COVID-19 Omicron variant.

In response to the pandemic in 2020, airlines rapidly switched focus to repatriating stranded people and moving urgent cargo. Indeed, all-cargo airline operators

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[10] The geographical scope is constant through the entire time period covered in this Chapter. Consequently, the data does not include UK for those years preceding Brexit.

[11] The EAO was prepared before the start of the invasion of Ukraine by Russia. At the time of writing, the impact on traffic is high for some States adjacent to Belarus, Russian and Ukraine. However, the overall impact on the full European network remains relatively small. The focus of the EAO is 2050.

Figure 1.1 All-cargo and business aviation have taken a larger share of flights during the COVID-19 downturn

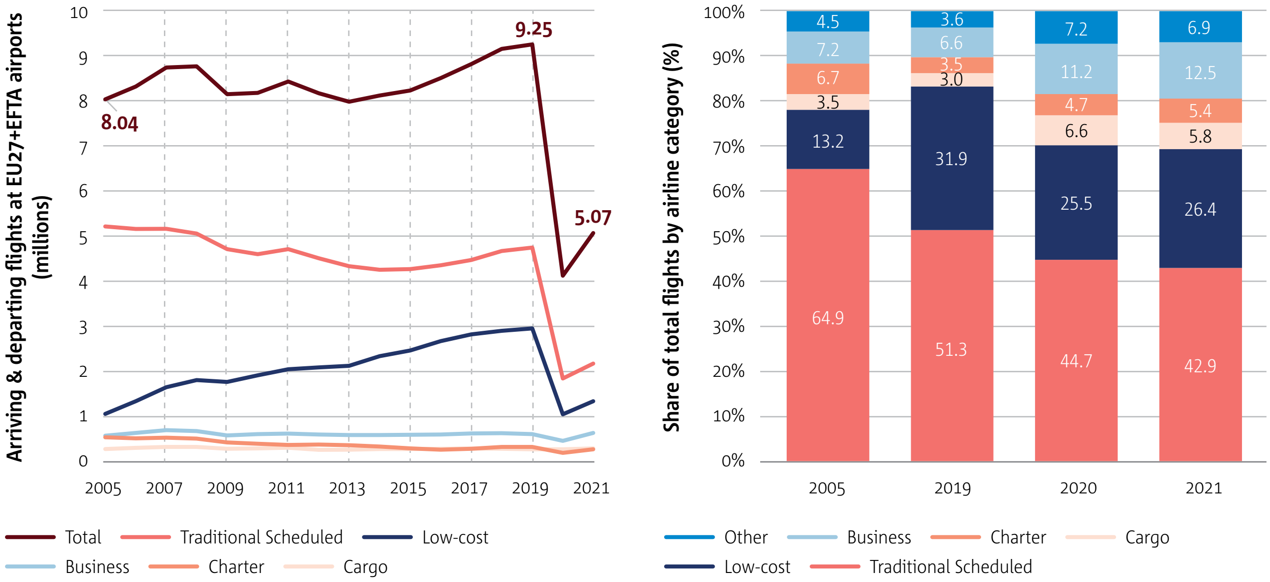
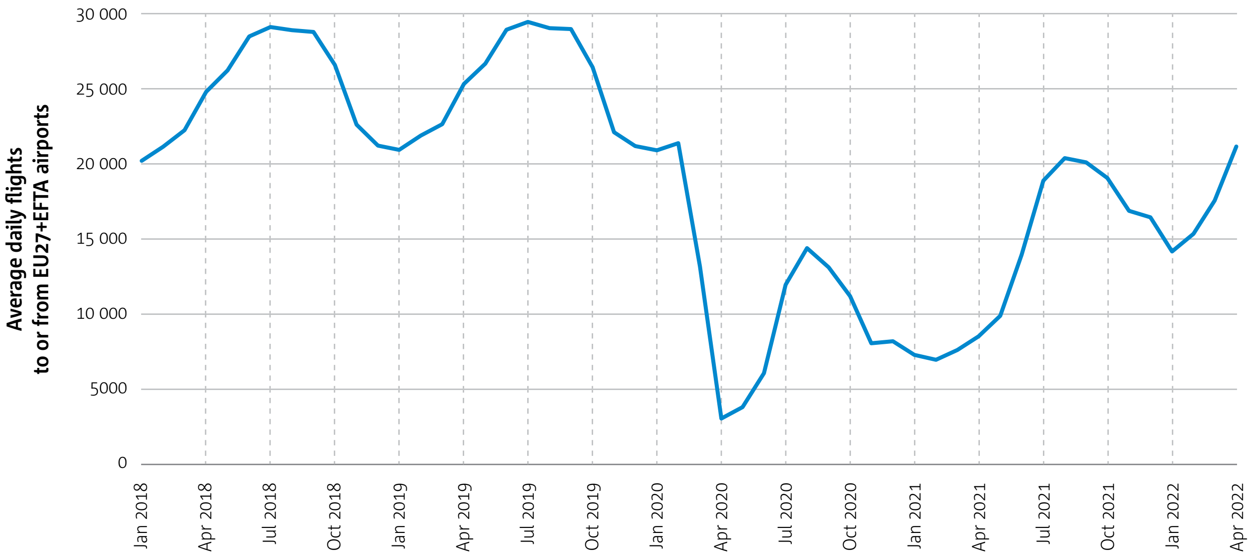


Figure 1.2 Summer 2021 traffic was about two thirds of pre-pandemic summer traffic



and business aviation largely escaped a decline in flights during 2020 and 2021, and consequently roughly doubled their market share (Figure 1.1). This does not take into account a significant number of passenger aircraft that were adapted for cargo use, while still being classified as 'traditional scheduled'. Domestic flights accounted for a larger share of the market, as they were less restricted than international travel. This was particularly relevant for countries such as Norway with its challenging geography and dispersed population that has a well-developed domestic aviation market.

The outlook is for a gradual recovery and then slower growth to 2050

The forecast out to 2050 includes three different scenarios for how Europe and European aviation might develop in the future (Figure 1.3). These scenarios take economic growth, sustainability goals and regulation into account, as well as airport capacity, high-speed rail and the arrival of new aircraft, fuel and propulsion. More details are provided in Appendix C. In the most-likely 'base' scenario flights recover from COVID-19 lows and then grow gradually towards 12.2 million flights at EU27+EFTA airports by 2050, which is an historically low average annual growth of 0.9% between 2019 and

2050. This represents around a 10-year delay in reaching the volume of flights described in the EAER 2019. The average annual growth rate of passenger kilometres between 2019 and 2050 is -0.3%, 1.1% and 1.7% for the low, base and high traffic scenarios respectively.

Connectivity held up better than flights in the face of COVID-19

Aviation delivers connectivity, and past editions of this report have described how the number of city pairs with a regular scheduled service had grown faster than flights. That trend continued into 2019 with the number of city pairs served increasing 51% since 2005 to 8,161 (Figure 1.4). Since flight growth was only 15% over the same period (Figure 1.1), that implies that many lower-frequency connections were added to the network. As Figure 1.4 shows, much of this growth came from low-cost carriers connecting 5,100 city pairs in 2019, while traditional scheduled carriers connected 4,500 city pairs. Indeed, low-cost carriers were already providing more connectivity by 2015.

Figure 1.3 **Following the recovery from the COVID-19 pandemic, numbers of flights are predicted to grow slowly out to 2050**

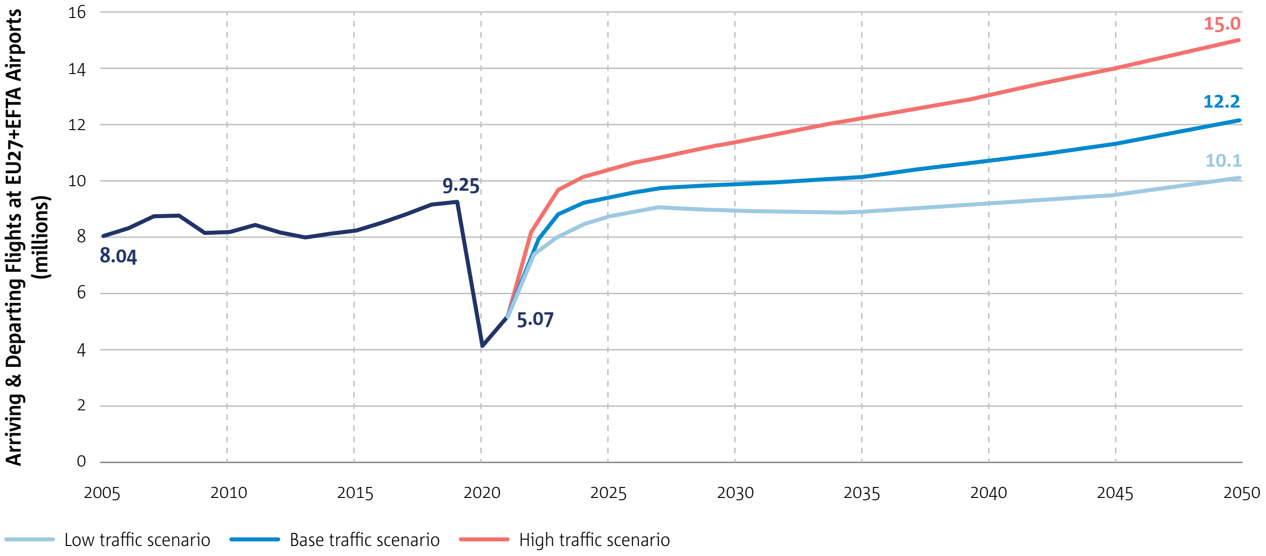
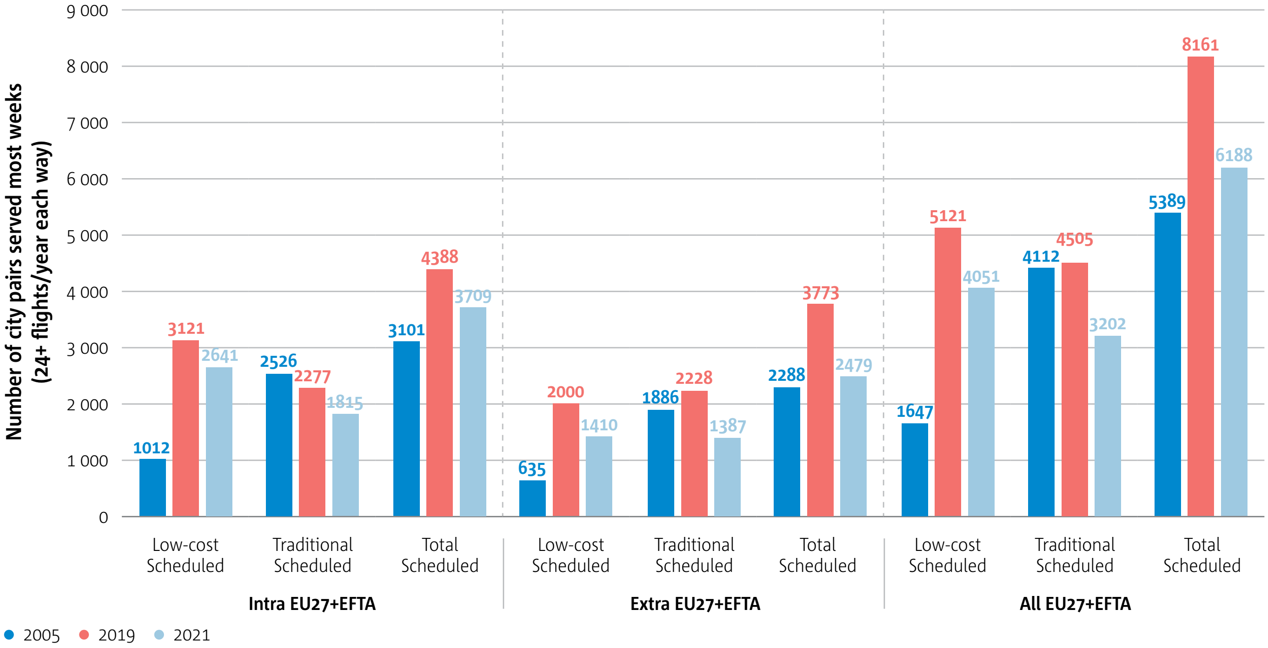


Figure 1.4 **Trend of increasing scheduled connectivity impacted by COVID-19 pandemic**



In the face of COVID-19, connectivity held up better (-24% in 2021 compared to 2019) than flights (-45% in 2021 compared to 2019). As flights were gradually re-introduced, many scheduled carriers prioritised the breadth of their network over the frequency of connections. This meant that passengers could still fly to their destination, but with less choice of departure times.

When comparing connections within Europe ('intra' EU27+EFTA) and between Europe and other regions ('extra' EU27+EFTA), the trends are similar. However, 'intra' connections offered by traditional scheduled carriers in 2019 have fallen by 10% compared to 2005, while 'extra' connections have increased 18%. This reflects the historic trend towards longer-distance flights and substitution by other transport modes over shorter distances.

Passenger fleet no longer ageing, but older cargo aircraft are lifting the average age of the total fleet

Depending on the market, an aircraft can remain in service for about 30 years. While an aircraft follows a specific maintenance cycle, its performance can degrade over time due to engine and aerodynamic deterioration, leading to additional CO_2 emissions [10]. Fleet renewal helps reduce aviation's environmental impact as newer aircraft tend to be more fuel-efficient and quieter, therefore the average age of the European fleet is a good indicator of its environmental performance. The previous two editions of this report indicated that the European fleet, particularly the passenger fleet, was gradually ageing. While airlines were adding new aircraft because of market growth and retiring older aircraft, they were not doing it quickly enough to prevent the average age from rising.

The grounding of the Boeing 737MAX aircraft in Europe from March 2019 until early 2021 led to an increase in the average fleet age due to the radically reduced supply of new aircraft. This may explain the slight acceleration in the ageing rate of low-cost carriers in 2019 (Figure 1.5). However, from 2020 this effect was outpaced by the impact of COVID-19. As during the financial crisis of 2008-2010, airlines responded to the impact of the pandemic in 2020-2021 by cutting costs, and grounding older and less-efficient aircraft.

The ranking of market segments by age is unchanged from previous reports: low-cost carriers have the youngest fleet on average, at 8.3 years in 2021, while charter and all-cargo have much older fleets, at nearly 22 years for all-cargo flights. While the passenger fleet (low-cost and traditional scheduled) was younger in 2021 than 2019, the increase in market share of cargo and business aviation has pushed the average age of the overall fleet up to 11.6 years.

Figure 1.5 **The average aircraft age per flight has increased to 11.6 years**

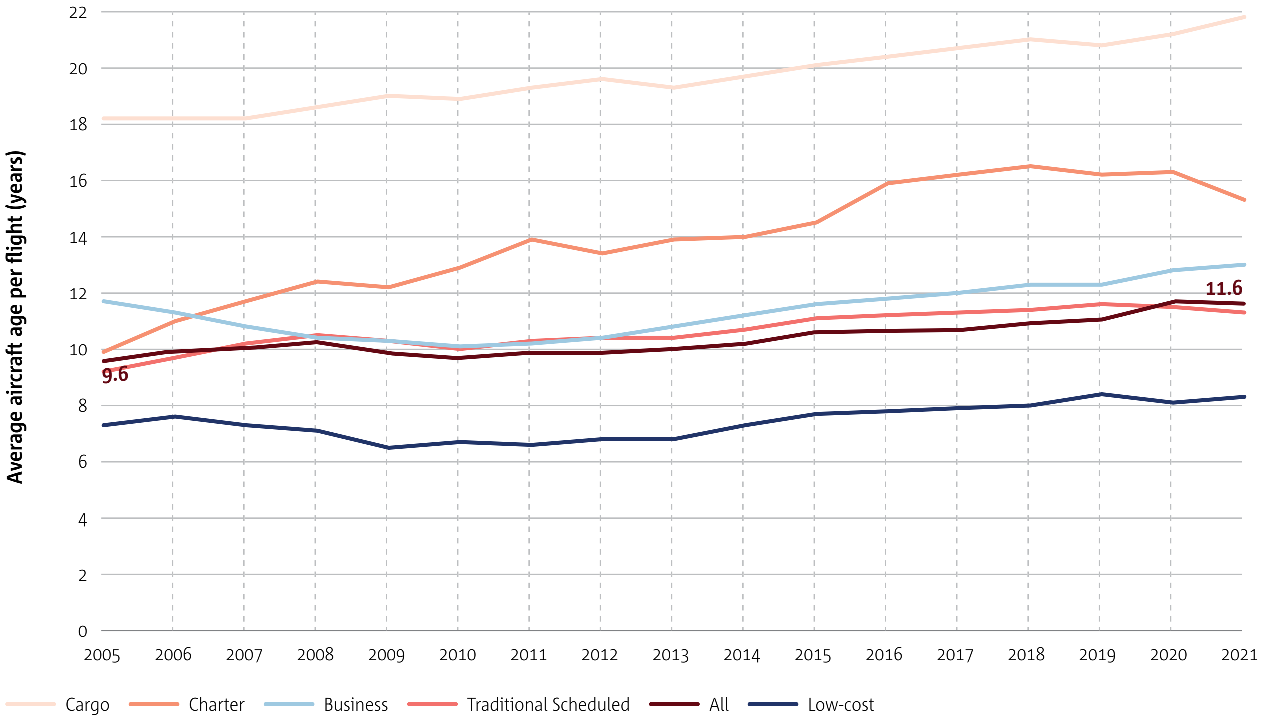


Figure 1.6 **The number of night time arrivals and departures increased until 2019**

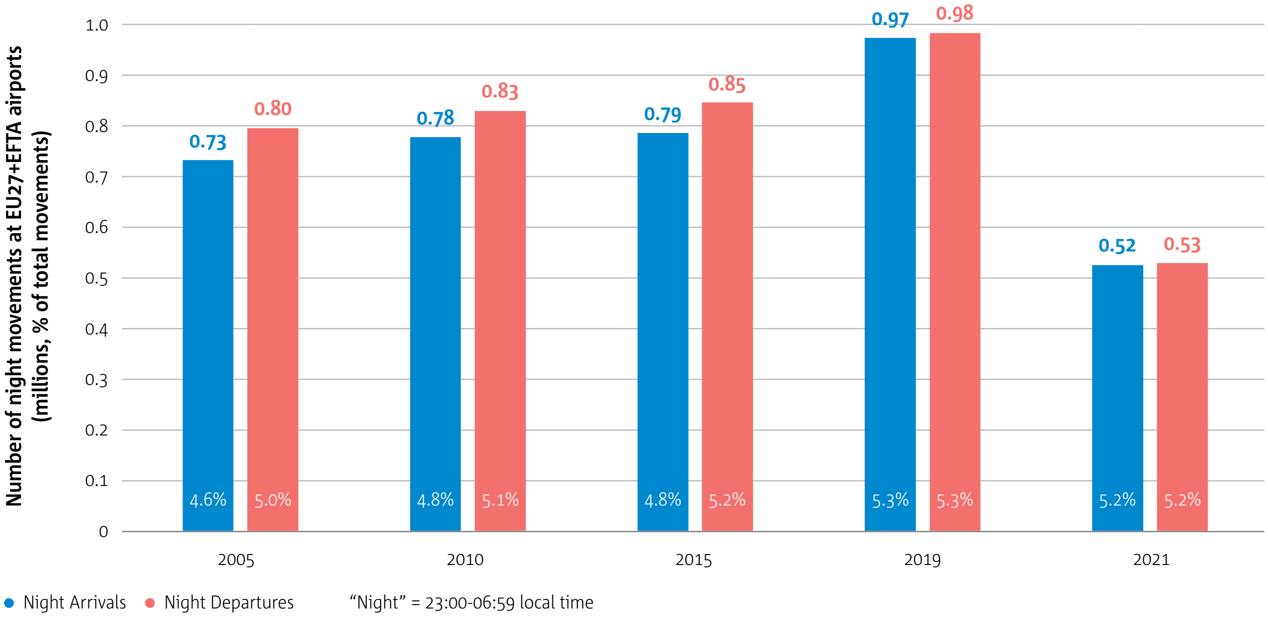


Figure 1.7 **Summary of air traffic indicators (% change to 2005)**

All passenger-related indicators are for commercial flight departures only (other indicators include arrivals) and their 2021 values are preliminary estimates. Passenger kilometres are based on the shortest (great circle) distance between origin and destination. Cargo is for both all-cargo and passenger aircraft.

The flying day is stretching towards midnight

The proportion of flights at EU27+EFTA airports that arrive at night (23:00 to 06:59) has gradually increased to match that of night departures, with 5.3% of total airport movements in 2019 (Figure 1.6). While this is a small percentage change, it amounts to 240,000 more night arrivals in 2019 than in 2005 due to the growth in air traffic over this period. The growth comes primarily from an increase in arrivals shortly after an airport opens in the 06:00 to 07:00 local time period, often medium- or long-distance flights arriving from outside of Europe. More recently, there has also been a larger increase in the 23:00 to 23:59 period, as airlines increasingly find passengers for whom this is an attractive offer. In 2019, the top 10 busiest airports during the night time period represented 26% of all night movements, which is similar to the share of the top 10 busiest airports during the day time period (27%).

1.2 NOISE

Airport noise exposure reached a peak before the COVID-19 outbreak

The average noise exposure around major EU27+EFTA airports, as measured by the L_{den} and L_{night} indicators[12], significantly increased during the five years preceding the COVID-19 outbreak. In 2019 the population exposed to L_{den} 55 dB and L_{night} 50 dB was respectively 30% and 50% larger than in 2005 (Figure 1.8 and Figure 1.9), and single-aisle jets accounted for 63% of the landing and take-off noise energy, against 22% for twin-aisle (Figure 1.13). Due to the drop in traffic in 2020, the total L_{den} 55 dB and L_{night} 50 dB population counts were about one third of the 2019 values.

Under the three traffic growth scenarios, fleet renewal[13] with the latest generation of quieter aircraft is expected to lead to a reduction in average noise exposure as measured with the L_{den} and L_{night} indicators over the next two decades. This is primarily due to the fleet penetration of the new single-aisle aircraft types (e.g. A320neo, Boeing 737MAX), which account for the majority of landing and take-off noise energy (Figure 1.13). In addition, there has been the closure of Berlin Tegel airport in 2020. However, these indicators may start to increase again in the longer term if manufacturers do not develop new quieter types of aircraft to offset the growth in traffic.

The local noise situation is very diverse among the 98 major EU27+EFTA airports covered within this assessment. Some airports have seen their L_{den} 55 dB contour area reduce by half between 2005 and 2019, while others have seen it grow by a factor 8. However, the majority of airports (82 out of 98) have increased their L_{den} 55 dB contour area over this time period. The top 10 airports in terms of L_{den} 55 dB population exposure during 2019 accounted for half of the total population exposure across all 98 airports.

To complement the average L_{den} and L_{night} noise indicators, the $N_{50}A_{70}$ population indicator[14] has also been assessed (Figure 1.9). In 2019, 1.3 million people were exposed to more than 50 aircraft noise events above 70 dB per day at the 98 major airports, which is 71% more than in 2005. This indicator could progressively increase over the next decades and exceed its 2005 level under a frozen technology scenario.

In 2019, using the dose-response curves[15] developed by the World Health Organization Europe [1], the number of people highly annoyed by aircraft noise was estimated to be 4.0 million, and the number of people suffering from aircraft-induced high sleep disturbance was estimated to be 1.7 million. This is respectively 24% and 31% more than in 2005.

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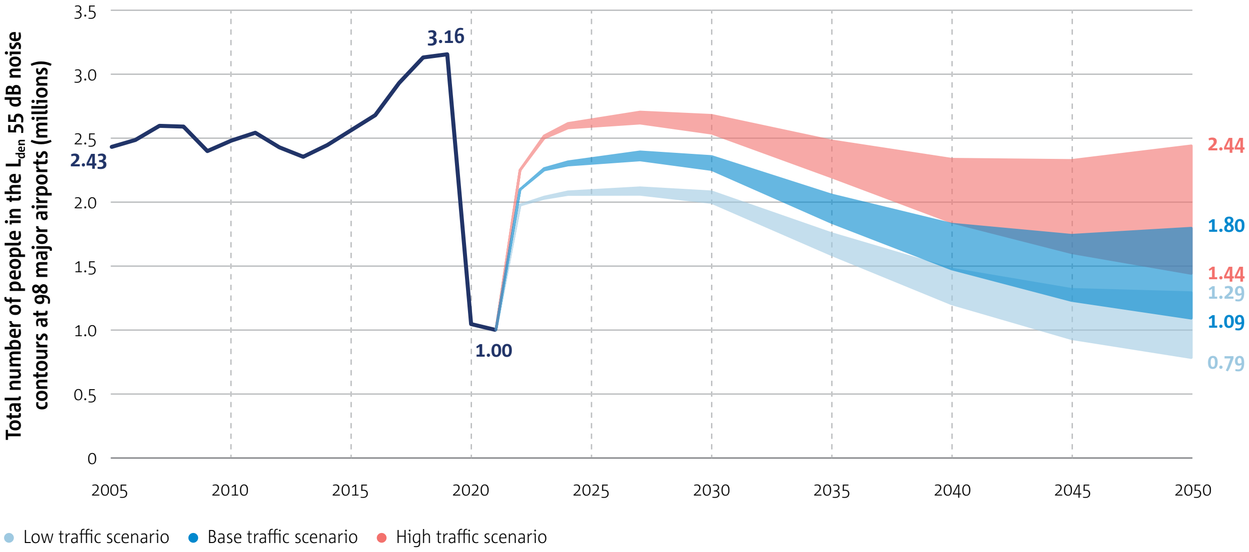
[12] L_{den} is the sound pressure level averaged over the year for the day, evening and night time periods, with a +5 dB penalty for the evening and +10 dB for the night. L_{night} is the sound pressure level averaged over the year for the night time period only.

[13] Under the base traffic forecast, new aircraft represent 42% of total operations in 2030, 77% in 2040 and 95% in 2050.

[14] This is the number of people exposed to more than 50 aircraft noise events exceeding 70 dB every day.

[15] Based on L_{den} values between 45 and 75 dB and L_{night} values between 40 and 70 dB (see Appendix C).

Figure 1.8 Noise exposure was reduced by two-thirds between 2019 and 2020 and may stay below 2005 levels after recovery from the COVID-19 outbreak

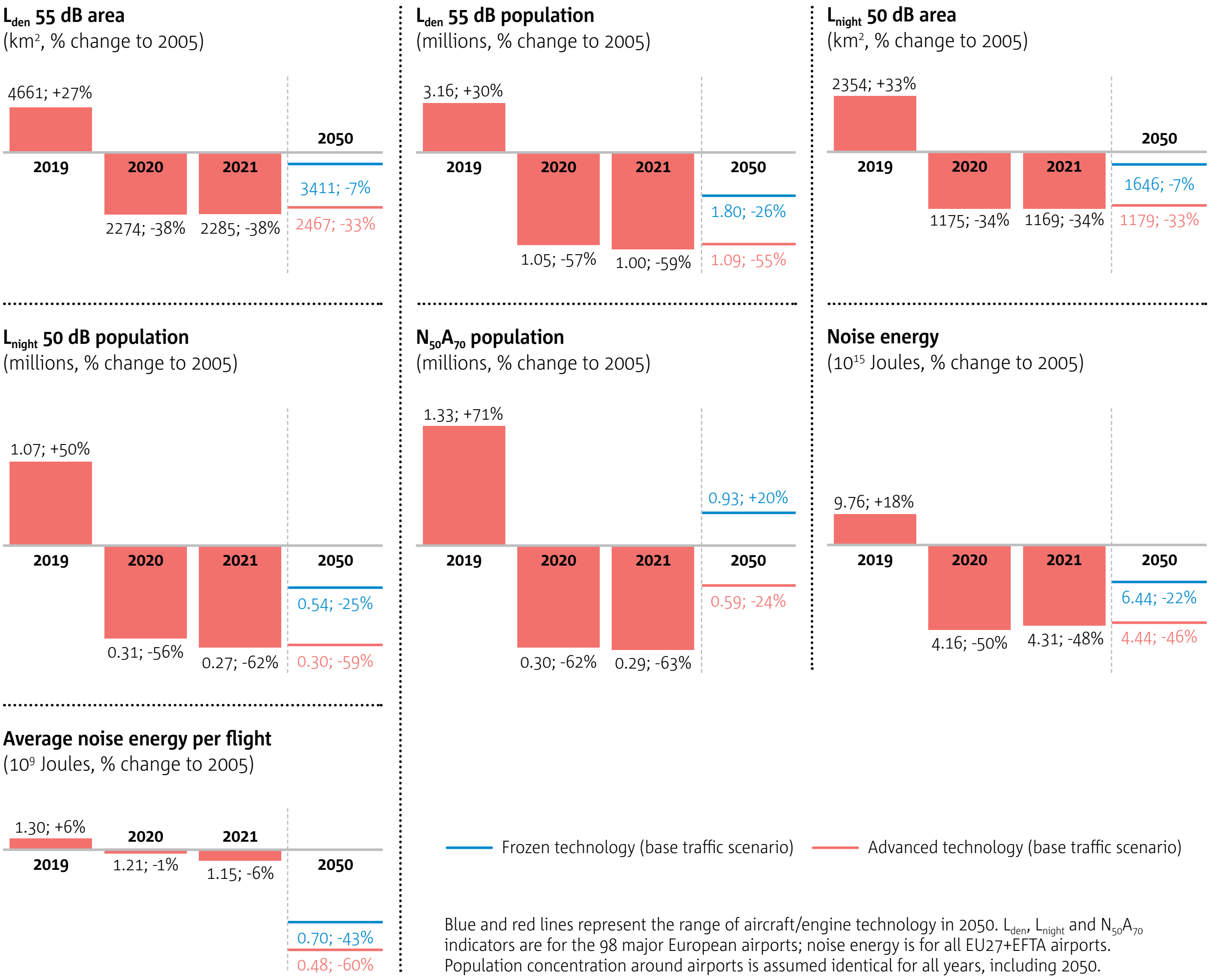


Assumptions:

- Infrastructure of each airport is unchanged (no new runway)
- Population distribution around airports is unchanged
- Local take-off & landing noise abatement procedures are not considered

For each traffic scenario, the upper bound of the range reflects fleet renewal with a 'frozen' technology scenario, and the lower bound reflects the 'advanced' technology scenario.

Figure 1.9 Summary of noise indicators (% change to 2005)

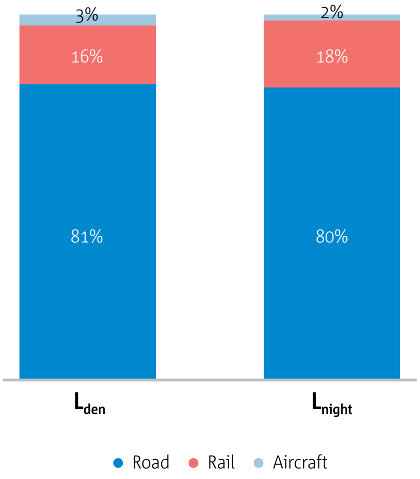


Blue and red lines represent the range of aircraft/engine technology in 2050. L_{den}, L_{night} and $N_{50}A_{70}$ indicators are for the 98 major European airports; noise energy is for all EU27+EFTA airports. Population concentration around airports is assumed identical for all years, including 2050.

Aviation noise in context

Based on data reported by Member States every five years under the Environmental Noise Directive 2002/49/EC, it is estimated that aviation represented 3% of the population exposed to transport noise in EU27+EFTA during 2017. This is slightly more than in 2012 (2.6%) [2]. While this is a smaller share than road and railway, aircraft noise is generally perceived as more annoying than road or railway noise and health effects exist at noise levels around 10 dB lower than other sources [1]. Further comparisons between the cost of aviation noise versus noise from other transport modes can be found in the EC's handbook on the external costs of transport [6].

Share of people exposed to harmful noise levels by transport mode (2017, EU27+EFTA)



1.3 EMISSIONS

Emissions grew steadily between 2013 and 2019 and may grow further beyond 2030

The full-flight carbon dioxide (CO_2) emissions of all flights departing from EU27+EFTA airports have followed a similar pattern to noise and continued to grow until an all-time high of 147 million tonnes in 2019. Figure 1.10a shows the trends in full-flight CO_2 emissions including future forecasts under different traffic, technology and air traffic management scenarios. Figure 1.10b shows the net (i.e. lifecycle) CO_2 emissions, including the effect of the EU Emissions Trading System (ETS) for the period 2013-2020 and that of in-sector measures including sustainable aviation fuels and new propulsion technologies (electric and hydrogen aircraft beyond 2035) under the base traffic scenario. No forecast of emissions reductions from market-based measures have been made due to on-going discussions on ETS and CORSIA at the European and ICAO level.

In 2019, aircraft operators covered 22% of their CO_2 emissions by purchasing allowances under the EU ETS. The ETS has not fully mitigated the growth in CO_2 emissions due to the growth in emissions from flights outside its applicability scope. CO_2 emissions dropped by 57% in 2020 due to the start of the COVID-19 pandemic. If the ReFuelEU mandate[16] for sustainable aviation fuels is met, net CO_2 emissions could be about 50% lower in 2050 than in 2019. Electric and hydrogen aircraft were assumed to deliver an additional 5% net CO_2 reduction by 2050 and are expected to have a larger emission reduction potential beyond this date.

Emissions of nitrogen oxides (NO_X) shown in Figure 1.12, as well as volatile particulate matter (PM), have followed an even steeper growth since 2005, respectively +46% and +40%. Emissions of carbon monoxide (CO), unburnt hydrocarbons (HC) and non-volatile PM have also grown but at a lower rate (+4% to +13%). Under the base traffic scenario, the most optimistic technology and air traffic management scenario would bring NO_X emissions close to their 2019 levels in 2050. The same applies to CO and volatile PM emissions, while HC and non-volatile PM emissions could reduce between 2019 and 2050 (Figure 1.15).

In 2019, long-distance flights (above 4,000 km) and twin aisle jet aircraft represented approximately 6% of departures and half of all CO_2 and NO_X emissions (Figure 1.13), while intra-EU+EFTA flights represented 77% of flights and 39% of CO_2 emissions (Figure 1.14).

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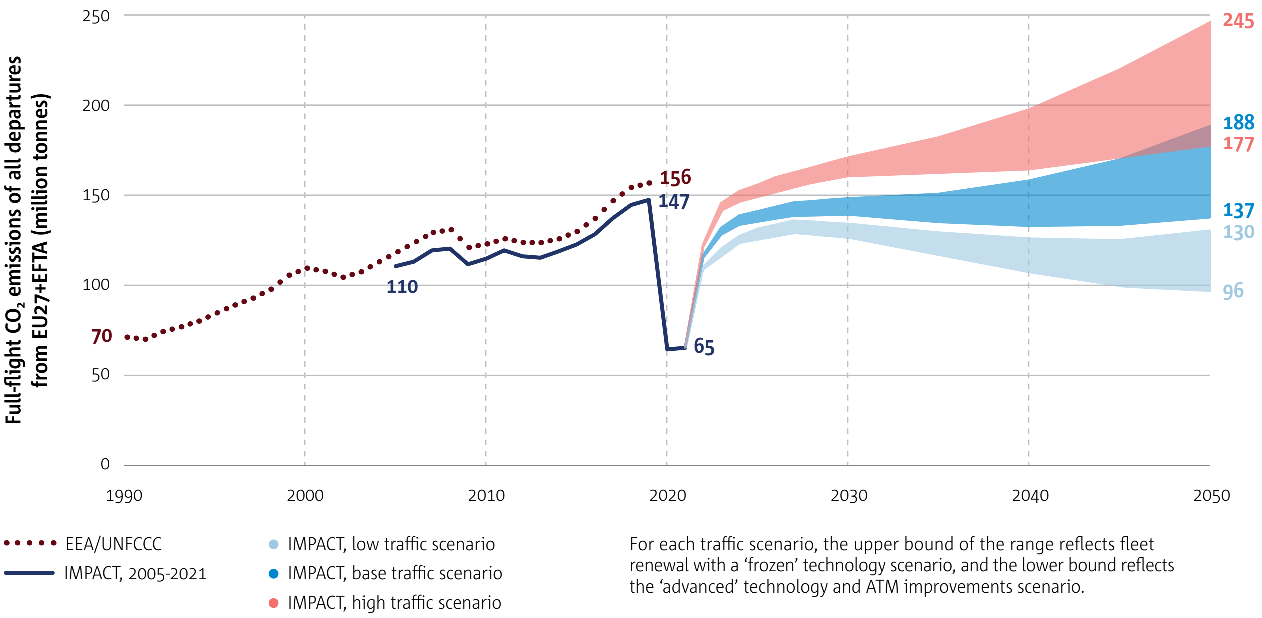
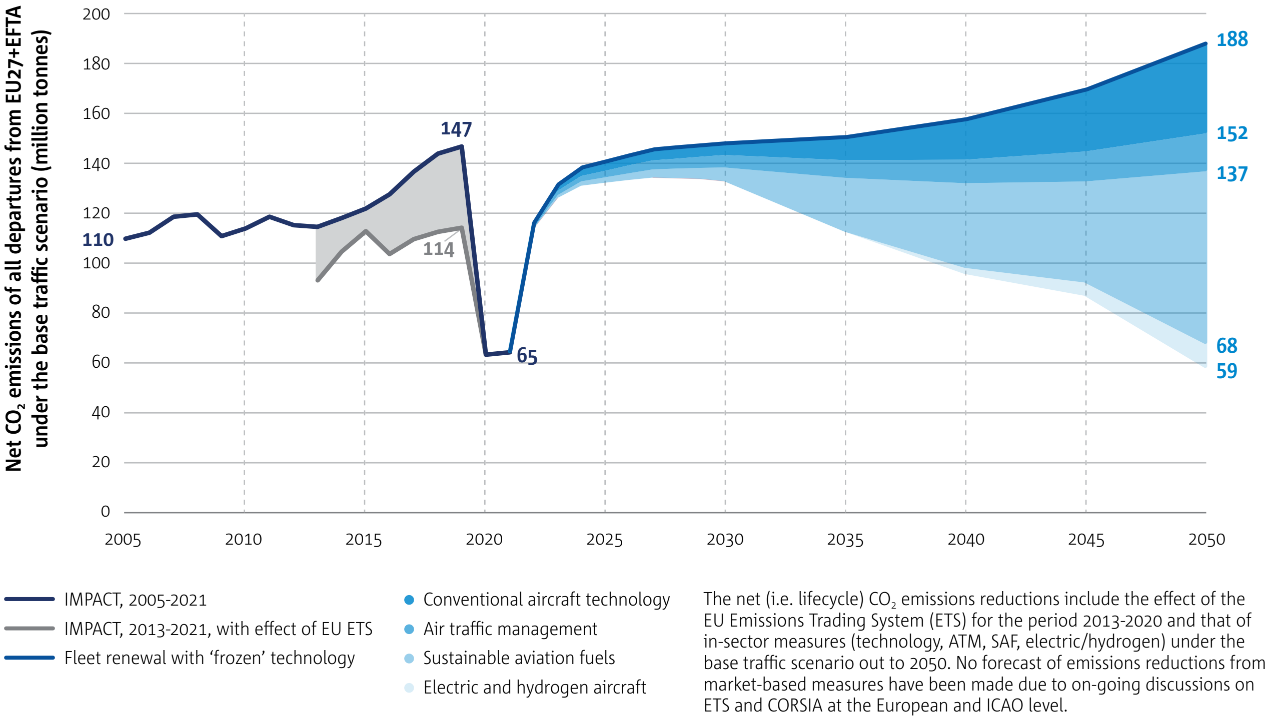
[16] As per the European Commission ReFuelEU Aviation Initiative proposal of July 2021.

Figure 1.10a Full-flight CO_2 emissions may grow beyond 2019 levels under the base and high traffic forecast



For each traffic scenario, the upper bound of the range reflects fleet renewal with a 'frozen' technology scenario, and the lower bound reflects the 'advanced' technology and ATM improvements scenario.

Figure 1.10b Net CO_2 emissions could be halved by 2050 using sustainable aviation fuels



The net (i.e. lifecycle) CO_2 emissions reductions include the effect of the EU Emissions Trading System (ETS) for the period 2013-2020 and that of in-sector measures (technology, ATM, SAF, electric/hydrogen) under the base traffic scenario out to 2050. No forecast of emissions reductions from market-based measures have been made due to on-going discussions on ETS and CORSIA at the European and ICAO level.

Figure 1.11 CO_2 emissions of traditional scheduled airlines saw significant growth between 2016 and 2019

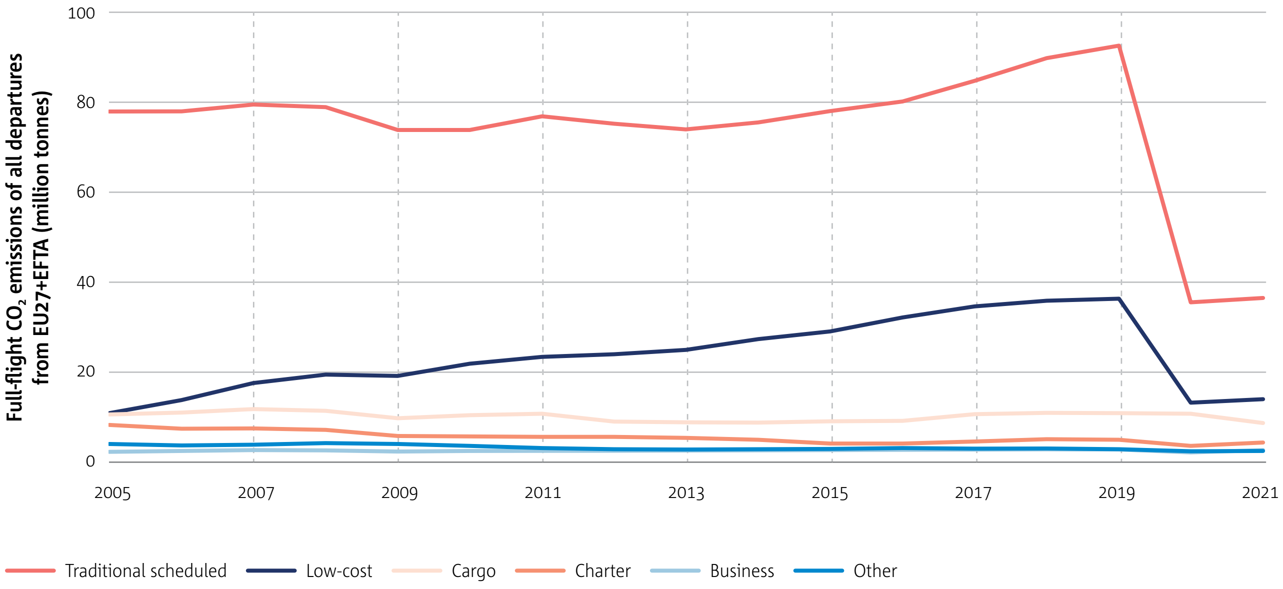
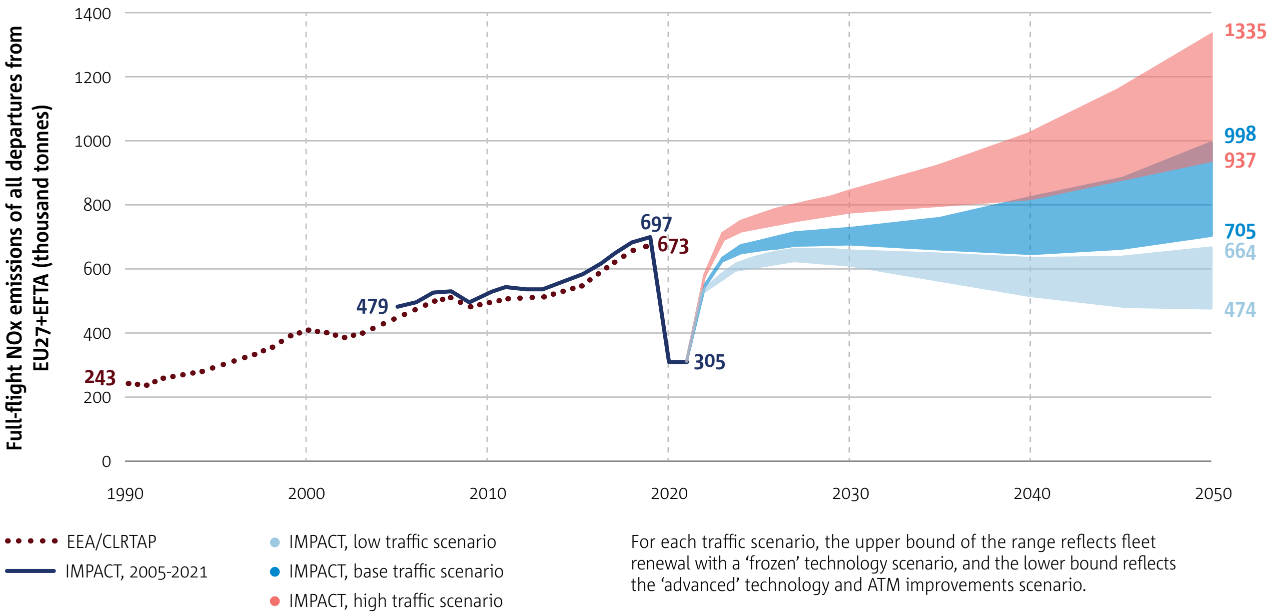


Figure 1.12 NO_X emissions reached about 700 thousand tonnes in 2019



For each traffic scenario, the upper bound of the range reflects fleet renewal with a 'frozen' technology scenario, and the lower bound reflects the 'advanced' technology and ATM improvements scenario.

Figure 1.13 Single-aisle jets have the larger share of flights and noise, but twin-aisle jets have the larger share of fuel burn and emissions in 2019.

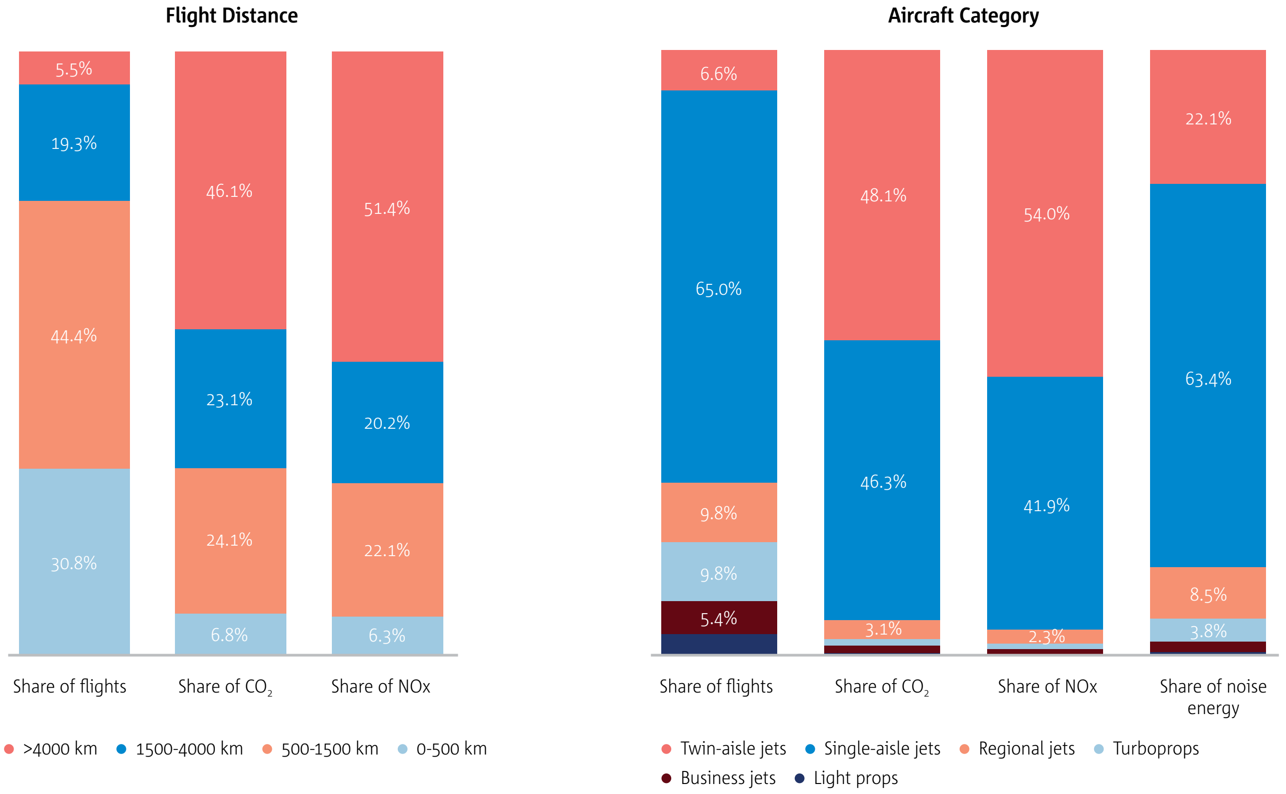


Figure 1.14 Share of flights and CO$_2$ emissions by destination region in 2019

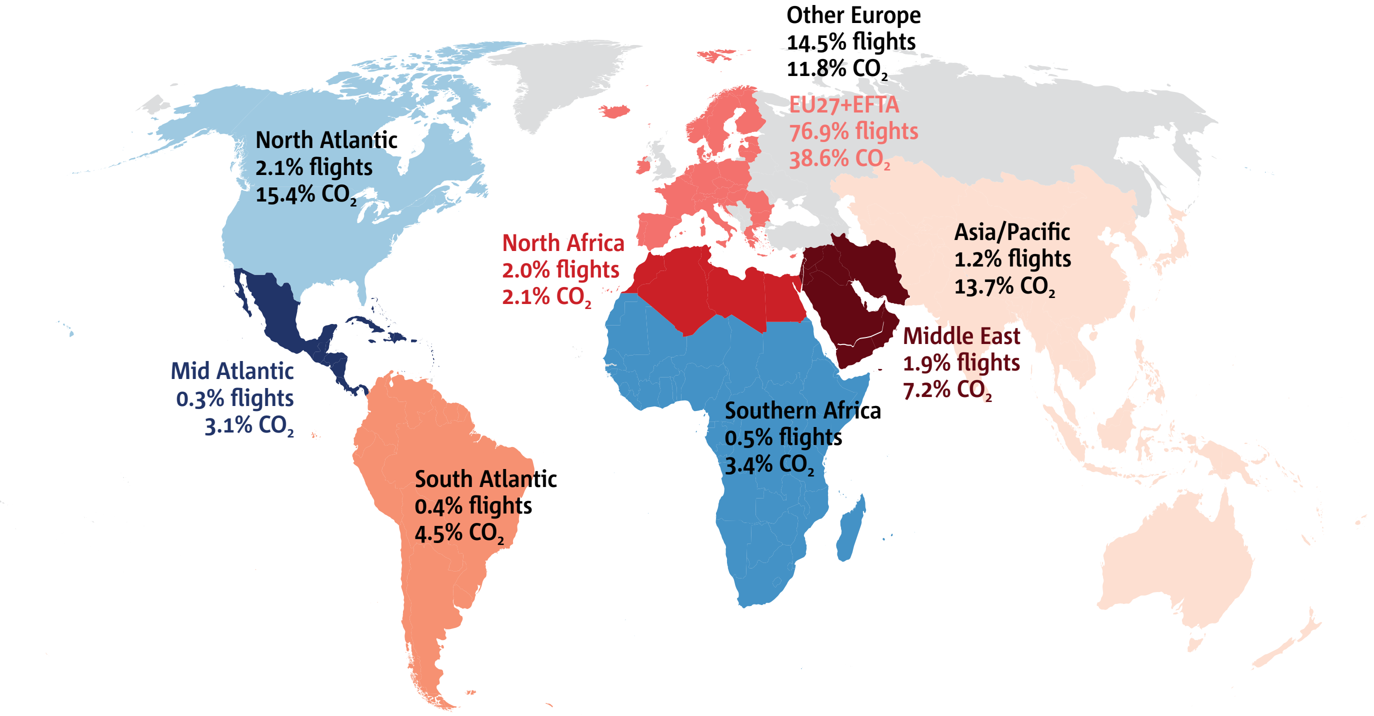
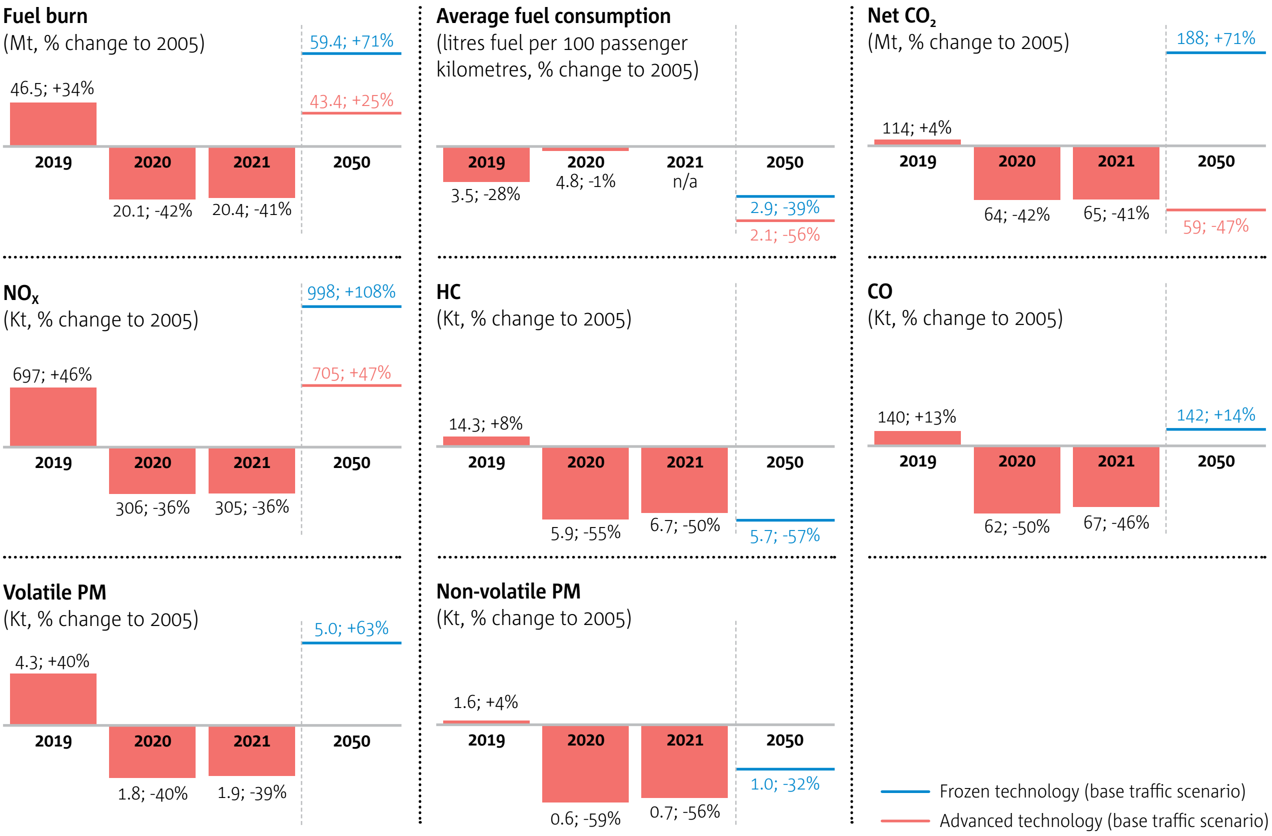


Figure 1.15 Summary of full-flight emission indicators (% change to 2005)



Blue and red lines represent the range of aircraft/engine technology and ATM improvements in 2050. The net CO_2 indicator also includes emission reductions from the EU ETS up to 2021, sustainable aviation fuels (SAF) and electric/hydrogen aircraft out to 2050. No assumptions on potential improvements to HC, CO and PM have been made out to 2050 from technology, ATM and SAF.

Average fuel consumption is for commercial passenger aircraft only and does not take into account belly freight. Kilometres used in this indicator represent the shortest (or great circle) distance between origin and destination, while fuel consumption is based on the actual flown distance (i.e. this indicator includes the effect of ATM horizontal inefficiency).

European aviation emissions in context

Flights departing from EU27+EFTA represented 16% of global aviation's CO_2 emissions in 2018. In 2019, all departing flights from Europe were accountable for 5.2% of the total EU27+EFTA greenhouse gas emissions (an increase from 1.8% in 1990) and 18.3% of emissions from the transport sector, making aviation the second largest source of emissions in the transport sector after road [3]. This increase is due to traffic growth outpacing fuel efficiency improvements and reductions of emissions from other sectors. In 2020, aviation emissions decreased to 1.9% of total EU27+EFTA greenhouse gas emissions and 9% of emissions from the transport sector.

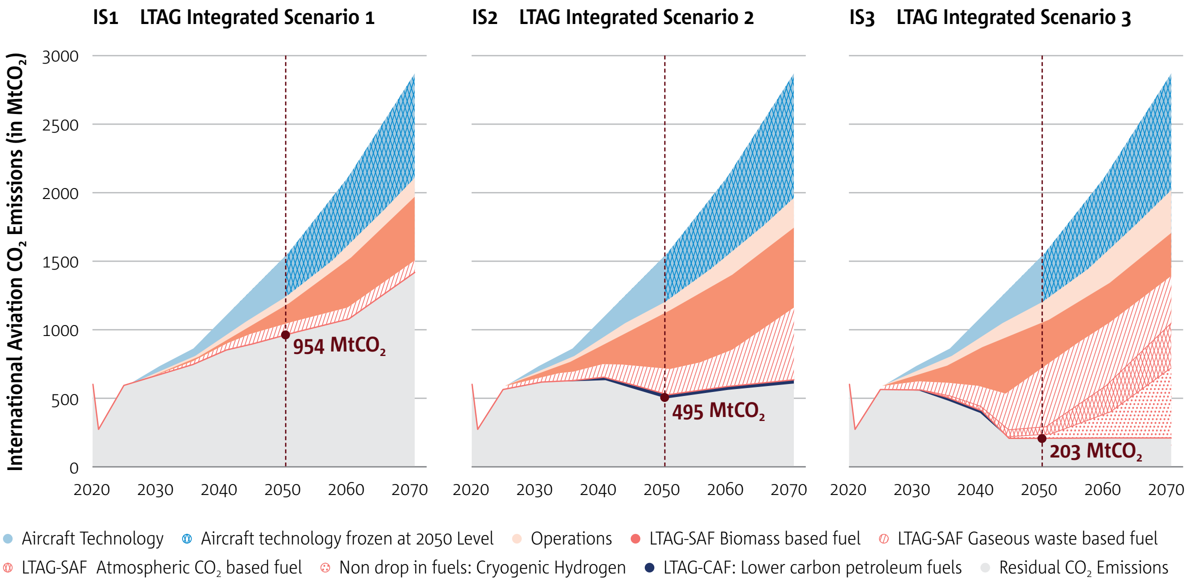
Aviation is also an important source of air pollutants, especially nitrogen oxides (NO_X) and particulate matter (PM). Compared to 2019, the 2020 share of aviation NO_X emissions within the transport sector has dropped from 22.8% to 13.4% within EU27+EFTA, while the share in total NO_X emissions almost halved from 10.6% to 6% [4]. In absolute terms, NO_X emissions from aviation have almost tripled since 1990, and their relative share has quadrupled, as other economic sectors have achieved significant reductions. For emissions of $PM_{2.5}$, the total share from aviation is less than 1% while it accounted for 5% from the transport sector. Emissions of $PM_{2.5}$ have slightly increased since 2000. The carbon monoxide (CO) and oxides of sulphur (SO_X) emissions from aviation have also increased since 1990, while these emissions from most other transport modes have fallen.

Towards decarbonisation of aviation

According to the UNEP Emissions Gap Report 2020 [5], domestic and international shipping and aviation currently account for around 5% of global CO_2 emissions and are projected to consume between 60% and 220% of allowable CO_2 emissions by 2050 under IPCC illustrative 1.5°C scenarios.

In 2021, the Science Based Targets initiative (SBTi) published guidance for passenger and cargo airlines to set their own CO_2 reduction targets [7]. This guidance helps companies understand how much and how fast they should reduce their greenhouse gas (GHG) emissions to align with the goals of the Paris Agreement. The target setting method for airlines is based on the SBTi's Sectoral Decarbonization Approach (SDA), which states that a company's GHG intensity (grams CO_2 equivalent per revenue tonne kilometre) should converge to the sector's average Paris-aligned GHG intensity by 2050.

In March 2022, ICAO published a report on the feasibility of a long-term aspirational goal (LTAG) for international civil aviation CO_2 emission reductions [8]. The study looked at various integrated scenarios combining in-sector measures (technology, operations and fuels) out to 2050 and 2070. While none of the scenarios in the study reached zero CO_2 emissions in 2050, the most ambitious one (IS3) led to residual CO_2 emissions of ~200 million tonnes (i.e. ~90% less than the baseline "do nothing" scenario or one third of emissions in 2019). Further discussions on the feasibility of an LTAG are due to take place at ICAO's 41st Assembly in October 2022.

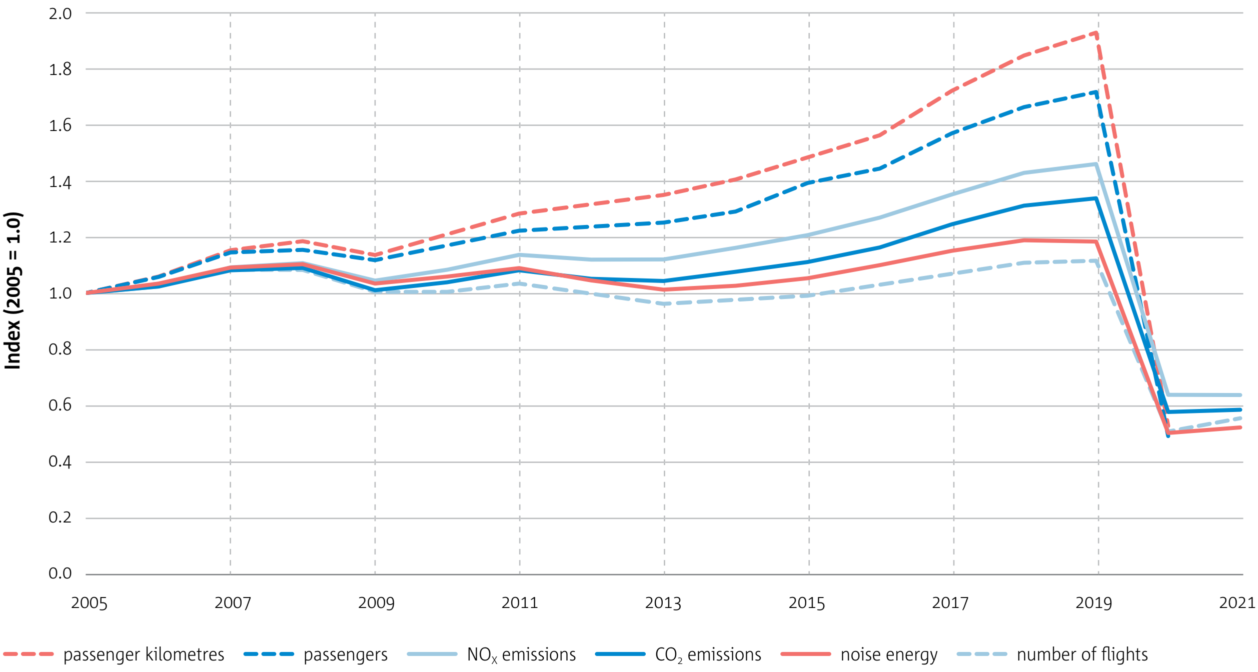


1.4 COMBINING INDICATORS

In the years preceding the COVID-19 pandemic, noise and emissions of European aviation have continued to grow, although at a slower rate than passenger kilometres. The average grams CO_2 per passenger kilometre (gCO_2/pkm) went down from 123 to 89 between 2005 and 2019, equivalent to an average 2.3% per annum fuel efficiency improvement over the period. However, it increased back to 122 gCO_2/pkm in 2020 due to the drop in average load factors.

Accelerated improvements in aircraft technology, air traffic management and sustainable aviation fuels will be necessary to curb the increase in the sector's environmental footprint if traffic resumes its growth at pre-pandemic rates.

Figure 1.16 Emissions and noise energy have grown slower than passenger kilometres but faster than number of flights



2

AVIATION ENVIRONMENTAL IMPACTS

- To mitigate adverse effects from aircraft noise on EU citizens' health, the World Health Organisation Europe recommends reducing aircraft noise levels below L_{den} 45 dB and L_{night} 40 dB.
- Air pollutant emissions from aviation have increased within the EU. Effective action requires better characterisation of aviation's specific contribution compared to other sources of emissions, especially on particulate matter.
- In addition to mitigation measures from aircraft operations and airport activities, airport surface access plans (e.g. good public transport links) can also effectively reduce air pollutant concentrations.
- The growth in aviation CO_2 emissions was accelerating prior to COVID-19, with almost half of global CO_2 emissions between 1940 and 2019 having occurred since 2000.
- In 2018, the estimated Effective Radiative Forcing (ERF) from non-CO_2 emissions accounted for more than half (66%) of the aviation net warming effect, although the level of uncertainty from the non-CO_2 effects is 8 times larger than that of CO_2.
- Environmental certification standards already exist for aircraft engine non-CO_2 emissions, including NO_X and nvPM, and further mitigation policy options are being considered.
- Where specific mitigation measures incur trade-offs between CO_2 and non-CO_2 emissions, a robust assessment methodology is essential to ensure an overall reduction in climate impact. In addition, 'win-win' options that reduce both simultaneously should be supported (e.g. appropriate sustainable aviation fuels).
- In 2022, the IPCC 6th Assessment Report noted that immediate, rapid, and large-scale reductions in greenhouse gas emissions are needed to limit warming to 1.5°C and that the avaition sector is still in the earlier stages of adaptation to increased climate hazards.

This chapter summarises the latest scientific understanding on the main environmental impacts of aviation, namely noise, air quality and climate change. A robust knowledge on these issues is crucial as a basis to inform policy-making assessments and decisions.

2.1 NOISE

Impact of aircraft noise

Exposure to aircraft noise affects the health and wellbeing of millions of people in Europe, with those living in residential communities in the vicinity of airports being particularly affected. These impacts can take the form of stress caused by annoyance, sleep disturbance, heart disease, premature mortality due to ischaemic heart disease and even learning impairments in children. To mitigate these adverse effects, the WHO Environmental Noise Guidelines for the European Region recommend reducing aircraft noise levels to L_{den} 45 dB and L_{night} 40 dB[17]. While noise from aircraft affects far fewer people than road or rail traffic noise, it is still an important source of noise as it is regarded as more annoying than road or railway noise [1].

Estimates of the above impacts, according to reported data by EU Member States under the Environmental Noise Directive (END), are provided in Figure 2.1 [2]. In 2017, close to one million European citizens suffered from high annoyance from aircraft noise. Data collected under the END also indicate that aircraft noise exposes approximately 3.6 million people in EU27 and EFTA (0.8% of total population) to levels of L_{den} 55 dB or higher during the day-evening-night period and 1.2 million to levels of L_{night} 50 dB or higher during the night time. A recent study estimated that, through the extrapolation of the 2017 END data, 15 million people in the EU27 could be exposed to aircraft noise levels of L_{den} 45 dB, although it should be noted that this value has a high level of uncertainty [3].

Airport noise action plans

Action plan summaries [4] submitted by airports under the END show that measures at source, such as those related to air traffic management, operational restrictions and economic measures are extensively used to reduce and manage air traffic noise at major airports (Figure 2.2). Other measures such as urban and land use planning and infrastructure changes account for a small percentage of the mitigation measures. Education and communication measures are more frequently used for managing the impacts of air traffic noise compared to road or railway sources.

Figure 2.1 Estimated number of people suffering from various health effects from aircraft noise in the EU27 and EFTA in 2017

HIGH ANNOYANCE
972 600

HIGH SLEEP DISTURBANCE
229 900

HEART DISEASE
700

PREMATURE MORTALITY
200

COGNITIVE IMPAIRMENT IN CHILDREN
10 300

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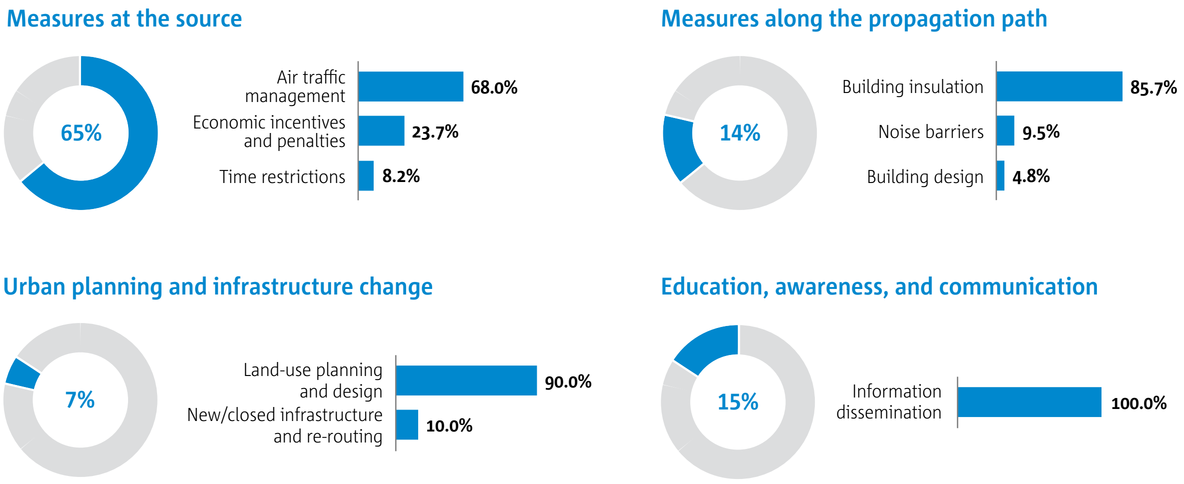
[17] L_{den} is the sound pressure level averaged over the year for the day, evening and night time periods, with a +5 decibel (dB) penalty for the evening and +10 dB for the night. L_{night} is the sound pressure level averaged over the year for the night time period only.

Figure 2.2 Main noise mitigation measures from 31 major European airports



Note: % of all measures reported in action plan summaries submitted under the END for 31 major airports of more than 50,000 movements /year (EU27, EFTA and 9 major airports in the UK)

Aviation Noise Impact Management through Novel Approaches (ANIMA)

The ANIMA project, funded under Horizon 2020, provided airports and aviation authorities with methods and tools that can be used for designing interventions that effectively reduce noise exposure as well as annoyance, thereby improving the quality of life of neighbouring communities [5].

Specifically, ANIMA explored how airports and authorities implement regulations, what their drawbacks or blind spots are, what factors influence annoyance and other health effects, and how to set up an appropriate dialogue that empowers all stakeholders to identify equitable solutions. Publicly available tool suites have been developed to support relevant stakeholders in decision-making. For instance, the Noise Toolset [6] supports trials to assess the effect of a new flight path or new aircraft movements on noise maps and on annoyance indicators.

In addition to providing tools and methodologies to simulate aircraft traffic scenarios and reduce annoyance, the ANIMA project proposed a specific indicator for assessing and predicting the probability of awakening people in the vicinity of airports during the night period [7].

2.2 AIR QUALITY

Air pollution has impacts on the health of the European population, particularly in urban areas [8]. The most significant air pollutants are particulate matter (PM), nitrogen oxides (NO_x) and ground-level ozone (O_3). Despite the overall decrease of emissions and improvements in general, air pollutant emissions from aviation have increased within the EU.

The EU Ambient Air Quality Directive [9] contains regulatory limits for PM, NO_2, O_3 and sulphur dioxide (SO_2) concentrations in ambient air. The World Health Organisation recently updated global guidelines with quantitative health-based recommendations for air quality management, expressed as long- or short-term maximum concentrations for a number of key air pollutants [10].

Aviation and air pollution

While a major source of air pollution in the vicinity of airports originates from aircraft operations, air quality is also impacted by ground support equipment, surface access road transport and airport on-site energy generation. Aircraft engines produce similar emissions to other sources of fossil fuel combustion with the most significant being nitrogen oxides (NO_X), particulate matter (PM), volatile organic compounds (VOCs), sulphur dioxide (SO_2), carbon monoxide (CO) and unburnt hydrocarbons (HC).

Nitrogen oxides (NO_X)

Aircraft engine NO_X emissions (nitric oxide – NO and nitrogen dioxide – NO_2) are primarily produced at high pressure and temperature combustor conditions during take-off, and are of a concern in terms of health impacts linked to impaired immune and respiratory functions as well as increased response to allergens. In the presence of heat and sunlight, surface NO_X reacts with VOCs, HC and CO to form ground level ozone or smog that cause health impacts [11, 12]. In addition, NO_X are precursors to other oxidised nitrogen compounds that contributes to the formation of secondary particulate matter[18]. Thus, NO_X have both a direct and an indirect impact on air quality and the environment.

Particulate matter (PM)

Particulate matter is a general term used to describe non-volatile (nvPM) or volatile particles (vPM) in various sizes and composition. At the engine exhaust, particulate emissions mainly consist of nvPM containing soot, or black carbon [13]. Health impacts from PM emissions include effects on the cardiovascular and respiratory systems, with ultrafine particles able to enter the bloodstream and act as carriers for toxic substances. EU air quality limits exist for PM_{10} and $PM_{2.5}$ concentrations, but not for ultrafine particle sizes. However, $PM_{2.5}$ mass is considered a good indicator of general risk associated with exposure to particulate matter. Increased surface $PM_{2.5}$ concentrations have been shown to lead to a rise in annual premature mortalities due to increases in cases of cardiopulmonary disease and lung cancer [14, 15].

Sulphur dioxide (SO_2)

SO_2 emissions result from the combustion of fuels containing sulphur. Most of the sulphur is emitted as gaseous sulphur dioxide (SO_2), but about 5% is fully oxidised to form gaseous sulphuric acid (H_2SO_4), which can subsequently condense on the surfaces of other ambient or soot particles in the atmosphere. While the current limit for sulphur in aviation fuel is 3,000 ppmv (parts per million by volume), actual levels are believed to be averaging ~600 – 800 ppmv although data availability is poor [13].

Ozone (O_3)

Ozone is a secondary pollutant, not emitted directly by aircraft engines, but produced when carbon monoxide (CO) or volatile organic compounds (VOCs) are oxidized in the presence of nitrogen oxides (NO_X) and sunlight. Low altitude ground level ozone is a major component of smog, which can cause several health issues, respiratory problems, and damage to crops and ecosystems [16].

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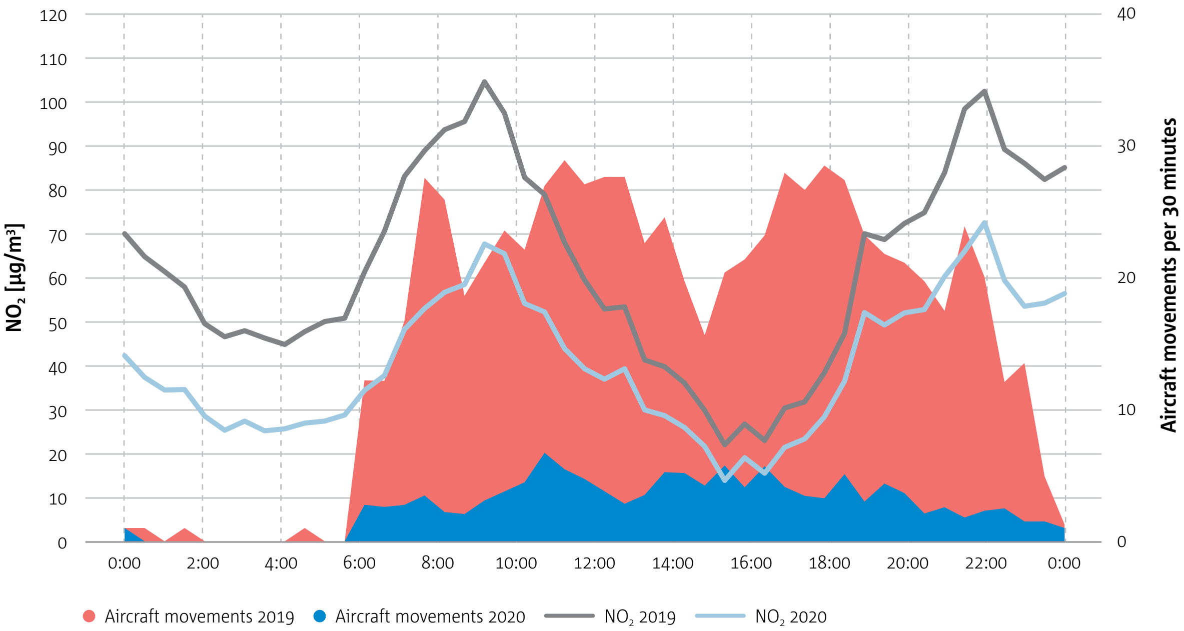
[18] Secondary particulate matter is formed from chemical reactions in the atmosphere from the gases ammonia (NH3), sulphur dioxide (SO_2) and nitrogen oxides (NO_X), and from organic compounds.

Impact of COVID-19 on airport air quality

The measures introduced by most European countries in response to COVID-19 led to significant reductions in emissions of air pollutants, particularly in the transportation sector. Zurich airport analysed air and road traffic, emissions and measured concentrations of various pollutants for a pre-COVID period in 2019 compared to a period in 2020 [21]. The study found that the 91% drop in air traffic led to an 87% reduction in NO_X emissions at the airport, but only a 44% reduction in NO_2. Reductions in ultrafine nvPM number were of a similar magnitude to NO_X. These results are also driven by influences from other-than-aircraft sources, such as regional road traffic, that also contribute to the emissions concentrations at the airport. It was also noted that the effects of emissions from airport sources significantly decrease over short distances from the airport, and that a decrease in concentrations at the airport is not carried over into the region level at the same rate. This confirmed previous modelling that shows a rapidly decreasing influence of the airport outside its perimeter.

Diurnal variation in NO_2



These findings are consistent with those from additional studies performed on this topic [22, 23]. While the effects of lockdown will be temporary, these findings provide insight into the potential for mitigating public health risk by reducing 'business as usual' air pollutant emissions from economic activities.

Impact of aviation emissions

A recent review of articles identified elevated levels of PM2.5 and ultrafine particles (UFP) in and around airports [17]. When assessing the impacts of PM on health, it is important to focus on the number count, as it is a more significant indicator for ultrafine particles than mass and size. As a significant source of UFP, aircraft engine emissions can cause increases in ground-level particle number concentrations (PNC) over large areas downwind of airports [18, 14]. The spatial extent and magnitude of the impact from UFP varies depending on factors including wind direction and speed, runway use pattern and flight activity. This can encompass large populations in cities where airports are located close to the urban residential areas, such as in Amsterdam, where the PNC was found to be elevated 7 km downwind of Schiphol Airport [19].

While a number of articles report adverse health effect impacts (e.g. increased rates of premature death), more research is needed on the link between particle size distributions and specific airport activities to evaluate long-term impacts. In order to better inform UFP exposure assessment efforts, it is important to distinguish aviation-related contributions from other urban sources and to characterise them independently. This can be particularly challenging in urban areas with dense road networks. However, key differences exist that can help distinguish between the spatial impact of road traffic and aircraft UFP emissions [20].

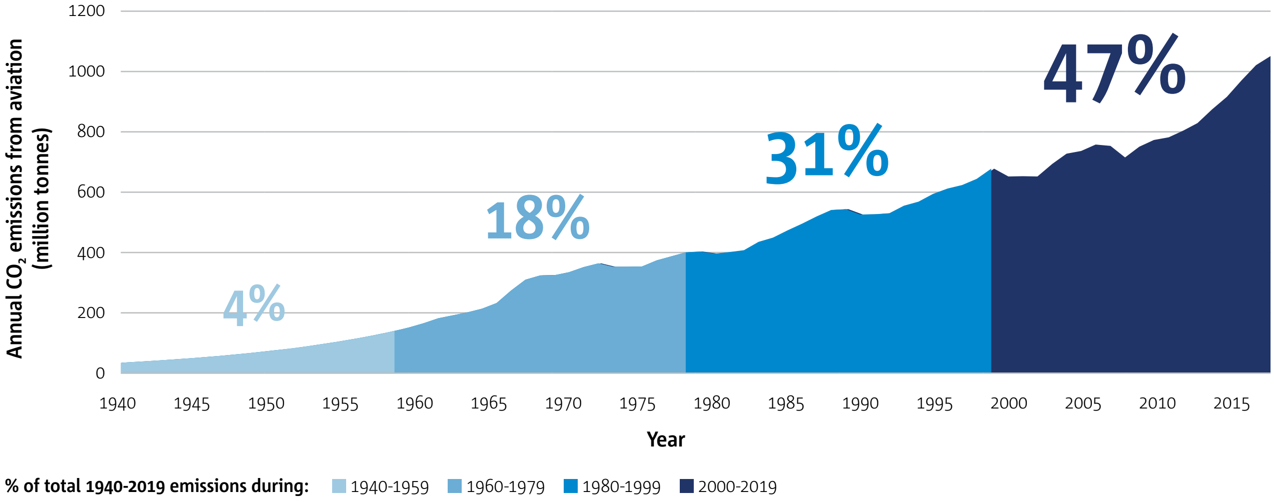
2.3 CLIMATE CHANGE

The Intergovernmental Panel on Climate Change (IPCC) is the international body that provides policy makers with regular assessments of the science related to climate change (Working Group I), its impacts and future risks (Working Group II), and options for adaptation and mitigation (Working Group III). In 2018, the IPCC produced a Special Report on the impact from global warming of a 1.5^{0}C temperatre increase compared to pre-industrial levels [24]. It concluded that reaching and sustaining net-zero global CO_2 emissions from human activities, and declining net non-CO_2 radiative forcing, would halt global warming on multi-decadal time scales.

The IPCC subsequently released its 6th Assessment Report of Working Group I in 2021, which showed that emissions of greenhouse gases from human activities are responsible for approximately 1.1°C of warming since 1850-1900 and that immediate, rapid and large-scale reductions in greenhouse gas emissions are needed to limit warming to 1.5°C. The Report of Working Group II was subsequently released in February 2022 identifying that if 1.5°C is reached in the near-term, it would cause unavoidable increases in multiple climate hazards. The magnitude and rate of these hazards and associated risks would depend strongly on near-term mitigation and adaptation actions. Finally, the Report of Working Group III was published in April 2022 highlighting that many transport sector climate change mitigation strategies have co-benefits, including air quality improvements. It was also recognised that international cooperation is a critical enabler for achieving ambitious mitigation goals [25]. These findings of the IPCC are reinforced by the World Meteorological Organization's report on the State of the Global Climate 2021 [26].

Since the publication of the IPCC Special Report on 'Aviation and the Global Atmosphere' in 1999 [27], the effects of aviation on climate from both its CO_2 and non-CO_2 emissions have been well established and continuously assessed. In order to halt aviation's contribution to global warming, the sector needs to achieve net-zero CO_2 emissions while also reducing the warming effect from non-CO_2 emissions.

Figure 2.3 Annual global CO_2 emissions from aviation (1940-2019) with % of total cumulative emissions broken down into 20 year periods



Aviation CO_2 emissions

Carbon dioxide (CO_2) emissions originate from burning fossil fuels. CO_2 emissions can remain in the atmosphere for hundreds to thousands of years[19] and so it is the cumulative emissions that matter as they accumulate in the atmosphere thereby increasing CO_2 concentrations.

While aviation's sectoral share of global CO_2 emissions remains at around 2.5% on an annual basis, both global emissions and aviation emissions have dramatically increased in recent years (Figure 2.3), with 47% of global aviation CO_2 emissions between 1940[20] and 2019 having occurred since 2000 [28].

Aviation non-CO_2 emissions

Unlike CO_2, the effect from aviation non-CO_2 emissions depends on where they are emitted. They are also termed 'short-lived climate forcers', since their effect operates on a timescale of hours to decades.

Nitrogen oxides (NO_X)

NO_X are gases that react with other chemical species within the atmosphere, resulting in both warming and cooling that is called the 'net NO_X' effect. In the short term (hours to days), NO_X leads to the formation of ozone (O_3) which is a greenhouse gas and thus has a warming effect. NO_X also leads to the formation of highly reactive species, including the hydroxy radical (OH). OH is the primary means by which ambient methane (CH_4) from other sources (e.g. agriculture, coal mining and combustion) is broken down, resulting in a cooling effect (decades). While there are additional small cooling effects associated with the methane reduction, and the formation of O_3 is influenced by the amount of surface emissions precursors, the overall balance between all these effects is currently considered to be a net warming.

Contrail-cirrus clouds

Contrails form behind aircraft, typically at cruising altitudes of 8 to 12 km, from the condensation of water vapour on soot particles to form ice crystals under conditions of temperature and humidity that leads to the saturation of air with water. While the formation of short-lived linear contrails is easy to predict, the formation of 'persistent contrails' that last from a few minutes to a few hours and can form cirrus cloud coverage are much harder to predict for purposes of avoidance [29]. The interaction of contrails and contrail cirrus with solar and infrared radiation results in a net warming that occurs mainly under night time conditions, as shown in Figure 2.4 [30].

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[19] At its simplest, carbon dioxide cycles between the atmosphere, oceans and land biosphere. Its removal from the atmosphere involves a range of processes with different time scales. About 50% of a CO_2 increase will be removed from the atmosphere within 30 years, and a further 30% will be removed within a few centuries. The remaining 20% may stay in the atmosphere for many thousands of years (IPCC Fourth Asessment Report, 2007). This is further elaborated in the fifth and sixth assessment reports of the IPCC.

[20] Due to limited commercial aviation activities prior to 1940, and the subsequent signature of the ICAO Chicago Convention in 1944, this date is often used to mark the beginning of the modern aviation industry.

Figure 2.4 The formation of contrails and timescales [30]

Steps in contrail lifetime and its effects on climate

Other non-CO_2 emissions

The emissions of soot particles and sulphate aerosols (primarily as SO_2 from sulphur present in the fuel) have a short-term (weeks) direct warming and cooling climate effect respectively, as well as a potential indirect effect through their interaction with clouds. The short-term direct climate effect of water vapour emissions is very small at subsonic cruise flight altitudes in the troposphere. However, water vapour emissions from an increasing number of flights above the tropopause, such as supersonic aircraft and certain subsonic business jets, can have a warming effect as they fly in the drier stratosphere.

Scientific understanding of CO_2 and non-CO_2 climate effects

Since the 1999 IPCC Special Report, a number of scientific assessments of aviation's climate impacts have been conducted [31, 33]. Despite these advances in the details of the underlying science, uncertainties on non-CO_2 effects remain. The climate effects of emissions from aviation were reassessed in 2020 and are presented as Effective Radiative Forcing (ERF) in Figure 2.5. Red bars indicate warming effects and blue bars indicate cooling effects. Numerical best estimate ERF and RF values are given in the columns with 5–95% confidence intervals along with ERF/RF ratios[21] and confidence levels.

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[21] The change in metric from RF to ERF resulted in a 50% reduction in the overall estimated climate change effect from contrail-cirrus.

Radiative Forcing Metrics

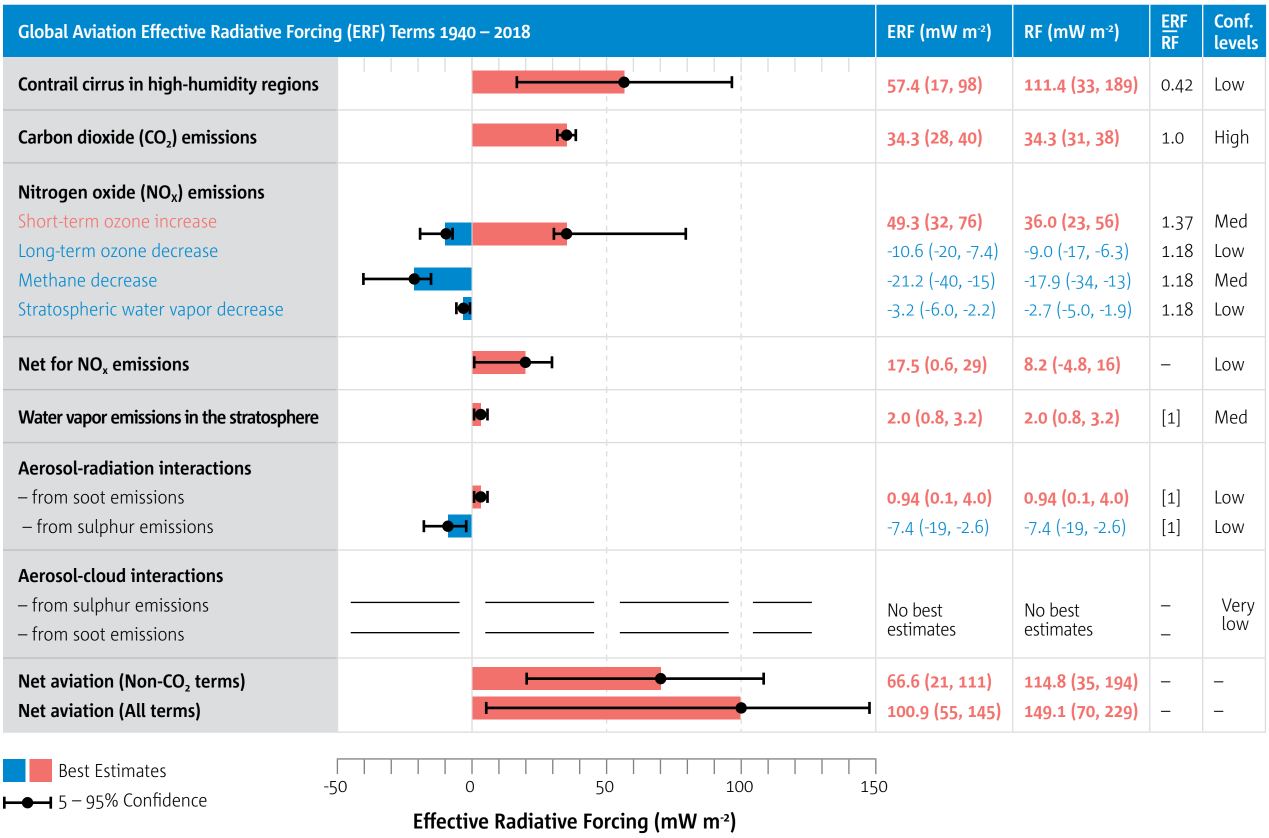
Radiative Forcing (RF) is a term used to describe when the amount of energy that enters the Earth's atmosphere is different from the amount of energy that leaves it. Energy travels in the form of radiation: solar radiation entering the atmosphere from the sun, and infrared radiation exiting as heat. If more radiation is entering Earth than leaving, then the atmosphere will warm up thereby forcing changes in the Earth's climate. The metric Effective Radiative Forcing (ERF) was introduced in the IPCC Fifth Assessment Report in 2013 as a better predictor of the change in global mean surface temperature due to historic emissions by also accounting for rapid adjustments in the atmosphere (e.g. thermal structure, clouds, aerosols etc.).

Figure 2.5 suggests that non-CO_2 emissions represent the largest fraction of the total ERF of aviation, at present, although the level of uncertainties from the non-CO_2 effects is 8 times larger than that from CO_2, and the overall confidence levels of the largest non-CO_2 effects are 'low'. While no best estimates of ERF have been provided for the aerosol-cloud interactions from sulphur and soot emissions, these should not be ignored since they could potentially be important.

Options to mitigate climate impacts

The effects of CO_2 on climate are well understood and well-quantified, and so measures put in place to reduce CO_2 will mitigate the contribution of aviation emissions to climate change. A similar level of understanding should be sought on the effects of non-CO_2 emissions. Based on the precautionary principle, cost-effective actions should be considered in order to reduce the overall climate impact from all aviation emissions, taking into account the prevailing uncertainties in non-

Figure 2.5 Best-estimates for climate forcing terms from global aviation from 1940 to 2018 [33]



Global Aviation Effective Radiative Forcing (ERF) Terms 1940 – 2018	ERF (mW m⁻²)	RF (mW m⁻²)	ERF/RF	Conf. levels
Contrail cirrus in high-humidity regions	57.4 (17, 98)	111.4 (33, 189)	0.42	Low
Carbon dioxide (CO_2) emissions	34.3 (28, 40)	34.3 (31, 38)	1.0	High
Nitrogen oxide (NO_X) emissions				
Short-term ozone increase	49.3 (32, 76)	36.0 (23, 56)	1.37	Med
Long-term ozone decrease	-10.6 (-20, -7.4)	-9.0 (-17, -6.3)	1.18	Low
Methane decrease	-21.2 (-40, -15)	-17.9 (-34, -13)	1.18	Med
Stratospheric water vapor decrease	-3.2 (-6.0, -2.2)	-2.7 (-5.0, -1.9)	1.18	Low
Net for NO_x emissions	17.5 (0.6, 29)	8.2 (-4.8, 16)	–	Low
Water vapor emissions in the stratosphere	2.0 (0.8, 3.2)	2.0 (0.8, 3.2)	[1]	Med
Aerosol-radiation interactions				
– from soot emissions	0.94 (0.1, 4.0)	0.94 (0.1, 4.0)	[1]	Low
– from sulphur emissions	-7.4 (-19, -2.6)	-7.4 (-19, -2.6)	[1]	Low
Aerosol-cloud interactions				
– from sulphur emissions	No best estimates	No best estimates	–	Very low
– from soot emissions			–	
Net aviation (Non-CO_2 terms)	66.6 (21, 111)	114.8 (35, 194)	–	–
Net aviation (All terms)	100.9 (55, 145)	149.1 (70, 229)	–	–

CO_2 effects as part of a risk-based assessment in order to ensure confidence in robust mitigation gains.

A recent study considered a scenario where global aviation CO_2 emissions were reduced by 2.5% every year from 2025 until 2050, and air traffic was reduced to about 50% compared to pre-COVID levels (similar to air traffic in summer 2020). It was concluded that the impacts of the continued rise in accumulated long-term CO_2 emissions and the fall in short-term non-CO_2 emissions would balance each other out, thereby leading to no further increase in current aviation-induced warming [28]. As such, the non-CO_2 share of total aviation climate forcing is not a constant and depends entirely on the rate of change of CO_2 emissions.

Environmental certification standards already exist for various aircraft engine non-CO_2 emissions, including NO_X and nvPM. In developing and implementing further EU policies to reduce aviation non-CO_2 emissions, the evolving scientific uncertainty of their precise climate change impact is important and needs to be taken into account. In addition, there is a need to assess possible trade-offs between the CO_2 and non-CO_2 climate impacts. A common scale known as a 'net CO_2-equivalent emissions metric' is often used, although it is important to note that this comparison will vary depending on the metric and time horizon used[22].

One possible policy option being considered is to lower the concentration of aromatics (and sulphur) in fuels in order to obtain a cleaner burn and potentially less contrail cloudiness, while another potential option is the mitigation of contrail-cirrus clouds through the re-routing of flights around ice-supersaturated air regions [32, 34, 35, 36, 37]. Win-win policy options that deliver reductions in both CO_2 and non-CO_2 emissions, such as the rapid uptake in Sustainable Aviation Fuels, could ensure 'no regret' actions.

Where trade-offs occur, a robust policy assessment methodology is essential to ensure the proposed policy leads to a reduction in the overall climate impact from aviation. Specific research to address knowledge gaps has been identified in order to inform potential policy options to abate the climate impact of non-CO_2 emissions [13].

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[22] For example, one such metric is the Global Warming Potential for aviation effects over a time-horizon of 100 years (GWP100), where a multiplier of 1.7 is applied to the CO_2 emissions in order to account for the impact of non-CO_2 emissions. In comparison, the Global Temperature Potential metric (GTP100) has a multiplier of 1.1.

2.4 ADAPTING AVIATION TO A CHANGING CLIMATE

Climate change-induced phenomena are a tangible and growing risk to the European aviation sector, with stakeholders already experiencing its impacts in the form of higher temperatures; changes in rain, snow, wind, and storm patterns; more frequent and persistent droughts and wildfires; sea level rises and thawing permafrost (Figure 2.6).

According to the ACI World 2020 stakeholder survey, 53% of the European respondents representing airports stated that they have already been affected by adverse weather [38]. However, the IPCC 6th Assessment Report of Working Group II on Impacts, Adaptation and Vulnerabilities notes that the sector is still in the earlier stages of adaptation [25].

By the end of the century, under a high warming scenario, up to 200 airports across the EU could face the risk of inundation due to sea level rise and extreme weather events. The majority of these are small airports with less than 10,000 air traffic movements per year. Nonetheless, many are important for connectivity and economic reasons. The cost of diverted and cancelled flights from a one-day closure at an airport due to full flooding is estimated to be around €3 million for medium-size airports and €18 million for large airports [39, 40].

In addition, higher temperatures will also impact aircraft performance, potentially necessitating a reduction in maximum take-off weight at airports with shorter runways [41]. As such, stakeholders need to further adapt and build resilience to these impacts by integrating climate change considerations into their planning processes and future investments.

Responding to climate impacts through policy and practice

At the international level, ICAO has published a Climate Change Adaptation Synthesis and guidance material on climate change risk assessment and adaptation planning [42]. Within the EU, the Climate Adaptation Strategy [43], in agreement with the Sustainable and Smart Mobility Strategy [44] and ongoing policy review of the Trans-European Transport Network, commits to actively mainstream climate resilience considerations in all relevant policy fields. This is to be done by integrating climate resilience considerations into the criteria applicable to construction and renovation of critical infrastructure. At the national level, according to a 2018 EEA survey, 17 out of the surveyed 23 European states responded that transport was covered in their national climate change vulnerability and risk assessments [45].

While climate-proofing critical infrastructure may add an additional upfront cost of around 3% to a project, resilience investments have a cost-benefit-ratio of about 1:4 [46]. European Standardisation Organisations have updated standards governing the safety and performance of infrastructure in a changing climate.

Knowledge gaps in the understanding of the links between long-term climate change and risks to the aviation sector need to be addressed, so as to inform a coherent strategy and short-term decision-making. This can be facilitated by greater coordination across the sector [47].

Figure 2.6 Climate change risks for European Aviation

	Climate effect	Impact on aviation		
Temperature increase	Europe continues to warm more quickly than the global average. Projected increase in mean and extreme temperatures across entire Europe.	Aircraft performance	Heat damage to infrastructure, equipment and cargo	Seasonal and geographical changes in tourism demand patterns
Changes to rain and snow patterns	Projected decrease in mean precipitation in the South, increase in the North More heavy rainfall events Less snow overall, but possibly heavier snowfall events	Delays and cancellations	Flooding of airports and access routes	Change in snow clearance needs
Changes to storm patterns	By 2050 major storms may be less frequent but more intense.	Delays, re-routing, increased fuel burn	Damage to airport terminals and navigation equipment	Convective weather affecting multiple airports
Changes to wind and windstorm patterns	Change in jet stream strength, position and curvature. Deviations in prevailing wind direction Increase in extreme wind speeds in North and Central Europe.	Damage to airport terminals and navigation equipment	Variability in trans-Atlantic times and routes	Crosswind changes affecting airport capacity
More frequent and persistent droughts	Droughts are expected to increase in the South. In Western and Central Europe increase of droughts is at medium confidence.	Changing ground conditions, subsidence	Damage to infrastructure such as runways and taxiways	Dust from dry soil reducing visibility
Increasing frequency and magnitude of wildfires	Currently predominantly affecting South Europe, where fire danger is projected to increase in the future. An expansion of fire-prone areas and longer fire seasons are projected in most European regions	Delays, rerouting and cancellations due to fire and smoke risks	Fire damage to infrastructure	
Sea level rise	Sea level rise Uncertainty over storm surges.	Permanent or temporary loss of airport capacity, infrastructure and access.	Operational disruption	
Permafrost thawing	High mountains and Northern Europe (Arctic region). Permafrost is very likely to undergo increasing thaw and degradation	Damage to infrastructure (runways/ taxiways and airport infrastructure)	Airport closures	

STAKEHOLDER ACTIONS

Climate Change Risk Assessment at Athens International Airport

In 2018, Athens International Airport (AIA) produced its first climate change risk assessment and Climate Change Adaptation Report for two timescales, 2040 and 2070. Changes to temperature and rain patterns are expected to be the main challenges. Maximum hourly summer temperatures will increase by 1.6°C in 2040, and by 4°C in 2070, which will significantly increase the number of days with thermal discomfort and strong cooling demand. Precipitation patterns will also change. Maximum 3-day rainfall[23] is expected to grow by 6% by 2040, and 20% by 2070. In addition, AIA is working with the national authorities to assess the risks to transport services to the airport, and to incorporate adaptation into future development plans.

AIA has identified a number of adaptation measures to protect outdoor employees from increased temperatures, such as increasing staffing levels to allow for shorter shifts, training in how to deal with heat during shifts, and the provision of air conditioning in public areas and airport vehicles. With regard to the projected increase in precipitation, good maintenance practices for both the drainage and fuel supply systems are considered essential. Design standards and construction practices are to be reviewed, and updated if required, for areas which may experience inundation. The risk assessment and adaptation plan is due to be reviewed every five years.

Climate adaptation at Norwegian airports

The climate in Norway is expected to become warmer and wetter, with more weather extremes. This will impact the 44 airports that Avinor is responsible for, but in different ways. Avinor started to investigate how a changing climate would impact the aviation infrastructure and operations in Norway at the start of this century. Several risk reduction measures have been carried out over the years, such as including preventive measures in master planning, wave barriers, erosion protection and improved drainage.

During Autumn 2021, the climate adaptation risk assessment was updated, taking into account the latest climate projections. The consequences of these findings are currently being assessed, and Avinor are looking into whether the previously proposed risk reduction measures are still adequate or if new measures are needed. Systems for monitoring and maintaining Avinor's airport infrastructure have also been significantly improved and now accommodate climate change risk reduction measures. Risk matrices in the revised report have been adapted to those used in Avinor's general Operational Risk Database, such that physical climate risk can be included in scorecards at airports and will provide for more systematic follow-ups.

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[23] The maximum rainfall experienced in one 3-day period in one year.

3

TECHNOLOGY AND DESIGN

- **New aircraft designs certified during the last 10 years (e.g. Airbus A320neo, A350 and Boeing 737MAX, 787) have a cumulative margin of 5 to 15 EPNdB below the latest Chapter 14 noise standard.**
- **While certification activities have recently reduced for conventional aircraft, they have increased in new market segments (e.g. Drones, Urban Air Mobility).**
- **EASA is developing dedicated noise certification standards for Drone and Urban Air Mobility aircraft that take into account their specific characteristics.**
- **In-production engine types were designed prior to the new non-volatile Particulate Matter (nvPM) standards and manufacturers are evaluating how to mitigate nvPM emissions in new engine designs.**
- **The engine NO_X/nvPM standards, and the aircraft noise/CO_2 standards, define the design space for products to simultaneously address noise, air quality and climate change issues.**
- **Pipistrel Velis Electro became the first fully electric general aviation aircraft to be certified by EASA in 2020 and is now being used by pilots to learn to fly.**
- **In 2021, the Airbus A330-900neo was the first aircraft to be approved worldwide against the new aeroplane CO_2 emissions standard, although certified aeroplane CO_2 data remains limited.**

The aviation industry is well known for driving forward leading-edge technological developments that filter through and benefit other sectors, such as the use of composites and 3-D printing. Following the certification of a variety of new aircraft types over the last decade (e.g. Boeing 787 and 737MAX; Airbus A350, A330neo and A320neo), the level of aircraft certification activity has reduced. The penetration of these aircraft types into the global fleet, and the accelerated retirement of older aircraft due to COVID, has led to improvements in the overall environmental performance of the European fleet.

Aircraft and engine environmental certification standards [1, 2, 3, 4] are implemented by EASA within the EU and EFTA. This Chapter focuses on the latest certified data for traditional subsonic aircraft and engine designs, which enables a comparison of the environmental performance of aircraft and their engines. It also provides an overview of the growing work associated with new environmental standards for emerging novel designs. Detailed data on products and interactive figures, as well as an overview of the noise and emissions certification measurement procedures, are available on the European Aviation Environmental Report website.

3.1 AIRCRAFT NOISE

Certified noise levels

The noise certification standards for the aircraft types in Table 3.1 are referred to as Chapters 3, 4 and 14[24], and they became applicable from 1977, 2006 and 2018 respectively.

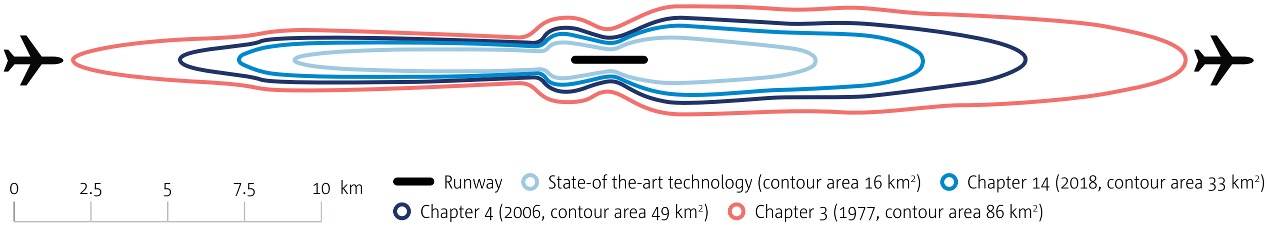
The noise contours in Figure 3.1 illustrate the differences on an operational basis between these noise certification standards. They represent three single aisle aircraft, with a maximum take-off mass (MTOM) of 75 tonnes, that just meet the limits of the Annex 16 Volume I Chapters and an aircraft that represents the state-of-the-art in-production single aisle aircraft technology. The footprints are areas that are exposed to noise levels greater than 80 dB during one landing and take-off, and indicate the reduction in aircraft noise from a technology/design perspective over time based on Annex 16 Volume I standards.

Figure 3.2 illustrates the historic trend in certified aircraft noise levels in terms of the cumulative[25] margin to the Chapter 3 limits for the heaviest weight variants and maximum thrust rating for an aircraft type [5]. Aircraft designs certified during the last 10 years (e.g. Boeing 737MAX, 787; Airbus A320neo, A350, A330neo) have a cumulative margin of 5 to 15 EPNdB below the latest Chapter 14 standard. The general trend over the last three years has seen marginal noise improvements to these aircraft designs.

Table 3.1 Description of aircraft categories

Aircraft Category	Definition	Examples of aircraft types
Twin-aisle jets	Large jet-powered aircraft for medium and long-range operations	Airbus A330, A340, A350, A380; Boeing 747, 767, 777, 787
Single-aisle jets	Jet-powered aircraft intended for short to medium-range operations	Airbus A319, A320, A321; Boeing 737-700, 737-800, 737-900, 737MAX
Regional jets	Jet-powered aircraft intended for short-range operations	Airbus A220; MHI CRJ Series; Embraer EMB145, ERJ-170, ERJ-190
Turboprops	Turboprop-powered aircraft (does not include small general aviation aircraft)	ATR 42, 72; DHC Dash 8
Business jets	Small jet-powered aircraft with a seating capacity of 19 or less	Beech 400A; Cessna 525, 650, 750; Dassault Falcon 2000, 7X; Gulfstream G450, G550

Figure 3.1 Single landing and take-off 80 dB noise contours for aircraft that just meet the noise limits of the Annex 16 Volume I chapters plus a state-of-the-art in-production aircraft



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[24] These are chapters of ICAO Annex 16 Volume I, a document that contains international aircraft noise standards.

[25] 'Cumulative margin' is the sum of the individual margins (difference between certified noise level and noise limit) at each of the three Chapter 3 noise measurement points, expressed in Effective Perceived Noise deciBels (EPNdB).

Figure 3.2 Reduction of certified aircraft noise levels over time in relation to the cumulative margin to Chapter 3

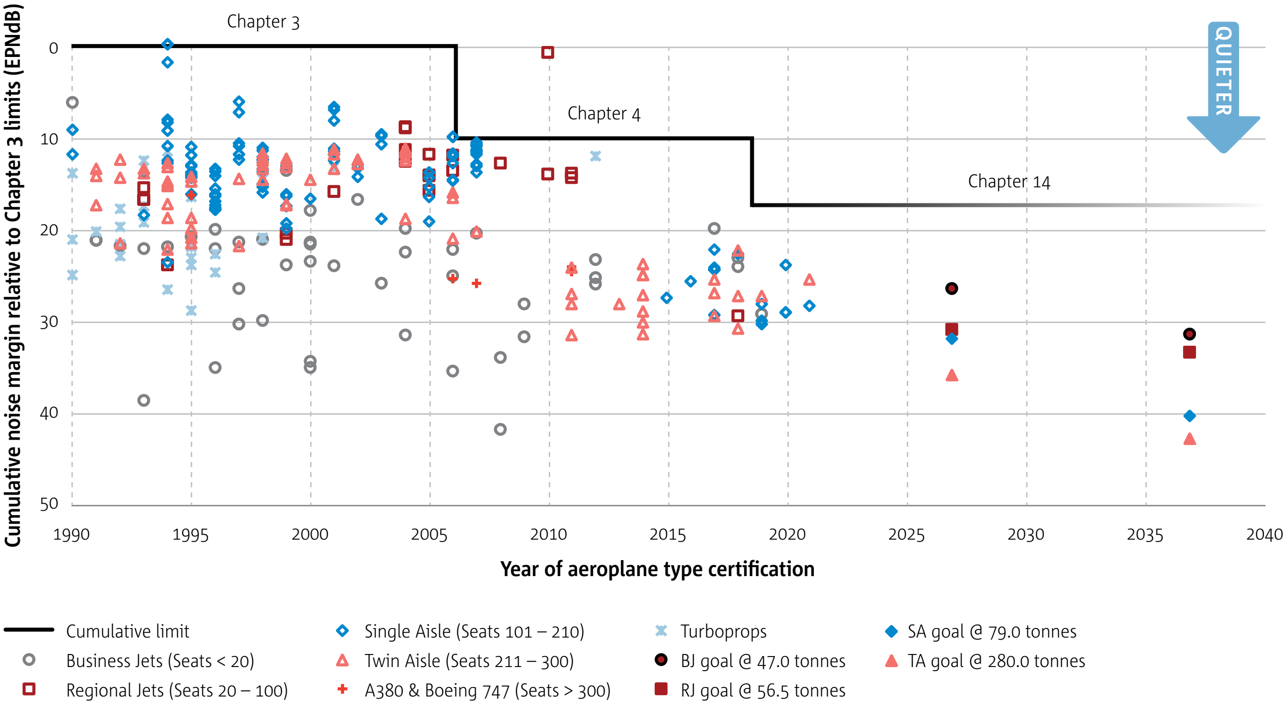
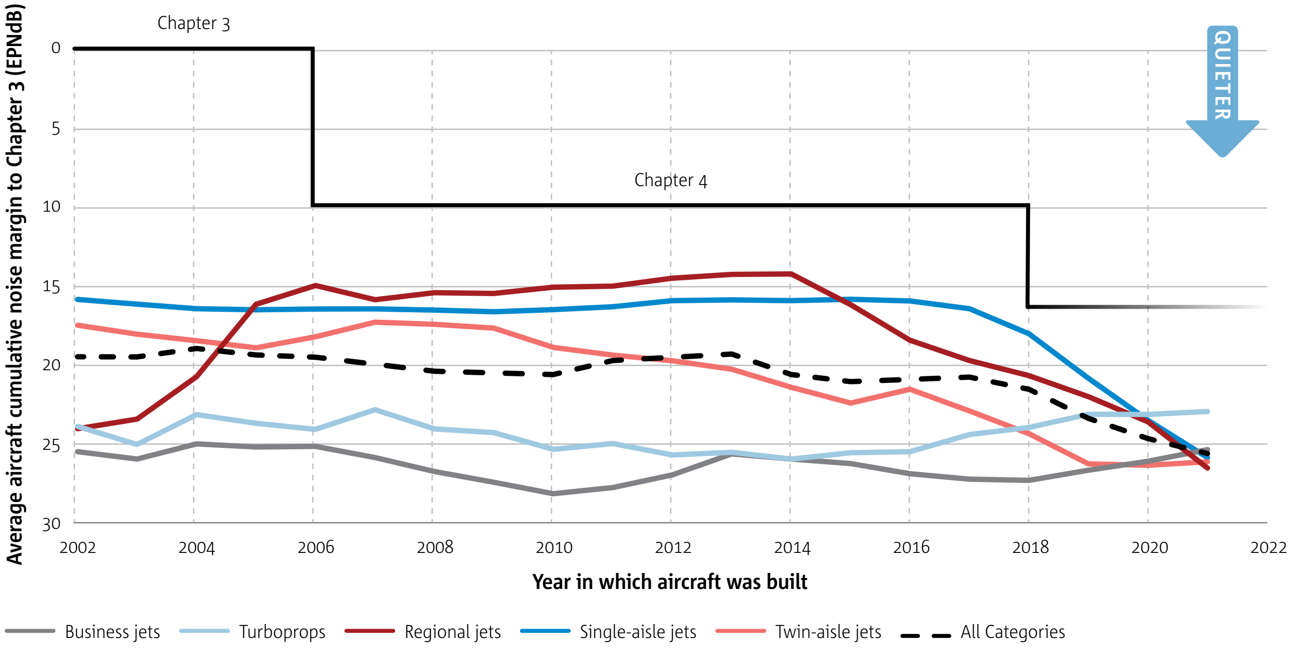


Figure 3.3 Average cumulative noise margin to Chapter 3 for in-service aircraft within the current European fleet



Future developments in technology were considered by an Independent Experts Panel on behalf of the ICAO Committee on Aviation Environmental Protection (CAEP) in 2019 [6]. In terms of what leading edge technology could achieve in 2027 and 2037, they agreed on noise goals across four aircraft categories that included business jets (BJ), regional jets (RJ), single aisle (SA) and twin aisle (TA). Figure 3.2 also captures these data points which provide an indication as to how aircraft noise performance may evolve in the future.

Noise performance of European fleet

In comparison to the section on certified data for specific products, this section provides insight into the noise performance of the in-service fleet registered in EU27+EFTA at the start of 2022. Figure 3.3 represents the average noise margin to the Chapter 3 limit for all aircraft built in a given year, and plotted according to the same categories as the certified data section.

As predicted in the last report, the average margin to the Chapter 3 limit for the single-aisle market has improved by about 10 EPNdB through the recent introduction of the Airbus A320neo and Boeing 737MAX aircraft. There has also been an equivalent reduction in the certified noise levels of regional jets due to the introduction of the Airbus A220 and the Embraer E2-series. Other categories show level or slightly rising noise levels in recent years.

3.2 AIRCRAFT ENGINE EMISSIONS

The reduction in fuel burn and related CO_2 emissions continues to be the overriding factor in engine technology developments. However, the higher temperatures and pressures needed for improved fuel efficiency often have a trade-off in the form of increased emissions of nitrogen oxides (NO_X) unless mitigated through the design of the engine and control of the combustion process. The engine NO_X and nvPM standards[26], and the aircraft noise and CO_2 standards, define the design space for products to simultaneously address noise, air quality and climate change issues.

NO_X emissions

The regulatory limits[27] for NO_X emissions from aircraft turbojet and turbofan engines have gradually been made more stringent between 1996 and 2014, and are typically referred to by the CAEP meeting in which they were agreed (CAEP/2, CAEP/4, CAEP/6 and CAEP/8).

Figure 3.4 contains certified engine NO_X emissions data, including recent data from 2019-2021 [7]. It highlights that the most advanced NO_X mitigation technology is not yet available across all engine types, and that engines at high Overall Pressure Ratios (OPR)[28] have a smaller margin to the latest CAEP/8 limit. The 2019 ICAO Independent Experts Panel goal for leading edge NO_X emissions performance in 2027 is also shown in the figure. While a number of engines with moderate OPR (<40) have almost reached this goal, it appears more challenging for engines with higher pressure ratios. A goal for 2037 was not set as more evidence was sought on the need in terms of harm to health and impact on climate.

In 2021, more than 95% of aircraft engines delivered were CAEP/8 compliant. As such we have seen a similar trend to aircraft noise (see Figure 3.3), where the average NO_X performance of aircraft in the current European fleet that have been built over the last few years has also improved due to the entry into service of the new aircraft types and their respective engines (e.g. CFM LEAP-1x, PW 11xxG).

nvPM emissions

The original engine Smoke Number standard was put in place during the 1970s to control the visible pollution from aircraft emissions. It was recognised that this did not directly address health impacts and therefore non-volatile Particulate Matter (nvPM) standards have subsequently been developed to replace it. As of 1 January 2020, a mass concentration nvPM standard has been applicable to all in-production engines, while the mass and number nvPM standards will become applicable as of 1 January 2023. EASA has integrated all of the new nvPM standards into European legislation

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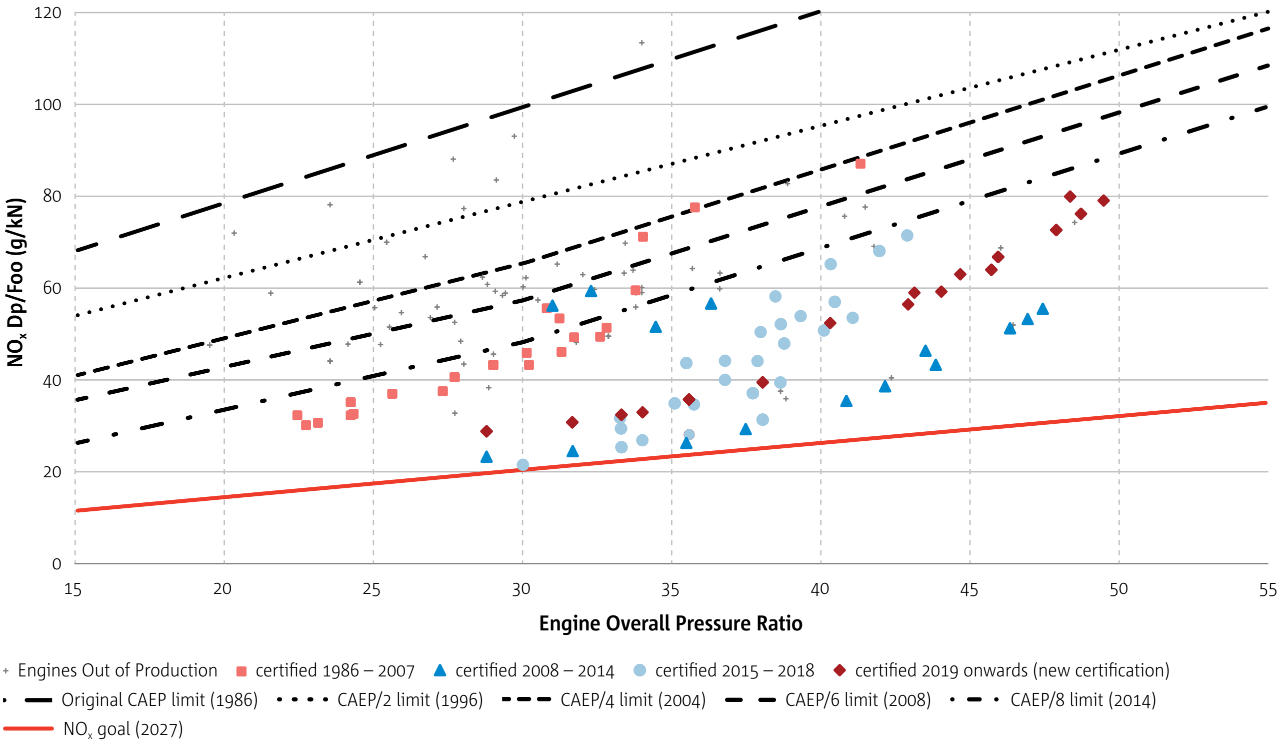
[26] ICAO Annex 16 Volume II contains international aircraft engine emissions standards.

[27] NO_X limits are defined as the mass (Dp) of NO_X emitted during the Landing and Take-Off (LTO) test cycle and divided by the thrust of the engine (Foo). The limit also depends on the overall pressure ratio of the engine.

[28] Ratio of total pressure at compressor exit compared to pressure at engine inlet.

Figure 3.4 Certified turbojet and turbofan engine NO_X emissions performance



[1], and has started to process certification applications prior to the applicability deadlines.

Figure 3.5 provides schematics of two main combustor concepts that are relevant for a reduction of NO_X emissions. Rich burn-Quick quench-Lean burn (RQL) combustors are characterized by an initial rich fuel-air mixture which is quickly turned (quenched) into a lean mixture by additional air intake. Dual Annular Combustors (DAC) and fuel staged Lean Burn combustors are characterized by two separate combustion zones maintained by a complex fuel injection system. The pilot flame zone is used in low power operation only, while at higher power and in cruise the main lean burner is utilized.

Figures 3.6 and 3.7 contain the new aircraft engine nvPM mass and number emissions data [7], grouped according to different combustor technologies. The y axis in these Figures have been plotted on a logarithmic scale in order to more easily differentiate the nvPM performance of the different combustor types. It should be noted that existing engine types were designed prior to the new nvPM standards coming into force in 2020, and certain designs such as lean burn combustors perform better than others in this area. The 2019 ICAO Independent Experts Panel did not set a technology goal for nvPM improvements as further technical data was needed on the climate and air quality impacts.

Figure 3.5 Schematic of RQL and Lean Burn engine combustors

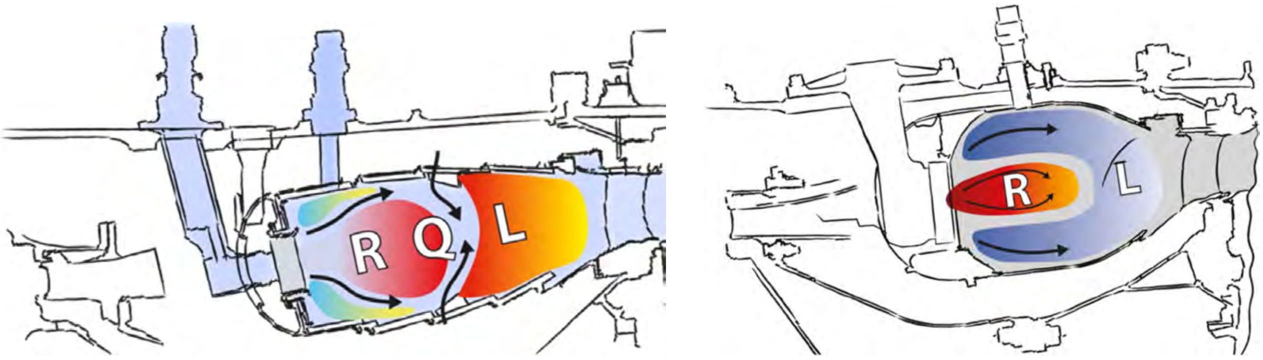


Figure 3.6 Certified data on engine nvPM mass emissions performance

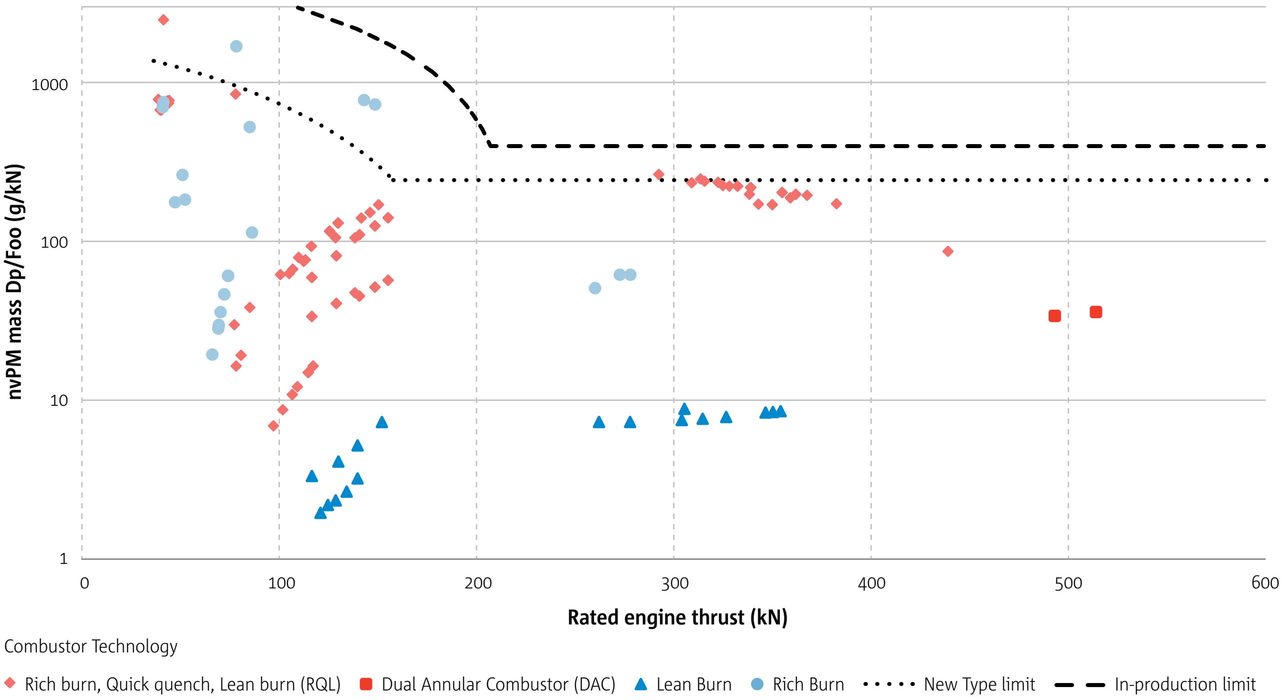
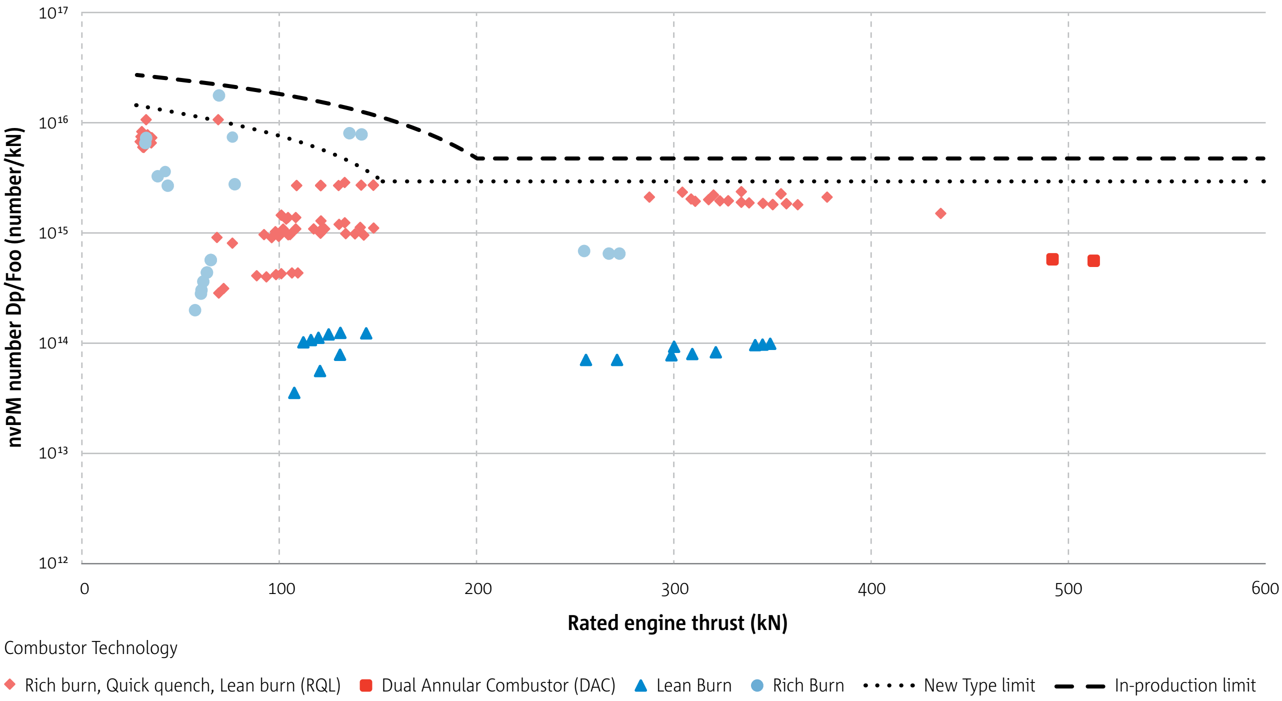


Figure 3.7 Certified data on engine nvPM number emissions performance



3.3 AEROPLANE CO_2 EMISSIONS

The new aeroplane CO_2 standard increases the priority of fuel efficiency in the overall aeroplane design process. It became applicable to new aeroplane types as of 1 January 2020. In comparison to nvPM where engine types were given four years to comply with the in-production standard, aeroplane types were given twelve years to comply with the in-production CO_2 standard, which becomes applicable from 1 January 2028. Consequently, the availability of certified CO_2 data is limited at the moment.

Airbus have voluntarily engaged early in the process and were the first ever manufacturer to apply to EASA to certify a product against the CO_2 standard in 2021. This data on the A330-900neo variants is provided in Figure 3.8 and, as per noise and NO_X, the 2019 ICAO Independent Experts Panel goals for leading edge CO_2 emissions performance in 2027 and 2037 are also shown.

Figure 3.9 presents the estimated average fuel burn performance of newly delivered commercial aircraft from 1960 to 2019 with 1970 as the baseline (1970 = 100) in two metrics – the metric used in the ICAO CO_2 standard and kilograms of fuel burn per tonne-kilometre.

While the annual rate of improvement has varied over time, the figure indicates that the two metrics are well correlated and that a reduction in the ICAO CO_2 standard metric should see an improvement in fuel efficiency in terms of day-to-day aircraft operations (e.g. reduction in fuel burn/tonne-kilometre).

The 2022-2025 work programme in the ICAO environmental committee (CAEP) is reviewing both the aircraft noise and CO_2 emissions standards.

Figure 3.8 **Limited new data on twin aisle aeroplane CO_2 emissions performance**

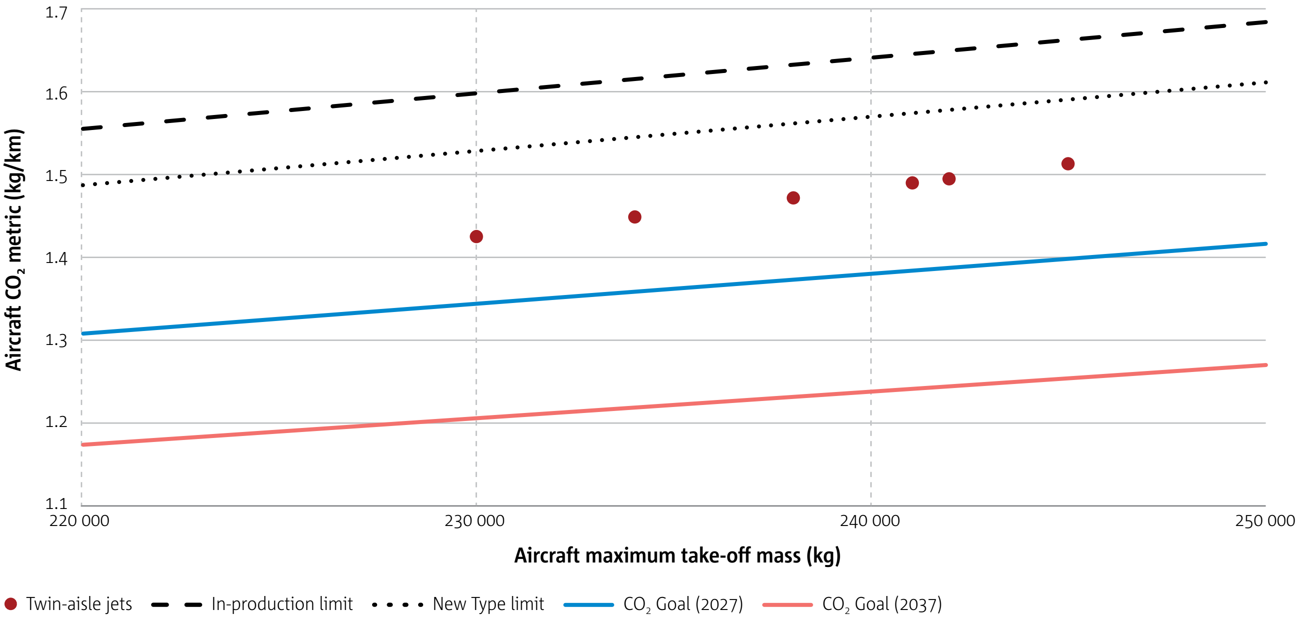
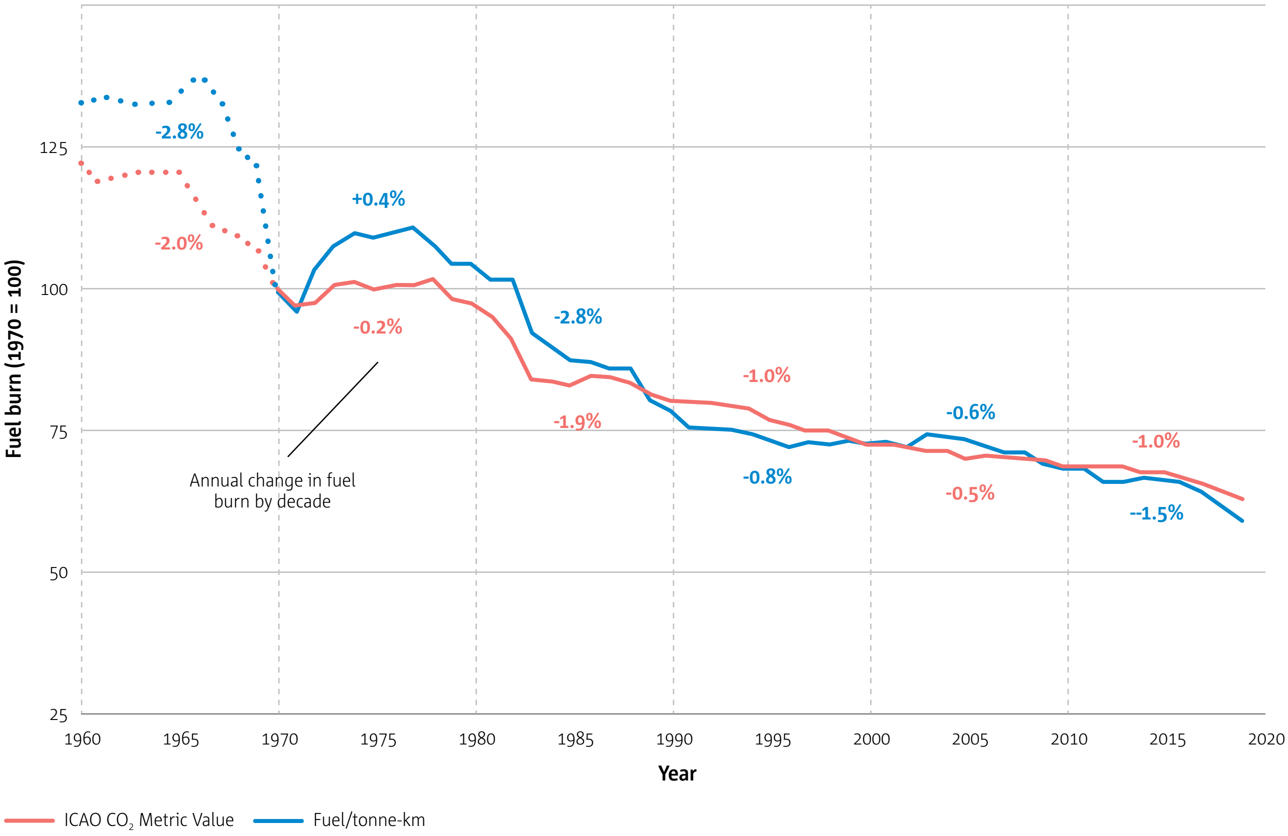
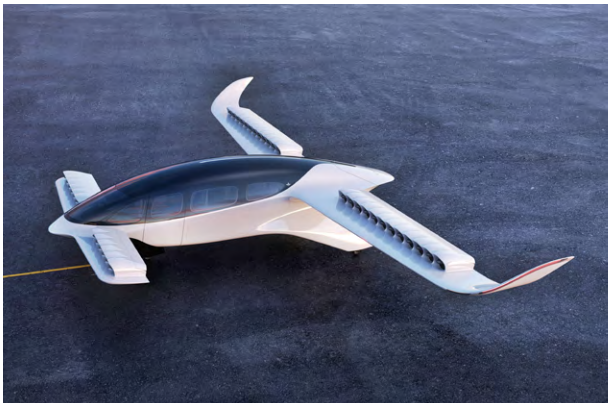


Figure 3.9 **Average fuel burn performance of new commercial jet aircraft, 1960 to 2019 (1970=100) [8]**



3.4 DRONES AND URBAN AIR MOBILITY VEHICLES

In recent years there have been an increasing number of novel technology concepts applying for EASA certification, such as Drones or Urban Air Mobility (UAM) vehicles.



During 2021 EASA published the results of a study on social acceptance of UAM in Europe [9], concluding that noise is the second main concern after safety. The study also confirmed that UAM noise is perceived to be more annoying than other city sounds. To ensure a uniform high level of environmental protection, and to address the noise-related concerns expressed by EU citizens, EASA is developing dedicated noise certification standards that take into account the specific characteristics of these products.

Although the use of electrical propulsion tends to reduce noise compared to conventional aircraft, multiple rotors can create a unique sound. As such, a system of measurement that properly accounts for the resulting annoyance is required, and to that end EASA is conducting extensive studies covering in-the-field testing and psychoacoustics.

In addition , Drones and UAM vehicles feature operational aspects that were not considered when existing aircraft noise standards were developed (e.g. operations close to densely populated areas, high performance climb and steep turn flight profiles due to no pilots or passengers being on board). Understanding how these vehicles are expected to fly, and what their typical missions will be, is also fundamental to developing appropriate noise certification standards [10, 11, 12].

UAM vehicles, such as Lilium, Volocopter and CityAirbus, could offer rapid point to point connectivity, such as between airports and suburban 'city gates' or between cities on a regional basis. A prototype modular vertiport test site, which can be scaled up depending on demand, is already being established by Groupe Aéroports de Paris with the objective of a first commercial flight by 2024. Flight test campaigns are due to start in 2022, during which mitigation measures to manage the noise impact from operations will be assessed in coordination with the local community.

3.5 SUPERSONIC AIRCRAFT

A new generation of supersonic transport (SST) aircraft are under development and are aiming to become operational before 2030. While Aerion, a manufacturer with one of the most advanced supersonic programmes, ceased operations in 2021, Boom Supersonic and others continue to develop their supersonic aircraft concepts.

SST aircraft face various challenges, especially due to the 'sonic boom' they generate when flying at supersonic speed. For this reason, Concorde was limited to subsonic speeds when flying over land and near coastlines. Furthermore, the high speed of supersonic aircraft is likely to result in an ICAO CO_2 standard metric value that is 2 to 3 times higher than comparable subsonic aircraft, and a better understanding is required on the climate change impact from SST non-CO_2 emissions at high altitudes [13, 14].

In the US, a flight demonstrator is being built by NASA to investigate quiet SST technology with the goal to mitigate sonic booms via specifically shaped airframes [15]. Various research projects on SST flight are also being conducted in Europe [16, 17, 18], and in the regulatory domain EASA is actively working on the development of appropriate noise and emissions standards for SST aircraft at both the European and ICAO level. [19]

3.6 NOVEL ENERGY SOURCES

Battery-powered electric aircraft

Electric propulsion was first introduced into the market of self-sustaining sailplanes in 2014. EASA subsequently certified the first ever fully electric general aviation aircraft during 2020 in the form of the Pipistrel Velis Electro. The aircraft is equipped with a battery-based energy storage system coupled with an electro-motor for propulsion that provides 57.6 kW of power. When charged on the basis of renewable energy sources, this allows for a zero emissions flying time of about 55 minutes. With no audible engine noise, it can be up to 10 decibels quieter than an equivalent Pipistrel piston-engine aircraft when measured according to the noise standard of ICAO Annex 16, Chapter 10, which is perceived by people as 50% quieter. The market response to the aircraft has been positive, with Pipistrel planning to increase production capacity to 120 Velis Electro aircraft per year in 2022.

Due to the enhanced noise and emissions performance and limited range, battery-powered electric aircraft have been identified as optimal for pilot training in the vicinity of airfields. They are already being used by Approved Training Organisations in various European States where a new generation of pilots are learning to fly in an electric aircraft. The transition has been incentivised through the use of solar panels on aircraft hangars with battery storage systems and chargers that can be used to support all electric vehicle activities at an airfield. Reductions in operational costs of around 30% have also been achieved through the reduced time needed to warm up the propulsion unit and perform pre-flight checks, leading to more actual flight time.

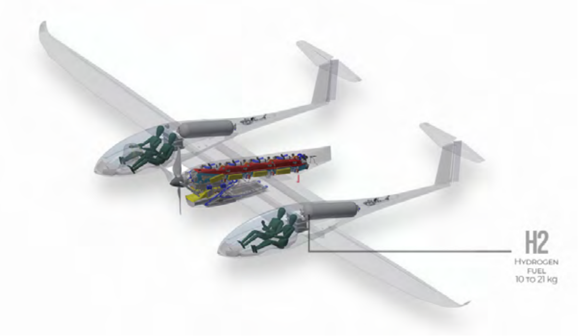
Additional projects are being taken forward by Heart Aerospace for Finnair in the form of a 19-seat regional electric turboprop and Eviation for DHL who expect to deliver an 'eCargo' aircraft in 2024. Hybrid aircraft configurations are also being developed, such as the Tecnam P2010 H3PS. Continuing technical challenges linked to battery technology include the need for increased energy density to reduce weight and increase flight time duration in order to expand the operational uses of electric aircraft.

Hydrogen-powered aircraft

The use of hydrogen as an aircraft fuel or energy source has previously been shown to be technically feasible, with one engine on a Tupolev Tu-155 modified to run on hydrogen in the 1980s. The price and availability of hydrogen within the aviation system, as well as the complexity of on-board storage have until recently made this architecture unattractive when compared to use of kerosene-based fuels. The increased focus on CO_2 emissions, coupled with the greater availability of renewable energy sources that permit the production of "green hydrogen" have rekindled interest in this potential alternative. The Airbus ZEROe initiative is aiming to develop a zero CO_2 emission commercial aircraft that will enter into service by 2035.

Hydrogen can be used in conjunction with fuel cells to produce electricity to power electric motors, or through combustion in a gas turbine engine, similar to kerosene, to provide mechanical energy. When used within fuel cells the only emission is water, whereas hydrogen powered gas turbines generate combusted emissions, including water and NO_X. In both cases the water vapour emissions are markedly higher than those from kerosene. However, particulate matter emissions are considered to be zero, and hence the formation of persistent contrail-induced cirrus is likely to be less pronounced. The latest estimates suggest that hydrogen used in conjunction with fuel cells could reduce the climate impact in flight by 75 to 90 percent, and when used for combustion the reduction could be 50 to 75 percent [20, 21]. However, further research is needed in this area to fully understand the emissions reduction that could be achieved and the associated impacts.

Some early hydrogen powered prototypes are being developed, such as APUS i-2, H2FLY's HY4 and ZeroAvia's retrofitted Piper M-class. However, technical challenges remain. While the higher energy density of hydrogen would allow for a significant reduction in required fuel mass, the volume of hydrogen would need to be four times more compared to kerosene for the same amount of energy, even when stored in liquid form at -253°C. In order to address these challenges, one of the three pillars within the Clean Aviation research initiative is hydrogen and is focused on developing the associated technology and regulatory requirements.



3.7 CIRCULAR ECONOMY

The 4R's of the circular economy concept (Redesign, Repair, Reuse, Recycle) consider the complete lifecycle of a product from production to disposal with the objective of an efficient use of resources and a reduction in waste.

In March 2020, the European Commission adopted the new circular economy action plan [22], including initiatives on the entire lifecycle of products within the Sustainable and Smart Mobility Strategy. From an aviation perspective, this involves the development of smart aeronautical products that consider sustainable life-cycle management during the initial design stage. Research on this topic is being taken forward within the SUSTAINAIR project [23], where EASA is providing advice on certification and regulatory aspects to reduce the time needed to bring these new technologies to the market.

Components representing on average 85% to 90% of an aircraft's weight are currently either recertified by an approved maintenance organisation as safe for reuse as spare parts or their material is recycled, while two manuals are currently available to ensure that best practices are applied in this process [24, 25].

3.8 CLEAN SKY

Clean Sky 2 (2014-2024), which is part of the EU Horizon 2020 programme, has a combined public and private budget of just under €4 billion. It aims to develop, demonstrate, and accelerate the integration of technologies capable of reducing CO_2, NO_X and Noise emissions by 20 to 30% compared to state-of-the-art aircraft in 2014, with a market deployment within the decade after the programme's end in 2024.

EASA Environmental Labelling

European citizens and passengers wish to be informed about the environmental footprint of their flights and make sustainable choices.[29] However, the figures of CO_2 emissions provided to passengers by various booking sites for their flight can vary by a factor of 2 to 5. Consequently, citizens have no verified and consistent source of information to make informed sustainable travel choices. The credibility of industry 'green claims' are also often questioned as regards environmental performance and carbon compensation schemes. In order to address this, the European Commission, EU Parliament, and Member States mandated EASA to develop Environmental Labelling for the aviation system as part of the Smart and Sustainable Mobility Strategy, with an initial technical delivery of the programme by the end of 2022 and further updates to be implemented in a phased approach. The programme is being closely coordinated with related European Commission initiatives including the Green Claims, Sustainable Products and CountEmissionsEU.

The labelling system aims to provide transparency on the environmental footprint at a flight level through a distinct score based on CO_2 emissions per passenger and flight, which is discounted by SAF emissions reductions and relies on actual fuel burn data. Online Travel Agencies and Global Distribution Systems have joined the programme to facilitate digital distribution of this information. It will also consider an airline label that tracks the airline path towards sustainable aviation through multiple stages with a mix of indicators to document continuous improvement in line with Green Deal and Paris Agreement objectives. Finally, an aircraft label will be based on EASA certified data for CO_2, noise, and engine emissions. In order to allow intermodal comparisons and future technologies, this methodology is being expanded to include the full life-cycle emissions of the aircraft.

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[29] 3 out of 4 European citizens would like an environmental label for aviation, according to a representative survey conducted by EASA in October 2020 with 9000+ respondents from 18 European countries.

The benefits and potential impact from Clean Sky 2 research are evaluated through a dedicated Technology Evaluator function with key assessment and reporting duties. Inputs for this assessment include criteria such as fuel saving, weight saving, maintenance or production improvement, overall aircraft system improvement, and noise reduction. The Technology Evaluator provides integral reports encompassing forecast performance of the Clean Sky 2 technological solutions at the aircraft, airport, and fleet level in terms of their contribution to Clean Sky's high level environmental objectives for CO_2, NO_X, and noise. An interim assessment by the Technology Evaluator was performed in 2021 [26] and concluded that good progress had been made towards the programme's objectives (Table 3.2) resulting in a reduction of CO_2 and NO_X emissions of about 15% and 31% per seat kilometre as compared to a 2050 global traffic scenario incorporating only 2014 reference technology.

CLEAN AVIATION

Building on Clean Sky 2, the new Clean Aviation Joint Undertaking was established in November 2021 and will pave the way towards the EU's ambition of climate neutrality by 2050. This new programme will focus research and demonstration in three areas that are expected to drive future energy efficiency and potential emissions reduction of future aircraft, including :

- **Hybrid electric and full electric architectures** – Research on novel electrical power architectures and their integration. Maturing technologies towards the demonstration of novel configurations, on-board energy concepts and flight control.

- **Ultra-efficient aircraft architectures** – Short, medium, and long-range aircraft architectures making use of highly integrated, ultra-efficient thermal propulsion systems to support the transition to low/zero emission energy sources (e.g. synthetic fuels, hydrogen).

- **Disruptive technologies to enable hydrogen-powered aircraft** – Enable aircraft and engines to exploit the potential of hydrogen as a non-drop-in alternative zero carbon fuel.

The programme will focus on early adoption and market deployment in the 2035 timeframe within the key market segments of regional, short, and short/medium range aircraft that cover over half of global aviation emissions. The targeted .performance levels are summarised in Table 3.3

Table 3.2 Interim Clean Sky 2 Technology Evaluator global assessment results

MISSION LEVEL ASSESSMENT			
Concept model	-CO_2	-NO_x	NOISE
Long Range	-13%	-38%	<-20%
Short-Medium Range	-17% to -26%	-8% to -39%	-20% to -30%
Regional	-20% to -34%	-56% to -67%	-20% to -68%
Commuter and Business Jet	-21% to -31%	-27% to -28%	-20% to -50%
AIRPORT LEVEL ASSESSMENT			
	-CO_2	-NO_x	NOISE AREA
Airport Level	-8% to -13.5%	-6.5% to -10.5%	-10% to -15%
FLEET LEVEL ASSESSMENT			
	-CO_2	-NO_x	FLEET RENEWAL
Global Fleet Level	-14% to -15%	-29% to -31%	70% to 75%

Table 3.3 Clean Aviation Targets

Aircraft Class	Key technologies and architectures to be validated at aircraft level in roadmaps	Entry-into-service (EIS)	Fuel burn reduction (technology-based)*	Net emissions reduction – i.e. including fuel effect **	Current share of air transport system emissions
Regional Aircraft	Hybrid-electric, distributed propulsion coupled with highly efficient aircraft configuration	~2035	-50%	-90%	~5%
Short-Medium Range Aircraft	Advanced ultra-efficient aircraft configuration and ultra-efficient gas turbine engines, ultra-high bypass (open rotor or ducted fan)	~2035	-30%	-86%	~50%

* Improvement targets are defined as fuel burn reduction compared to 2020 state-of-the-art aircraft available for order/delivery.

** Assumes full use of SAF at a state-of-the-art level of net 80% carbon footprint reduction compared to fossil based fuels (or where applicable zero-carbon electric energy). SAF figures do not refer to potential emissions reduction based on hydrogen as energy. For this and assuming renewable production of hydrogen, the CO_2 emissions would be zero.

STAKEHOLDER ACTIONS

AeroSpace and Defence Industries Association of Europe (ASD)

ASD is the European Aeronautics, Space, Defence and Security Industries with 19 major European companies and 23 national associations from 18 countries. In 2020, 884,600 people were employed by more than 3,000 companies generating a turnover of €229.7 billion.

ZEROe – The future of flight with green hydrogen

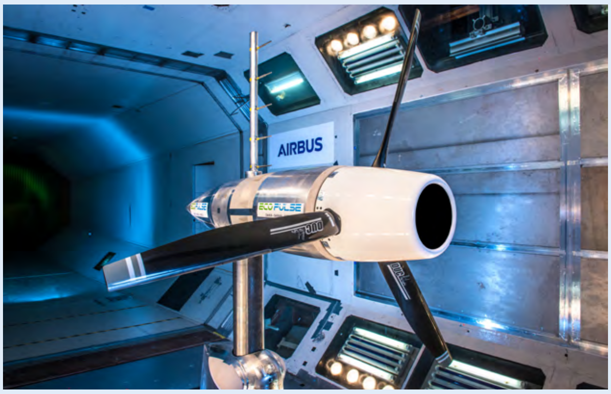
In 2020, Airbus announced their ambition to develop the world's first zero-emission commercial aircraft by 2035. Hydrogen propulsion will help deliver on this ambition. The Airbus ZEROe concept aircraft are enabling the company to explore a variety of configurations and hydrogen technologies that will shape the development of their future zero-emission aircraft.

Electrical/Accel – Electrifying aviation

Rolls-Royce electrification work, for projects such as small propeller aircraft, air taxis, commuter and regional aircraft, ranges from kilowatt to megawatt (MW) power. One example is Accel that has set an air speed record for an electrically-powered aircraft using a class-leading battery system, which is a potential power and propulsion system for pure and hybrid-electric aircraft designers. The 2.5MW Power Generation System 1 is also currently being tested for use in powering future hybrid-electrical regional aircraft.

EcoPulse – Distributed hybrid propulsion

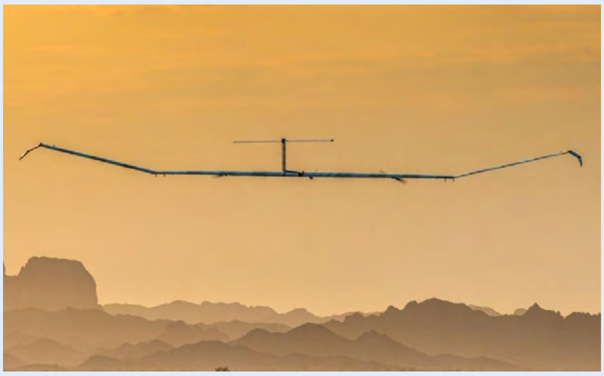
A Distributed Propulsion System consists of breaking down thrust generation into many small engines spread out along the span of the wing. The EcoPulse distributed propulsion hybrid aircraft demonstrator has successfully completed wind tunnel testing and is an integral part of the decarbonisation roadmap, increasing the knowledge on these systems and paving the way for electric and hybrid-electric, emission-free aircraft.



AeroSpace and Defence Industries
Association of Europe

Zephyr – Solar-powered high-altitude flight

In 2021, the Airbus Zephyr S (a solar-powered High Altitude Platform System) completed a successful test flight campaign. The "Carbon Neutral" Zephyr uses sunlight to fly and recharge its batteries, using no fuel and producing zero emissions in flight. It provides the potential to revolutionise disaster management, including monitoring the spread of wildfires or oil spills, as well as world's changing environmental landscape.



MAESTRO & IRON – The future of Small Air Transport and Regional propulsion

The Clean Sky 2 MAESTRO demonstrator, coordinated by Avio Aero and supported by the EU GE Aviation entities, has matured and validated radical technology solutions for small turboprop engines, delivering at least 20% improvement in fuel efficiency and NOx emission reductions compared to the current state of art. Several MAESTRO technologies have been already implemented in Catalyst™, the first all-new, clean-sheet engine design for the business and general aviation turboprop market in more than 50 years. Avio Aero is also paving the way for the electrification of flight with CS2 MAESTRO and IRON demonstrators investigating the potential of hybrid-electric configurations on future small air transport and regional aircraft.

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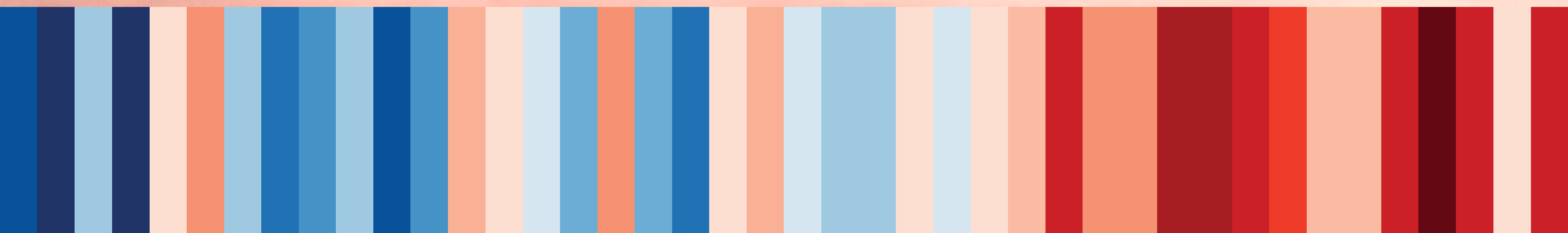

SUSTAINABLE AVIATION FUELS

- **Current SAF supply remains low at less than 0.05% of total EU aviation fuel use.**
- **The European Commission has proposed a SAF blending mandate for fuel supplied to EU airports, with minimum shares of SAF gradually increasing from 2% in 2025 to 63% in 2050, and a sub-mandate for Power-to-Liquid SAF.**
- **To achieve this mandate, 2.3 million tonnes of SAF would be required by 2030. Approximately 14.8 million tonnes of SAF would be required by 2040, and 28.6 million tonnes by 2050.**
- **Drop-in SAF will play a key part in decarbonising the aviation sector as they can be used within the existing global fleet and fuel supply infrastructure.**
- **SAF pathways such as Hydroprocessed Esters and Fatty Acids (HEFA), Alcohols to Jet, Biomass Gasification + Fischer-Tropsch, and Power-to-Liquid (PtL) are expected to play a major role in decarbonisation in the short/medium term, and will remain the main contributor for long-haul flights in the long term.**
- **Currently certified SAF are subject to a maximum blending ratio of 50% with fossil-based jet fuel depending on the feedstock-production pathway considered, but industry and fuel standard committees are looking into the future use of 100% SAF by 2030.**
- **SAF are certified by Sustainability Certification Schemes against criteria defined at EU level in the Renewable Energy Directive and at global level in the CORSIA framework.**
- **While SAF are currently more expensive than fossil-based jet fuel, cost savings are expected notably through future production economies of scale. SAF prices can vary depending on the production pathway, associated production costs and fluctuations in the energy market.**

4.1 WHAT ARE SUSTAINABLE AVIATION FUELS?

In order to decrease its emissions significantly, the aviation sector needs to reduce its current exclusive reliance on fossil-based jet fuel and accelerate its transition to innovative and sustainable types of fuels and technologies.

Definition

A Sustainable Aviation Fuel (SAF) is a sustainable, non-conventional, alternative to fossil-based jet fuel. Several definitions and terminology may apply, depending on regulatory context, feedstock basis, and production technology.

According to the ReFuelEU Aviation regulatory proposal [13], SAF are defined as drop-in aviation fuels that are either biofuels produced from feedstocks listed in Annex IX of the Renewable Energy Directive (RED II) [1] or synthetic aviation fuels, and which comply with the sustainability and greenhouse gas (GHG) emissions reductions criteria in Article 29 of the RED II. A variety of terminologies are used for synthetic fuels, such as Renewable liquid transport Fuels of Non-Biological

Origin (RFNBO), Electrofuels, e-Fuels and Power-to-Liquid (PtL).

Drop-in SAF production pathways

In order to be used in commercial aircraft, drop-in SAF have to go through an exhaustive approval process [2, 3] to fulfil strict certification criteria and prove that their physical and chemical characteristics are almost identical to fossil-based jet fuel [4] and can therefore be safely blended together. This enables SAF to be used within the existing global fleet and does not require any adaptation to the aircraft or fuel supply infrastructure.

As of January 2022, seven SAF production processes have been approved [3]. In addition, two pathways for the co-processing of renewable feedstocks in petroleum refineries are approved [4] with a blending limit of 5%.

The technological maturity of each production pathway can be defined through a Technology Readiness Level (TRL) [5], which ranges from 1 for basic ideas, to 9 for an actual system proven in an operational environment (see Table 4.1).

Table 4.1 Drop-in SAF approved production pathways

Production pathway	Feedstocks[30]	Certification name (blending limit)	TRL
Biomass Gasification + Fischer-Tropsch (Gas+FT)	Energy crops, lignocellulosic biomass, solid waste	FT-SPK[31] (up to 50%)	7-8
Hydroprocessed Esters and Fatty Acids (HEFA)	Vegetable and animal fat	HEFA-SPK (up to 50%)	8-9
Direct Sugars to Hydrocarbons (DSHC)	Conventional sugars, lignocellulosic sugars	HFS-SIP[32] (up to 10%)	7-8 or 5[33]
Biomass Gasification + FT with Aromatics	Energy crops, lignocellulosic biomass, solid waste	FT-SPK/A[34] (up to 50%)	6-7
Alcohols to Jet (AtJ)	Sugar, starch crops, lignocellulosic biomass	ATJ-SPK (up to 50%)	7-8
Catalytic Hydrothermolysis Jet (CHJ)	Vegetable and animal fat	CHJ or CH-SK[35] (up to 50%)	6
HEFA from algae	Microalgae oils	HC-HEFA-SPK[36] (up to 10%)	5
FOG Co-processing	Fats, oils, and greases	FOG (up to 5 %)	-
FT Co-processing	Fischer-Tropsch (FT) biocrude	FT (up to 5 %)	-

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[30] The listed feedstocks are technologically feasible for the specific production pathway, but not necessarily applicable under certain regulations (e.g. ReFuelEU Aviation)

[31] FT-SPK: Fischer-Tropsch synthesised paraffinic kerosene.

[32] HFS-SIP: hydroprocessed fermented sugars to synthetic iso-paraffins.

[33] TRL 7-8 for conventional sugar feedstock; TRL 5 for lignocellulosic sugar feedstock.

[34] FT-SPK/A: Fischer-Tropsch synthesised paraffinic kerosene with Aromatics.

[35] CH-SK: catalytic hydrothermolysis synthesised kerosene.

[36] HC-HEFA-SPK: Synthesised paraffinic kerosene from hydrocarbon-hydroprocessed esters and fatty acids.

The following four production pathways are expected to play a major role in the near future.

Hydroprocessed Esters and Fatty Acids (HEFA)

Potential feedstocks include waste and residue fats (e.g., vegetable oil, used cooking oil, animal fats) and purposely grown plants (e.g., jatropha, camelina). Feedstock is converted using hydrogen to remove oxygen and produce hydrocarbon fuel components. HEFA is currently the only commercially used SAF with a TRL of 8-9. However, the availability of sustainable feedstock, and competition with other sectors, e.g. road, is a limitation to the supply capacity.

Alcohols to Jet (AtJ)

Currently at TRL 7-8, AtJ SAF can be produced from the fermentation of processed lignocellulosic feedstocks (agricultural and forest residues) as well as sugar or starch crops (e.g. corn, sugarcane, wheat). Some AtJ pathways have the possibility to produce SAF that contain aromatics. While reducing the aromatic content of fuels is beneficial for air quality and the environment, fuel that does not contain any aromatics may have airworthiness consequences for parts of the aircraft engine (e.g. rubber seals). This makes AtJ fuels an option for future 100% SAF certification, exceeding today's blending limits (see text box on next page).

Biomass Gasification + Fischer-Tropsch (Gas+FT)

Biogas, or syngas, is obtained from the gasification of feedstock and subsequently processed within a Fischer-Tropsch reactor. The Gas+FT pathway can process similar feedstocks as the AtJ, as well as municipal solid waste. Both Gas+FT and AtJ are considered advanced biofuels if produced from feedstock listed in Annex IX Part A of the RED II, and have significant emissions reduction and supply potential, but are not yet available on a commercial scale within the EU.

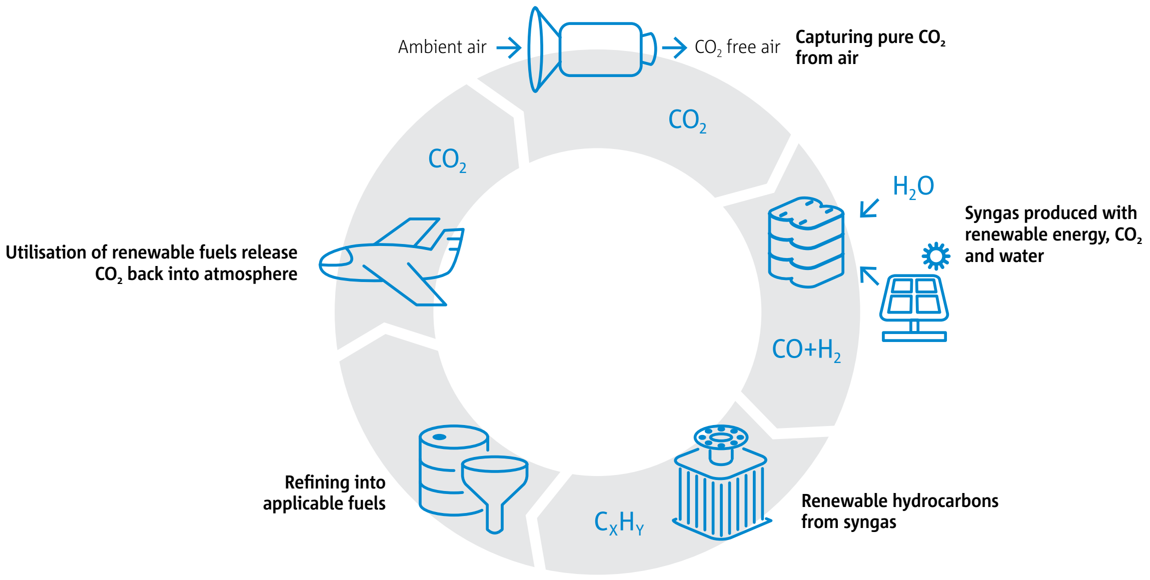
Power-to-Liquid (PtL)

Water and electricity are used in an electrolyser to produce hydrogen, which is subsequently synthesised with CO_2 into syngas. The resulting syngas is then further processed into fuel by the Fischer-Tropsch (FT) reactor or alternatively by methanol synthesis. The CO_2 needed for the PtL process can be sourced from industrial waste gases, biomass or captured directly from the atmosphere.

The production of the electricity and the sourcing of CO_2 are the determining factors in the sustainability as well as the overall costs of PtL. As with other pathways, several by-products (e.g. synthetic road fuel or materials for the chemical industry) from the process offer resilience and potential additional income from PtL production. PtL fuels are already approved if produced through the FT production pathway.

Figure 4.1 Carbon cycle in producing PtL SAF

Renewable fuels created from CO_2 and Water



Non-drop-in SAF

Non-drop-in fuels (e.g., hydrogen) would not necessarily be compatible with the existing global fleet and thus would potentially require aircraft redesign and certification, as well as new supply infrastructure.

Achieving 100% SAF

Approved SAF currently have associated maximum blending ratios (Table 4.1) that may limit the ability to use larger amounts of SAF in the future. As such, dedicated task groups within fuel standard committees are assessing options to facilitate the use of 100% SAF in aircraft engines, with an initial timeline of having approved fuels ready by 2030.

One drop-in option is to blend two or more SAFs to produce a fuel with characteristics that are fit for purpose in terms of 100% use. Another option is the adaptation of currently used raw materials and production processes to produce a fully formulated 100% SAF in a single process stream (e.g. AtJ, FT-SPK/A and CHJ) or the use of new raw materials and processes yet to be developed and approved.

The aviation industry is already performing the needed research and test flights to evaluate the effects of 100% SAF on emissions and the performance of aircraft, with promising early results [6] [7] [8]. For example, in October 2021 the first in-flight study of a single-aisle aircraft running on unblended SAF was launched. An Airbus A319neo aircraft operated on 100% fuel made from cooking oil and other waste fat (HEFA). In March 2022, a ground engine test campaign was completed with the same fuel, to correlate with the flight tests emissions and to evaluate the benefit of SAF on airport air quality [6].

Rolls-Royce Trent-1000 engine operating with 100% SAF on a Boeing 747-200 Flying Test Bed.

4.2 HOW SUSTAINABLE ARE SAF?

Sustainability criteria

Table 4.2 provides an overview of the sustainability criteria used within both the RED II [1] and the ICAO Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA) [9].

GHG emissions reductions

As the emissions from the combustion of drop-in SAF are comparable to fossil-based jet fuels, except for marginal efficiency gains, the majority of the reductions in GHG emissions originate from the production process. In order to assess the overall climate benefit from using SAF, a Lifecycle Analysis (LCA) is performed to account for all the stages in the lifecycle of aviation fuels. It includes feedstock recovery and transportation, fuel production and transportation, and fuel consumption by aircraft.

The GHG emissions of fuels are provided in terms of gCO_2e/MJ, which can be compared to the relevant baseline emissions used for fossil-based jet fuel in order to calculate the overall GHG emissions reduction.[37] Figure 4.2 illustrates the components of typical well-to-wing lifecycle analysis steps for fossil-based jet fuel and SAF.

Table 4.2 **SAF sustainability criteria**

Scheme	Sustainability criteria
Renewable Energy Directive (RED II) (2018), Article 29	**GHG reductions** – GHG emissions on a lifecycle basis from biofuels must be lower than from the fossil fuel they replace (fossil fuel baseline = 94 g CO_2e/MJ): at least 50% lower for installations older than 5 October 2015, 60% lower for installations after that date and 65% lower for biofuels produced in installations starting operation after 2021. For renewable fuels from non-biological origin the savings shall be at least 70%. **Land use change** – Carbon stock and biodiversity: raw materials for biofuels production cannot be sourced from land with high biodiversity or high carbon stock (i.e., primary and protected forests, highly biodiverse grassland, wetlands and peatlands). Other sustainability issues covered by the reporting obligation are set out in the Governance regulation [19] and can be covered by certification schemes on a voluntary basis. ReFuelEU Aviation further restricts the RED II criteria by only allowing fuels made from feedstock listed in Annex IX.
CORSIA Sustainability Criteria for CORSIA eligible fuels (November 2021)	**GHG reductions** – CORSIA eligible fuel / SAF will achieve net GHG emissions reductions of at least 10% compared to the baseline life-cycle emissions values for aviation fuel on a lifecycle basis (fossil fuel baseline = 89 g CO_2e/MJ). **Carbon Stock** – CORSIA eligible fuel / SAF will not be made from biomass obtained from land converted after 1 January 2008 that was primary forest, wetlands, or peat lands and/or contributes to degradation of the carbon stock in primary forests, wetlands, or peat lands as these lands all have high carbon stocks. For batches produced on or after 1 January 2024, additional criteria are applicable and are addressing the following themes: • Water • Soil • Air • Conservation (biodiversity) • Waste and chemicals • Human and labour rights • Land use rights and land use • Water use rights • Local and social development • Food security

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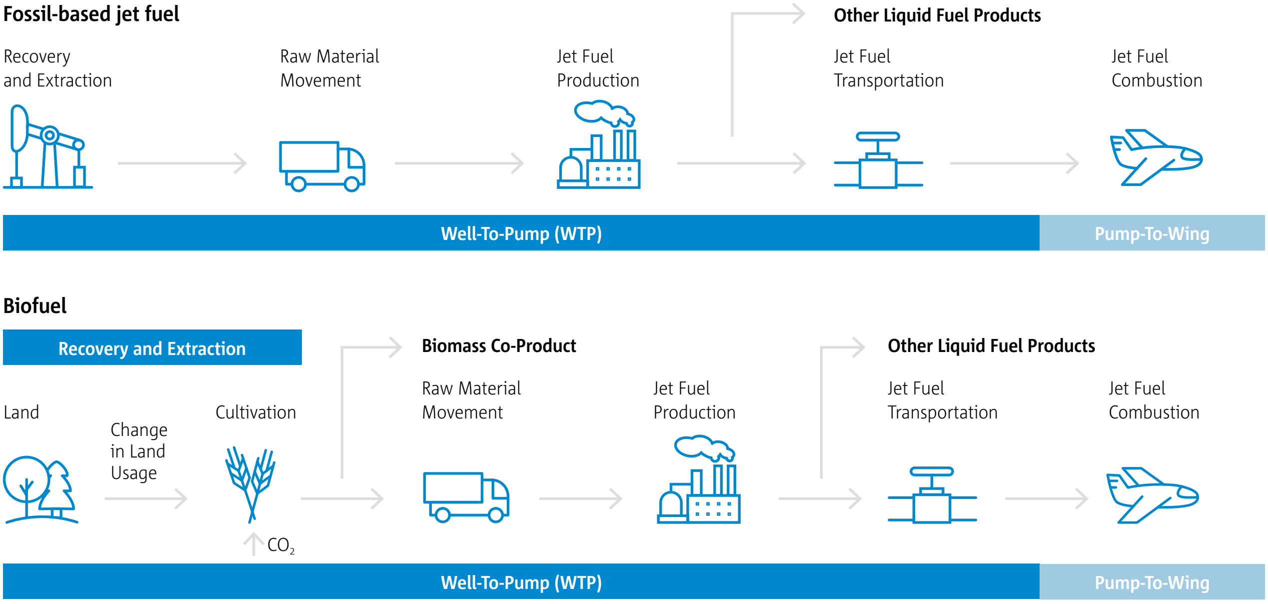
[37] Greenhouse gas emissions are expressed as grams of carbon dioxide equivalent (gCO_2e) emissions of CH_4, N_2O and non-biogenic CO_2 calculated on the basis of a 100-year global warming potential (GWP), consistent with the Intergovernmental Panel on Climate Change (IPCC). CO_2e are calculated per energy unit expressed as megajoule of fuel produced and combusted in an aircraft engine (gCO_2e/MJ).

Figure 4.2 Components of typical well-to-wing LCA for fossil-based jet fuel and biofuel



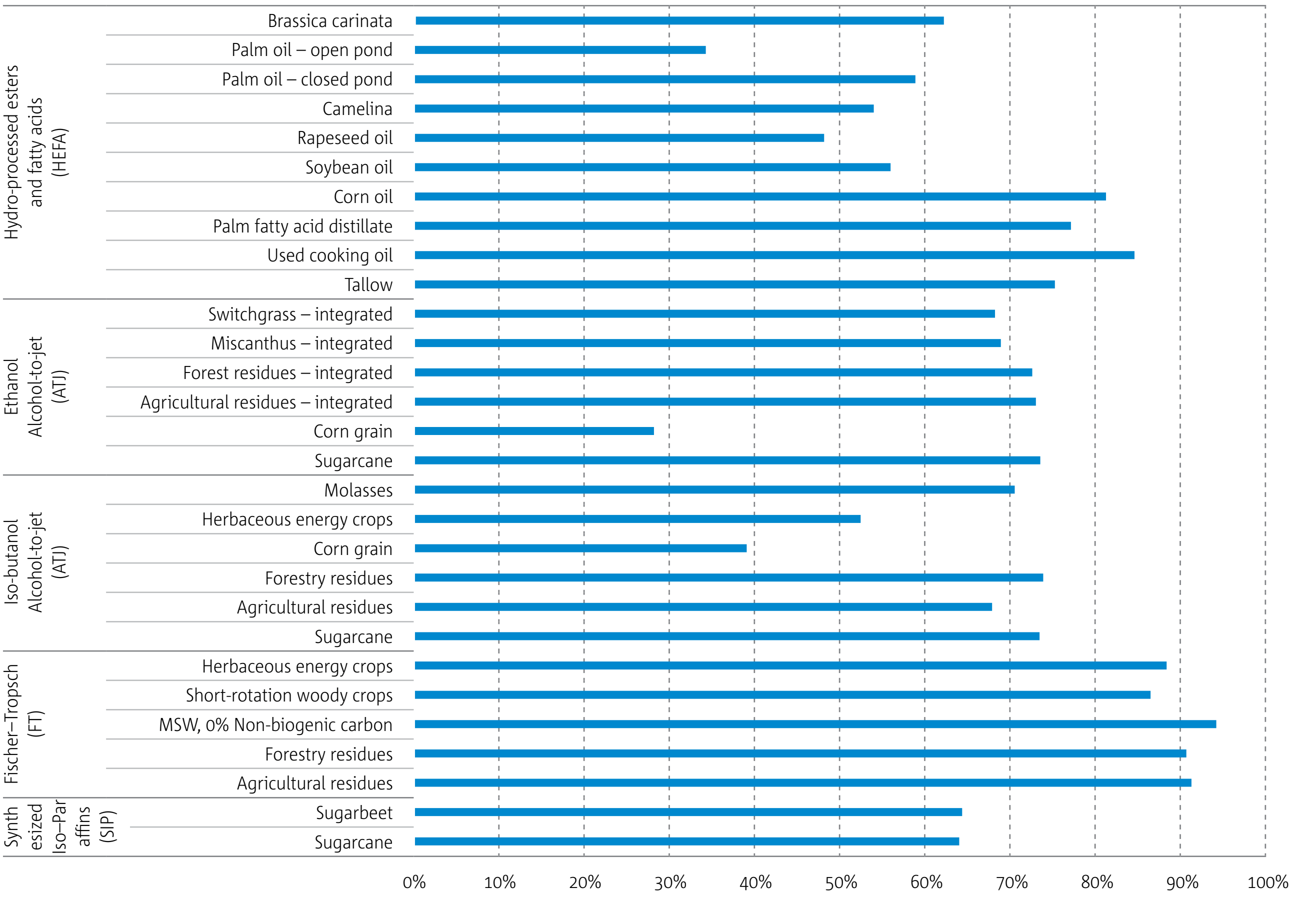
The LCA of a fuel is a complex process and many variables (e.g., origin and type of feedstock, electricity mix, production method) can have a considerable impact on the total GHG emissions. Figure 4.3 provides an overview of modelled direct emissions reductions under CORSIA for approved SAF production pathways as of January 2022. Work is ongoing to approve GHG emissions reductions for Power-to-Liquid fuels, but with a fully decarbonised supply chain, emission reductions of up to 100% can be achieved compared to a fossil fuel reference.

Additional effects from use of SAF

The SAF feedstock and production process typically results in very low levels of sulphur and aromatic content, which form part of volatile and non-volatile particulate matter (PM) emissions. Studies on the use of SAF blended into fossil-based jet fuel have shown that PM emissions behind the aircraft at cruising altitudes are reduced by 50-97% compared to fossil-based jet fuel. The highest reductions can be observed at low engine power, typically applied when the aircraft is taxiing, and hence SAF can also improve local air quality and reduce health impacts [10]. As such, due to their different physio-chemical composition, SAF drop-in fuels can have a positive impact on both air quality around airports as well as climate change through the reduction in the formation of contrail-cirrus clouds. This is assuming that there are no increases in the aromatic and sulphur content of the fossil-based part of the blended fuel that negates the SAF benefits.

Land use impacts are a common concern surrounding some aviation biofuels. Direct land use changes (DLUC) occur when existing farmland is converted for the growth of feedstock for biofuel production, while indirect land use change (ILUC) occur when the increasing demand for biofuel lead to land expansion elsewhere, including the conversion of land with high carbon stock such as forests (e.g., deforestation and the release of CO_2 stored in trees and soil) [11, 12]. The impact of ILUC is estimated through complex modelling and the range of values can be wide. Studies have shown that the conversion of land with very high biodiversity, such as rainforest or peatlands, can release up to several hundred times more CO_2-equivalent emissions than what the biomass subsequently grown on that land is able to reduce annually [12]. For the above reasons, under RED II, the contribution of biofuels produced from food and feed crops towards EU Member States' renewable energy targets for transport are capped. The contribution of biofuels from food and feed crops for which a "significant expansion of the production area into land with high carbon stock" is observed is also capped at 2019 level and phased-out by 2030. For the same reasons, biofuels produced from food and feed crops are not eligible under the proposed ReFuelEU Aviation.

Figure 4.3 **LCA emissions reductions for CORSIA eligible SAF pathways and feedstock compared to a fossil fuel reference value (89 g CO_2e/MJ) [11][38]**



4.3 SAF POLICY ACTIONS

As part of the ‘Fit for 55’ package of July 2021, the Commission proposed a Regulation to boost the uptake of SAF in air transport in the context of the ‘ReFuelEU Aviation’ initiative. In order to meet the EU’s climate objectives, the proposed rules set out EU-level harmonised obligations on fuel suppliers and aircraft operators for scaling up SAF used for flights departing from all EU airports above a certain traffic threshold. According to the regulatory proposal, fuel suppliers would be required to blend 2% of SAF by 2025, 5% by 2030 and at least 63% by 2050 (Figure 4.4) and airlines would be required to use the SAF-blended fuel available at EU airports. This proposal for an EU SAF blending mandate focuses on advanced biofuels and synthetic e-Fuels. Due to their high decarbonisation potential and with a view to upscaling their production at a reasonably quick pace, synthetic e-Fuels (e.g. PtL) are subject to a sub-mandate [13].

The ReFuelEU legislative proposal also foresees a thorough monitoring and reporting system of SAF supply and usage that will provide an overview of the European SAF market and form part of future editions of this report.

Some European States have introduced, and others are considering, policies to incentivise the future uptake of SAF. Since January 2020, Norway introduced a SAF blending mandate of 0.5% from 2022 with an ambition to increase over time. Sweden is following a similar path with a mandate gradually increasing to 27% by 2030. France defined its SAF roadmap in 2019 (SAF consumption objectives of 2% by 2025, 5% by 2030 and 50% in 2050) and started regulating fuel suppliers with

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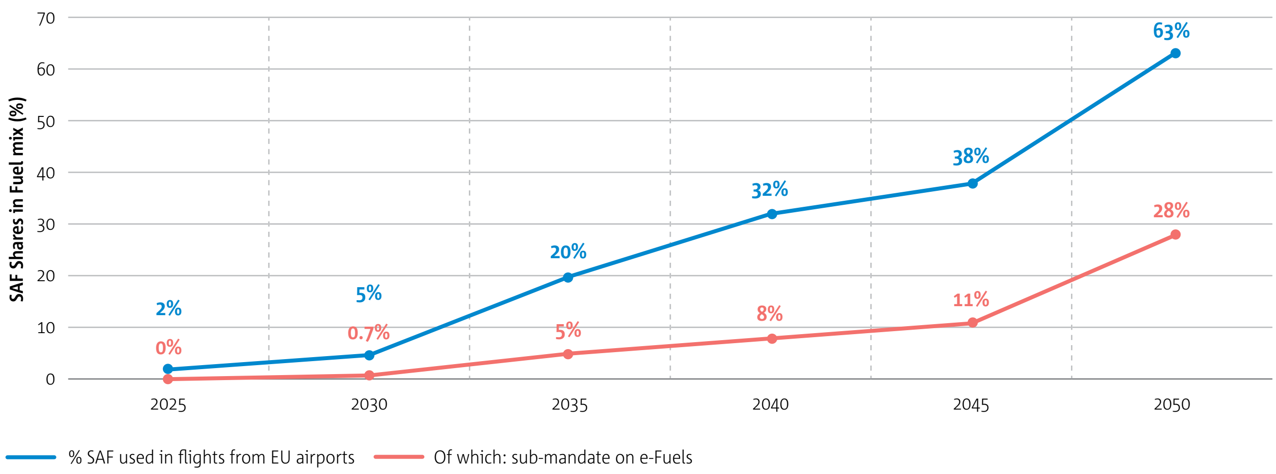
[38] Two different ATJ conversion plant layouts can be considered. The integrated plant layout (displayed here) assumes co-locating the ATJ process with ethanol production and emissions reductions as a result of heat integration. The standalone configuration assumes that ethanol is taken from the market or a separate ethanol production facility.

Figure 4.4 Proposed ‘Fit for 55’ SAF mandate

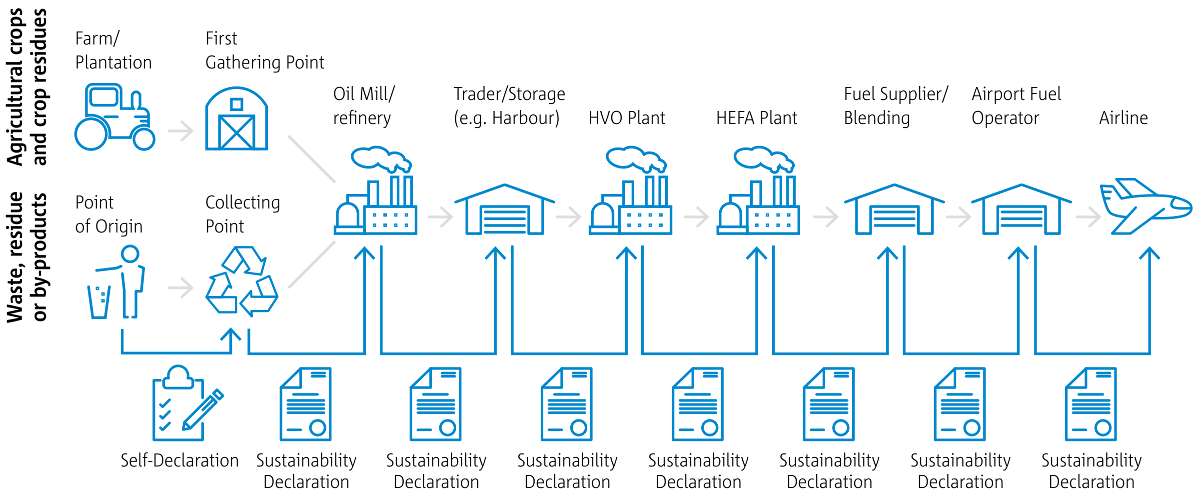


Sustainability Certification Schemes – Securing the sustainability of SAF

To ensure that SAF meet robust sustainability criteria, Sustainability Certification Schemes (SCS) control compliance of economic operators with the sustainability requirements along the SAF supply chain on a lifecycle basis (i.e., from feedstock provider all the way to blending). Each economic operator commissions an audit from an officially recognised third-party verification body, according to the requirements set by the certification system. If the sustainability criteria are met, the economic operator is granted a certificate confirming compliance with the certification systems’ requirements. This certificate puts the economic operator in the position to produce SAF from certified feedstock in accordance with the relevant sustainability requirements (e.g. RED II, CORSIA).

Sustainability certification ensures:

- Transparent compliance of feedstock with a defined set of robust sustainability requirements;
- Traceability of sustainable material through SAF supply chains; and
- Verified reductions in GHG emissions of the final SAF.



a target for advanced biofuels and fuels produced from waste oils and fats (1% of jet fuel demand in 2022) [23].

Germany is focussing on PtL fuels as part of its National Hydrogen Strategy with an objective to ramp up production to 200 thousand tonnes by 2030 (2% of German jet fuel sales in 2019) [22]. The Netherlands are considering a 14% share of SAF by 2030 and to completely replace fossil-based jet fuel by 2050. Outside of Europe, the United States introduced the SAF Grand Challenge to produce at least 3 billion gallons (approx. 8.6 million tonnes) per year by 2030 [25]. In addition, countries such as South Korea, Japan, Singapore, Brazil and New Zealand have announced various initiatives to advance the uptake of SAF [26] [27] [28].

Corporate targets have also been announced by European airlines. For instance, the International Airlines Group (IAG)[39] and Ryanair have committed to use 10% and 12.5% SAF by 2030 respectively [14, 15]. At global level, Airlines for America (A4A), an association of major US airlines, pledged in March 2021 to facilitate making around 6 million tonnes of SAF commercially available in the US by 2030, which would represent approximately 10% of their forecast 2030 jet fuel consumption [16].

While providing a boost to the production and usage of SAF, it is unlikely that these actions alone will enable development of SAF at a competitive price and incentivise their usage across the EU in sufficient volumes so as to achieve significant emissions reductions from the aviation sector. Moreover, stakeholders have repeatedly called for a harmonised and long-term policy landscape as the most important measure to mitigate obstacles to SAF production and its uptake.

4.4 CURRENT LANDSCAPE AND FUTURE OF SAF INDUSTRY

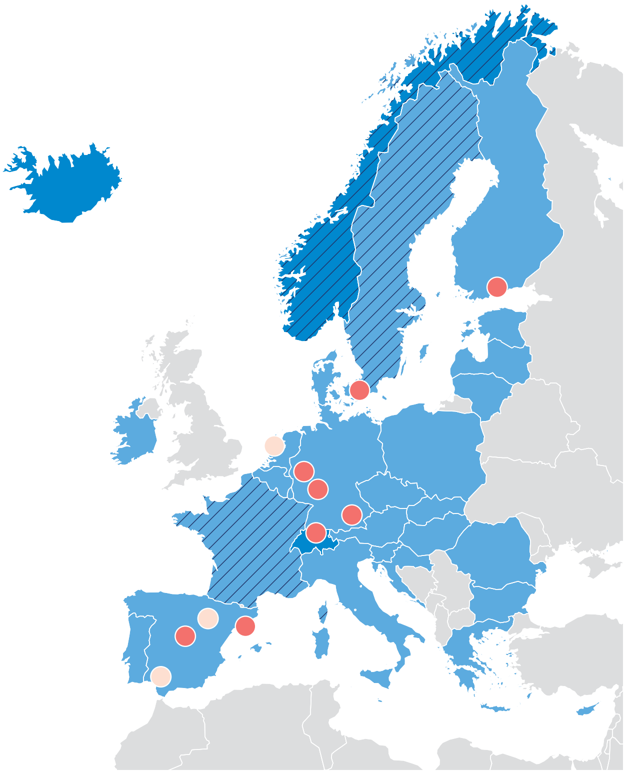
From a production capacity and demand point of view, the SAF industry today is still at an early stage of development with an estimated EU supply of less than 0.05% of total jet fuel demand in 2020 (Figure 4.5) [12, 20, 21]. The following section provides an overview of the current landscape, while also looking into the future on how the sector may be able to meet the proposed SAF mandates, which fixes the minimum level of both supply and demand, starting from 2025 and increasing every 5 years thereafter (Figure 4.6).

Production capacity and demand – 2020 to 2030

According to the supporting study for the ReFuelEU Aviation initiative [17], with the introduction of a SAF blending mandate at EU level, demand for aviation fuel at EU airports would amount to around 46 million tonnes in 2030. In order to reach 5% of SAF by 2030 for all flights departing from EU airports, approximately 2.3 million tonnes of SAF would be required.

Currently, the maximum potential SAF production capacity in the EU is estimated at around 0.24 million tonnes, i.e. only 10% of the amount of SAF required to meet the proposed mandate by 2030. Announcements

Figure 4.5 SAF supplied in Europe, March 2022



▨ Countries with SAF blending Mandate in place
🟦 EU (SAF blending Mandate in preparation)
■ EFTA
● Airports that regularly offer SAF
○ Airports that received batches of SAF in the past

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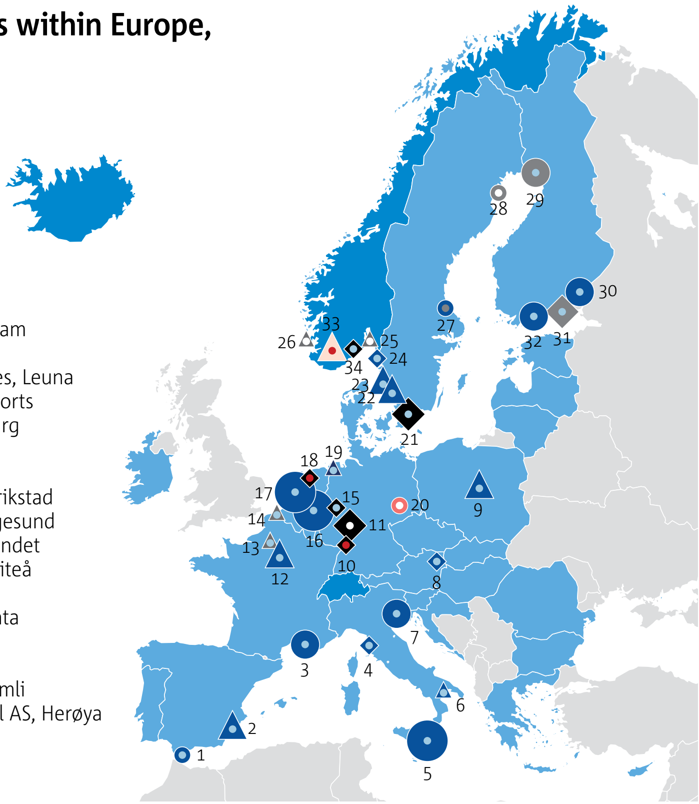
[39] IAG members in 2021: British Airways, Iberia, Aer Lingus, Iberia Express, LEVEL and Vueling

of significant capacity increases from these existing SAF producers, combined with production from new market entrants, means that the 2030 mandate level is ambitious but realistic.

More companies have announced plans to enter the SAF market by 2030. An analysis showed that if all existing biofuel facilities in Europe were calibrated to maximise SAF production, potential capacity could reach around 2.3 million tonnes. It is estimated that more than 60% of the European SAF supply in 2030 would be covered by HEFA and Alcohol-to-Jet pathway fuels (Figure 4.7), followed by imports and PtL fuels. As such, the majority of the needed feedstock is expected to be used cooking oils, animal fats and waste oils, cover crops and other sustainable biomass.

Figure 4.6 Current announced SAF projects within Europe, March 2022



Facility state:
1) Cepsa, San Roque
2) Repsol, Cartagena
3) Total Energies, Marseille
4) ENI, Livorno
5) ENI, Gela
6) ENI, Taranto
7) ENI, Venice
8) OMV, Schwechat
9) PKN ORLEN, Plock
10) Gevo/HCS Group, Speyer
11) Caphenia, Frankfurt1
12) TotalEnergies/NextChem, Grandpuits
13) Avril, Venette
14) TotalEnergies, Dunkirk
15) Shell, Wesselling
16) Neste, Rotterdam
17) Shell, Rotterdam
18) Synkero, Amsterdam
19) SkyNRG, Delfzijl
20) Global Bioenergies, Leuna
21) Copenhagen Airports
22) Preem, Gothenburg
23) ST1, Gothenburg
24) Preem, Lysekil
25) Quantafuel, Fredrikstad
26) Quantafuel, Haugesund
27) Colabitoil, Norrsundet
28) LTU Greenfuels, Piteå
29) Kaidi, Kemi
30) UPM, Lappeenranta
31) UPM, Kotka3
32) Neste Oil, Porvoo
33) Biozin Holding, Åmli
34) Nordic Electrofuel AS, Herøya

Facility state

500k – 1000k	100k – 500k	<100k	
◇	◇	◇	planned
△	△	△	in construction
○	○	○	in operation

Production [ton/yr]

SAF type
- ● HEFA-SPK
- ● ATJ-SPK
- ● PtL
- ● G+FT
- ● IH2*

Facility type
- ● Commercial
- ● Demo
- ○ Pilot

- ● EU
- ● EFTA

* Production pathway currently in approval process.

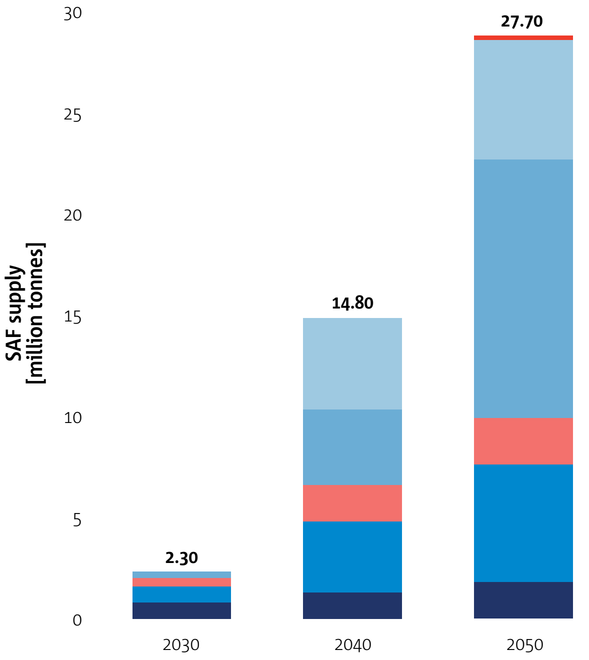
Production capacity and demand – beyond 2030 to 2050

Forecasting the production and demand in 2040 and 2050 is challenging due the lack of public announcements from fuel producers. However, modelling performed under the ReFuelEU Aviation Initiative offers a useful outlook on the achievability of the mandated targets and the required resources.

The ReFuelEU Aviation proposal would require that 32% and 63% of jet fuel consumed by flights departing from EU airports be SAF in 2040 and 2050, respectively. With the proposed SAF blending mandate in place, the total EU demand for aviation fuel is estimated to be 46 million tonnes in 2040, and 45 million tonnes in 2050. This implies that approximately 14.8 million tonnes of SAF would be required annually by 2040, and 28.6 million tonnes by 2050 (Figure 4.7).

The ReFuelEU Aviation study noted that 7 additional SAF production plants would be needed in the EU by 2030, and 104 additional plants by 2050. To cover the demand for PtL fuels, it is estimated that 0.4% and 5.5% of EU's renewable electricity generation would be needed by 2030 and 2050, respectively. Other studies suggest an even bigger need, with approximately 30 additional SAF plants by 2030 and 250 plants by 2050 [18] and a higher share of EU's electricity demand to produce the estimated volume of PtL fuels [24]. These projections demonstrate the magnitude of the scale-up that must be achieved in SAF production to support the decarbonisation of the aviation sector.

Figure 4.7 ReFuelEU modelled SAF supply per production pathway in the EU27 [13]



	2030	2040	2050
● Electricity	0.00	0.00	0.20
● Gasification+FT	0.00	4.50	5.90
● PtL	0.30	3.70	12.70
● Imports	0.40	1.80	2.30
● ATJ	0.80	3.50	5.80
● HEFA	0.80	1.30	1.80

Overall CO_2 emissions reductions

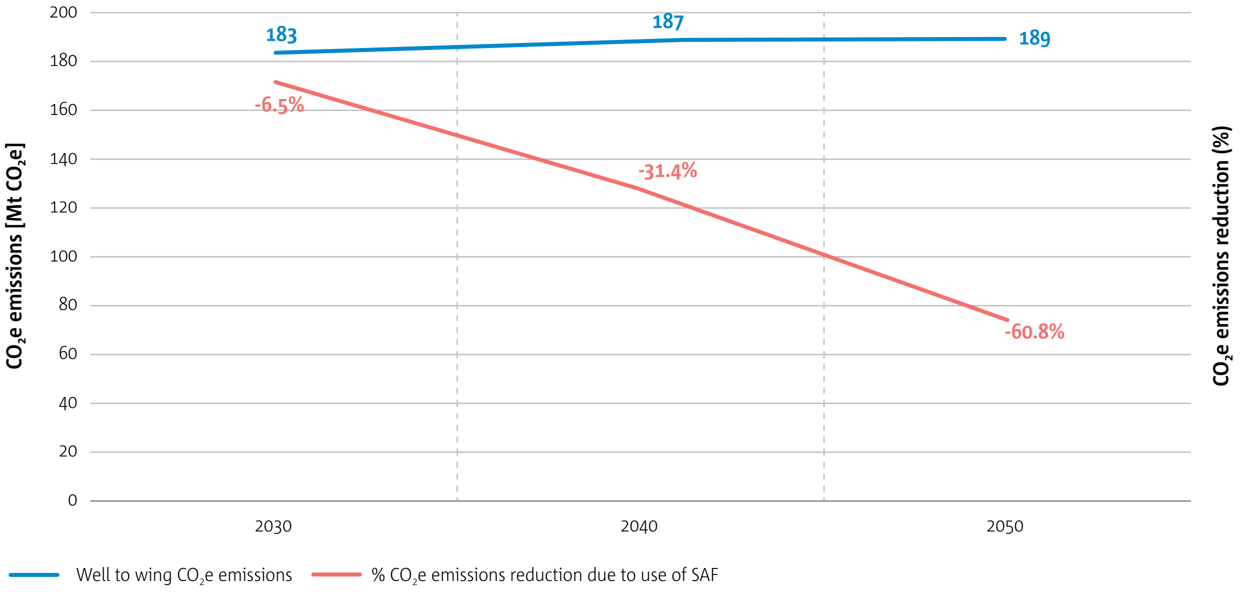
Based on the percentage CO_2e emissions reductions of the different SAF pathways, combined with modelled future SAF production and mandated usage, Figure 4.8 illustrates the significant impact SAF uptake could have on the overall emissions of the European aviation sector and its contribution in reaching the objectives of 2030 Climate Target Plan.

SAF Price

The price of fossil-based jet fuel is approximately €600 per tonne [13], while current SAF prices can range from 1.5 to 6 times higher. There are various reasons for this wide range, including different levels of SAF industrial and technological maturity and a low level of certainty on the production costs of certain SAF pathways.

It is difficult to accurately predict how SAF prices will evolve in the future. Feedstock prices and the evolution of electricity mix prices depend on many factors, including the uncertainty linked to the COVID-19 pandemic and the increased reliance of States around the world on bioenergy to decarbonise. Nevertheless, the long-term trend is expected to be a reduction in SAF production costs enabled by economies of scale and technological advancements. Additional economic incentives from market-based measures (e.g. EU ETS, CORSIA) and potential tax credits will also help in reducing the price gap relative to fossil-based jet fuels.

Figure 4.8 Estimated well-to-wing CO_2e emissions (Mt) in 2030, 2040 and 2050 and % reduction potential of SAF under ReFuelEU proposal [13]



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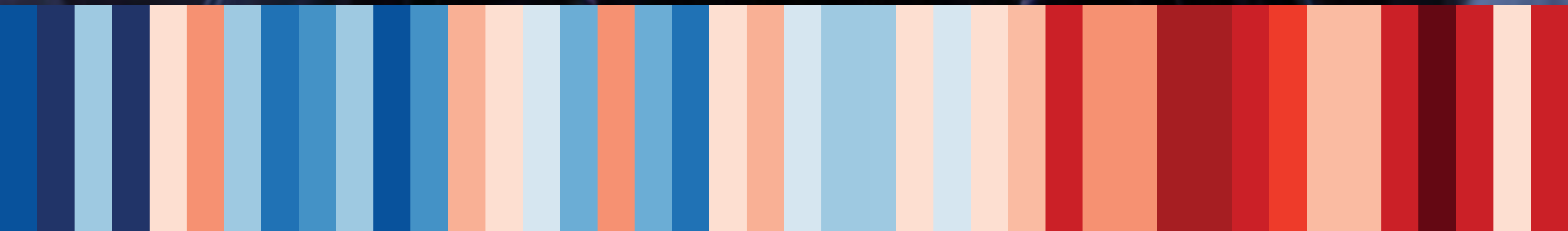

AIR TRAFFIC MANAGEMENT AND OPERATIONS

- Operational ATM improvements can provide an important contribution to reducing CO_2 emissions with progress achieved in both airspace design and deployment of interoperable technologies. As such, their implementation should be accelerated to reduce fragmentation of ATM systems in Europe.
- The European Green Deal requires a more ambitious, comprehensive and holistic approach involving all stakeholders to accelerate solutions to enable greener operations in the short term.
- In 2019, excess fuel burn on an average flight by flight basis within the Network Manager area was estimated to be between 8.6% (XFB10) to 11.2% (XFB5), with excess fuel burn decreasing as the flight distance increases.
- The European ATM Master Plan, managed by the SESAR 3 Joint Undertaking (JU), defines a common vision and roadmap for ATM stakeholders to modernise and harmonise European ATM systems, including an aspirational goal to reduce average CO_2 emission per flight by 5-10% (0.8-1.6 tonnes) by 2035 through enhanced cooperation, compared to 2017.
- Single European Sky (SES) union-wide environment targets were not reached during the entire Reference Period (RP) 2 (2015-2019), with performance worsening in the second part of RP2. In 2020, whilst performance did improve, several Member States still did not achieve their environment targets despite the dramatic drop in traffic due to the pandemic.
- The KPI reflecting the relationship between flight routing and environmental impact is considered inadequate and needs to be re-evaluated, taking into account environmental indicators based on actual CO_2 emissions.
- The proportion of flight time flown in free route airspace was 68% in 2021 with around 10 million tonnes CO_2 saved through the implementation of Free Route Airspace since 2017.
- As traffic returns to pre-COVID levels, efficiency improvements observed in 2020 should be maintained through ‘green’ recovery principles such as dynamic use of airspace constraints that are only applied when justified and the use of optimised flight planning by aircraft operators.
- It has been estimated that, in 2018, 21% of ECAC flights performed fuel tankering, representing a net saving of €265 million per year for the airlines, but burning an unnecessary 286,000 tonnes of additional fuel (equivalent to 0.54% of ECAC jet fuel used).
- Within the new SESAR 3 JU Digital European Sky programme a significant portion of the new partnership’s budget of €1.6 billion will be dedicated to a flagship programme on the Aviation Green Deal that should bring crucial environmental improvements in the system.

5.1 SINGLE EUROPEAN SKY

The Single European Sky (SES) initiative was launched in 2004 [1] to reduce the fragmentation of European airspace and to improve the performance of Air Traffic Management (ATM) in terms of safety, capacity, cost-efficiency and the environment. The number of flights to or from EU27+EFTA airports during 2019 was 9.25 million, which led to congestion, re-routings, delays and above all significant excess CO_2 emissions. While this dropped sharply in 2020 (-55%) and in 2021 (-45%) due to the COVID pandemic, air traffic is expected to ultimately return to 2019 levels and these issues will reappear unless action is taken.

Achieving the goal of climate neutrality by 2050 calls for the EU to ensure decarbonisation of the air transport sector. This ambitious target cannot be achieved without an ATM system that supports and incentivises air navigation service providers, airport operators and aircraft users to optimize the efficiency of their operations and thus reduce excess fuel burn and emissions to a minimum. The European ATM Master Plan [2] currently includes a goal to reduce average CO_2 emission per flight by 5-10% (0.8-1.6 tonnes) by 2035, compared to 2012.

In September 2020, the European Commission proposed a reform of the SES to improve ATM and to support the ambitions of the European Green Deal. The aim is to modernise airspace management and air navigation services in order to increase the system's ability to adapt to variations in traffic and reduce aviation's carbon footprint, whilst maintaining or improving levels of safety, increasing capacity and improving cost-efficiency.

Part of this proposal is the possibility to introduce a common unit rate across the entire SES area. This would replace the current system where unit rates vary strongly between charging zones thereby providing airspace users with an adverse incentive to fly routes with the lowest charges at the cost of potentially higher CO_2 emissions. In order to make sure that the scheme does not affect the revenues of the air navigation service providers, the proceeds from the air navigation charges would need to be reallocated. The proposal also requires the modulation of air navigation charges that rewards aircraft operators with the best environmental performance and penalizes the worst performers, while being overall revenue neutral for air traffic service providers.

It is also recognised that the current SES environmental Key Performance Indicator has serious limitations (see section 5.2), and the possibilities of the current SES regulatory framework have not been fully exploited, including the option for EU Member States to introduce local environmental incentive schemes. Hence, there is a need to strengthen the regulatory framework and to develop more appropriate indicators and incentives for the fourth Reference Period (RP4).

As of mid 2022, the European Parliament and the Council are still discussing the SES reform proposals.

Network Manager

The Commission Implementing Decision (EU) 2019/709 of 6th May 2019 [4] renewed the appointment of EUROCONTROL as Network Manager (NM) for the period 2020-2029. Following the revised ATM Network Functions Regulation [3] in 2019, EASA continues to act as the competent authority that certifies and oversees the NM. The role of the NM is to coordinate operational stakeholders in order to manage demand through flow and capacity management, and thereby optimise the performance of the European aviation network to limit unnecessary fuel burn and emissions.

Single European Sky ATM Research (SESAR)

SESAR [5] is the technological pillar of the SES framework. It defines, develops and deploys technologies to transform air traffic management in Europe, as defined in the European ATM Master Plan. The innovative technological and operational solutions needed to deliver the 'Digital European Sky', and the associated environmental benefits, are developed and validated by the SESAR 3 Joint Undertaking, after which they are deployed locally, or in a synchronized manner at the European level by the SESAR Deployment Manager in coordination with all relevant stakeholders.

Performance Scheme

The SES Performance Scheme [6] defines Key Performance Indicators (KPIs) with mandatory local and EU targets that cover the fields of environment, safety, cost efficiency and capacity. Following Brexit, the geographical scope of the SES Performance Scheme was changed, and the UK is no longer subject to the performance scheme in RP3 (2020-2024).

The scheme aims to capture the relationship between flight routing and environmental impacts, and the KPIs have been regarded as reasonable proxy measures of Air Navigation Service Provider (ANSP) efficiency that can be used to incentivise improved performance over time. The pandemic has challenged this assumption with relatively small improvements in the environmental KPI despite a dramatic reduction in traffic (see Sections 5.2 and 5.3).

5.2 SES ENVIRONMENTAL PERFORMANCE AND TARGETS

Overall context

The SES Performance Scheme Reference Periods (RP) are divided into five year periods. This report captures the results of RP2 and the start of RP3, while highlighting intentions for the remainder of RP3 and RP4.

Reference Period 2 (RP2)	2015-2019
Reference Period 3 (RP3)	2020-2024
Reference Period 4 (RP4)	2025-2029

In 2019, the SES Performance Review Body (PRB) Annual Monitoring Report [7] highlighted the challenges imposed upon the ATM system due to the traffic growth of 11.8 % during RP2 according to the STATFOR forecast. This led to significant increases in delays, particularly in the summer periods of 2018 and 2019, and consequently the SES Performance Scheme environmental targets were not reached. Consequently, the PRB recommended that structural issues in the ATM system should be addressed and that the Network Manager (NM) should work with ANSPs and Member States to improve re-routing proposals and minimise route restrictions, as well as support more closely the implementation of Free Route Airspace and Flexible Use of Airspace [8].

Following the dramatic reduction of traffic beginning in 2020, it was expected that the environmental performance of the ATM system would improve significantly due to reductions in capacity constraints. However, while the target for the Horizontal En-route Flight Efficiency KPI was met in 2020, the magnitude of improvement from 2.95% to 2.51% was limited in view of the significant traffic reduction. Furthermore, the PRB observed that several Member States did not achieve their environment targets despite experiencing very low traffic, suggesting that the KPI reflecting the relationship between flight routing and environmental impact may need to be re-evaluated. It should be noted that other environmental performance indicators were able to capture the performance improvement from more direct routeings and optimised vertical flight efficiency (see section 5.3).

In light of the European Green Deal, a more ambitious and holistic approach when applying the Performance Scheme appears necessary. Improvements should be based upon an assessment of the interrelatedness between the Performance Scheme, existing market-based measures, as well as future regulatory measures which are currently under discussion within the EU institutions. On-going work is currently considering new performance indicators for RP4 that more closely correlate with actual CO_2 emissions and, where possible, using metrics based solely upon ANSP performance.

Key Performance Indicator (with targets): Horizontal en-route flight efficiency

The total additional distance flown in 2019 (RP2) within the SES area was 256 million kilometres, which resulted in approximately 3.5 million tonnes of additional CO_2 emissions. In comparison, an additional 120 million kilometres was flown in 2021[40] (RP3) leading to approximately 1.6 million tonnes of additional CO_2. The SES Performance Scheme includes one binding target at the EU level for the entire 2022-2024 period that is set at a maximum of 2.4% for the en-route flight inefficiency of the actual trajectory (KEA). The last filed flight plan inefficiency indicator (KEP) is no longer being used beyond 2020 as the focus is on the more tactical KEA indicator.

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[40] Although the UK was not participating in the SES Performance Scheme in RP3 (2021) the numbers are shown for comparative purposes. In 2021, without the UK, the additional distance flown was 110 million kilometres.

Figure 5.1 Horizontal en route flight inefficiency for 2009 to 2021

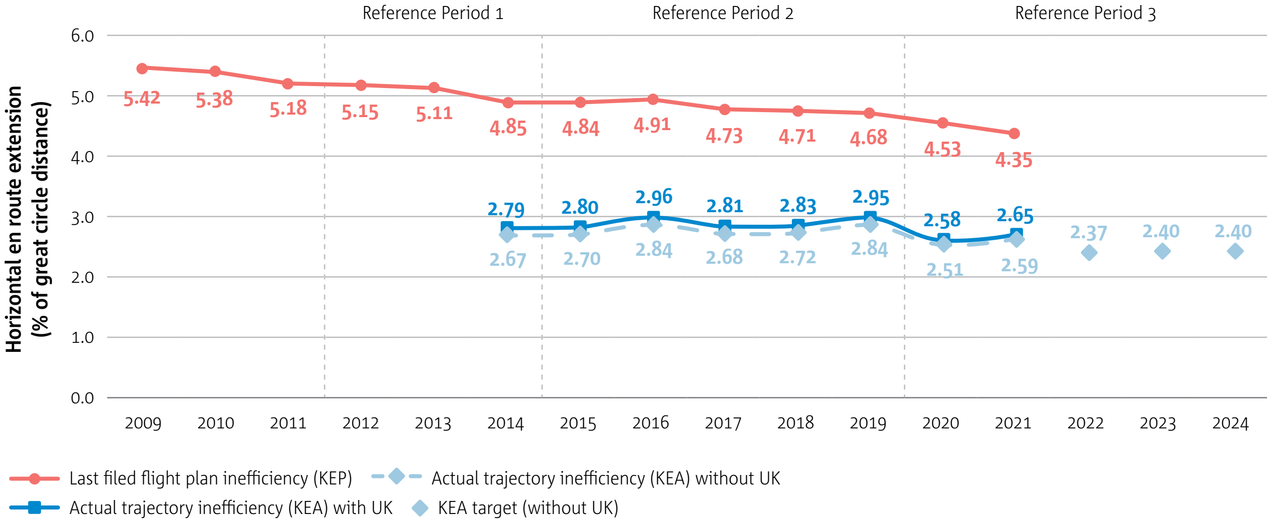


Figure 5.1 shows that KEA decreased to 2.51% in 2020 and increased to 2.59% in 2021. Following Brexit, these figures no longer include UK data as the UK is no longer subject to the SES Performance Scheme. In order to take into account the COVID pandemic, the KEA targets for 2021 and 2022 were subsequently revised taking into account existing circumstances [9], while the targets for years 2023 and 2024 were maintained on the basis of the expected recovery. The decrease in KEA across the network in 2020 can largely be explained by the removal of around 1,200 network restrictions (both horizontal and vertical) during the pandemic measures together with more efficient direct routings [10]. As traffic increased in 2021, several of these constraints were reinstated in order to maintain both safety and capacity.

As traffic starts to return to pre-COVID levels, the challenge will now be to maintain these efficiency improvements promoting ‘green’ recovery principles such as more dynamic use of airspace constraints [10] that are applied only at times and traffic conditions in which they are fully justified.

Performance Indicator (without targets): ASMA

The Performance Scheme includes various indicators that are only monitored at either EU-level or local level with no binding targets. Two of these indicators are highlighted below for the top 40 airports in terms of flight movements across the Network, including the UK.

The average additional Arrival Sequencing and Metering Area (ASMA) time, which measures the delay in the arrival flow of air traffic, for the top 40 airports remained fairly constant from 2014 to 2019 at around 2.0 minutes per arrival (range of 1.91-2.04 mins), but decreased significantly to 1.22 minutes in 2020 and 0.92 minutes in 2021 (Figure 5.2).

It should be noted that the ASMA indicator is currently subject to consultation based on stakeholder feedback. This exercise includes a potential revision of the Taxi-out time and the development of a Taxi-in time indicator.

All airports experienced a reduction in ASMA time from 2019 to 2020, although significant variations can be observed at an airport level (Figure 5.3). Arrival flow inefficiencies at the top 40 airports resulted in 1.9 million minutes of additional ASMA time and approximately 0.3 million tonnes of additional CO_2 emissions, down from a peak of 9.2 million minutes in 2019. Likewise, the average additional taxi-out time per departure almost halved between 2019 (3.9 minutes) and 2020 (2.0 minutes) due to the lower traffic levels. This reduction continued in 2021 (1.9 minutes).

Figure 5.2 Average additional ASMA and taxi-out times at the busiest 40 airports

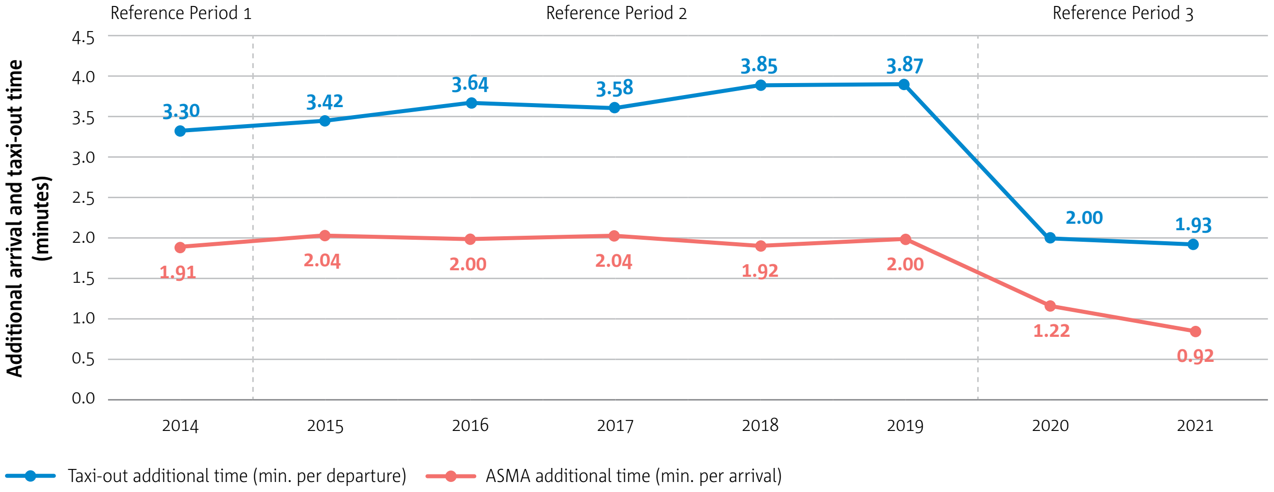
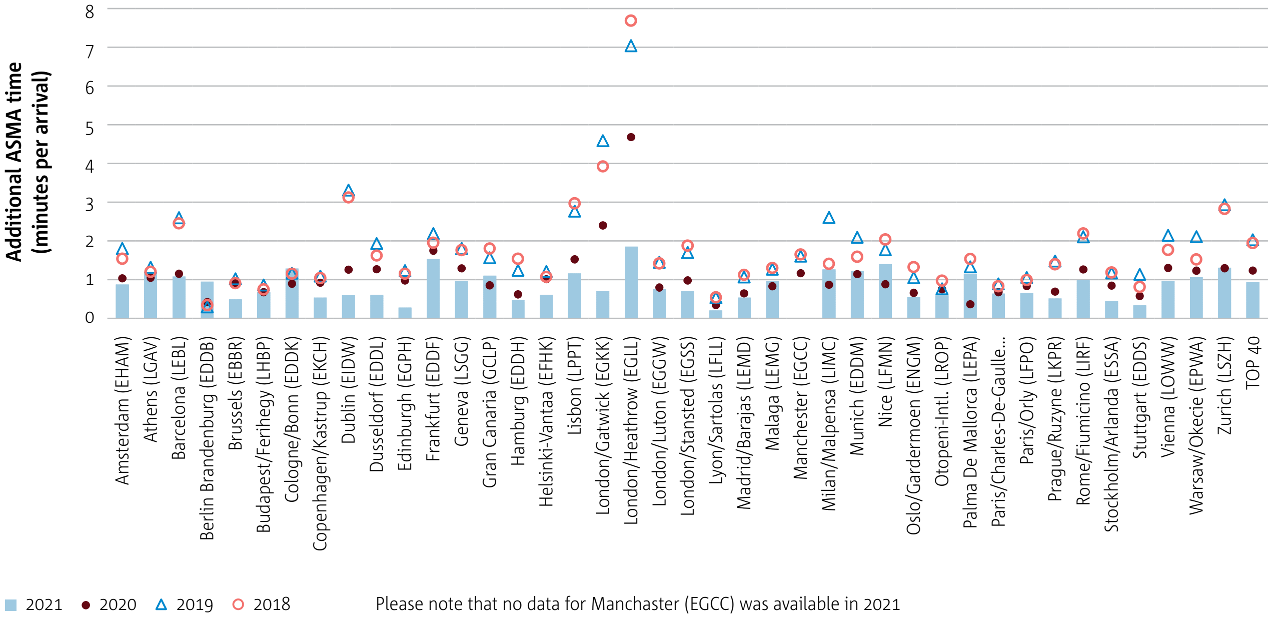


Figure 5.3 ATM related inefficiencies on the arrival flow (ASMA) at the 40 busiest airports (2018-2021)



Please note that no data for Manchester (EGCC) was available in 2021

Excess CO$_2$ emissions due to network flight inefficiency

Fuel burn per flight can be broken down across flight stages. SES Performance Scheme data has been used to compare the gate-to-gate actual trajectories of all European flights every year up to 2020 against their unimpeded trajectories[41]. Figure 5.4 provides the average excess CO$_2$ emissions per flight, broken down into different flight phases. While this is not an official indicator within the SES Performance Scheme, it does highlight that 75% of excess fuel burn originates from the en-route horizontal / vertical inefficiency as well as horizontal inefficiency during arrival (ASMA).

This figure also demonstrates that although traffic decreases were significant in 2020, there are still constraints that prevent the optimal unimpeded trajectory from being flown. It should be noted that 100% efficiency may not be achievable due to various

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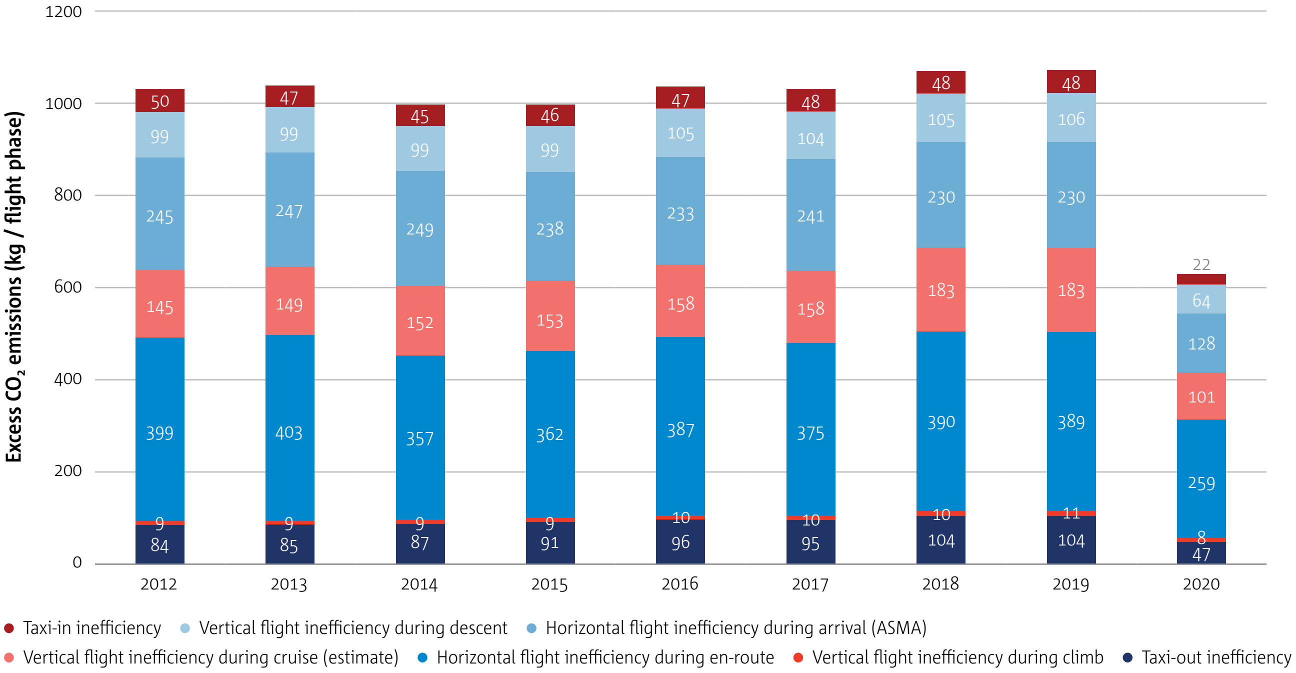
[41] Unimpeded trajectories are characterised by: zero additional taxi-out time, no level-off during climb (full fuel CCO), no sub-optimal cruise level, en-route actual distance equal to great circle distance (as weather influences are excluded), no level-off during descent (full fuel CDO), no additional time in the Arrival Sequencing and Metering Area (ASMA), zero additional taxi-in time.

Figure 5.4 **Breakdown by flight phases of gate-to-gate excess CO_2 emissions for an average flight in Europe, 2012-2020**



reasons (e.g. adverse weather, avoidance of 'Danger Areas', non-standard events, diversions etc.). It should be understood that the shortest route, as described by the optimum unimpeded trajectory, does not necessarily equal the most environmentally optimal route as other factors such as winds need to be considered.

It should be noted that the calculation of the excess CO_2 emissions based on SES performance Scheme data is no longer supported by EUROCONTROL, and from 2021 the focus will be on measuring gate to gate fuel burn and CO_2 emissions by using the NM excess fuel burn indicator (see section 5.3).

5.3 OPERATIONAL PERFORMANCE INDICATORS

Figure 5.4 estimates ATM-related inefficiency based on proxy indicators. Ongoing work has highlighted that further inefficiencies related to all stakeholders may be demonstrated by the use of indicators that are based directly on fuel burn or CO_2 emissions as opposed to operational proxies such as time or distance flown. Any new metrics should be measured and monitored according to the interdependency of all the stakeholders involved in the evolution of the flight trajectory and their impact upon fuel efficiency.

As explained in 5.2, discussions have already been triggered on the limitations of existing metrics. The sector should aim to move away from proxy metrics based on additional time or distance flown to those based on actual CO_2 emissions. EASA and EUROCONTROL, together with ANSPs, are currently working to identify and develop a suite of metrics that could more accurately measure ATM performance and the benefits from the actions of individual stakeholders.

One such metric being considered, developed by the Network Manager in 2019, is referred to as the Excess Fuel Burn indicator (XFB) and is based on actual operational data and modelled fuel burn [11]. The XFB is the fuel inefficiency on a particular route for a particular aircraft type, compared to a reference based on the best performer on that city pair / aircraft type combination (it can either be the 10th percentile - XFB10[42] or the 5th percentile - XFB5). Based on this indicator, the average excess fuel burn per flight in the Intra-Network Manager (Intra-NM) area in 2019 was estimated to be 8.6% and 11.2% for XFB10 and XFB5 respectively. It should be emphasised that the XFB

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[42] The 10th percentile (XFB10) reference means in effect that for a city pair / aircraft type combination 90% of flights burnt more fuel than the reference and 10% of flights burnt the equivalent or less fuel

Figure 5.5 Intra-NM Area[43] proportion of excess fuel burn (kg) – XFB10

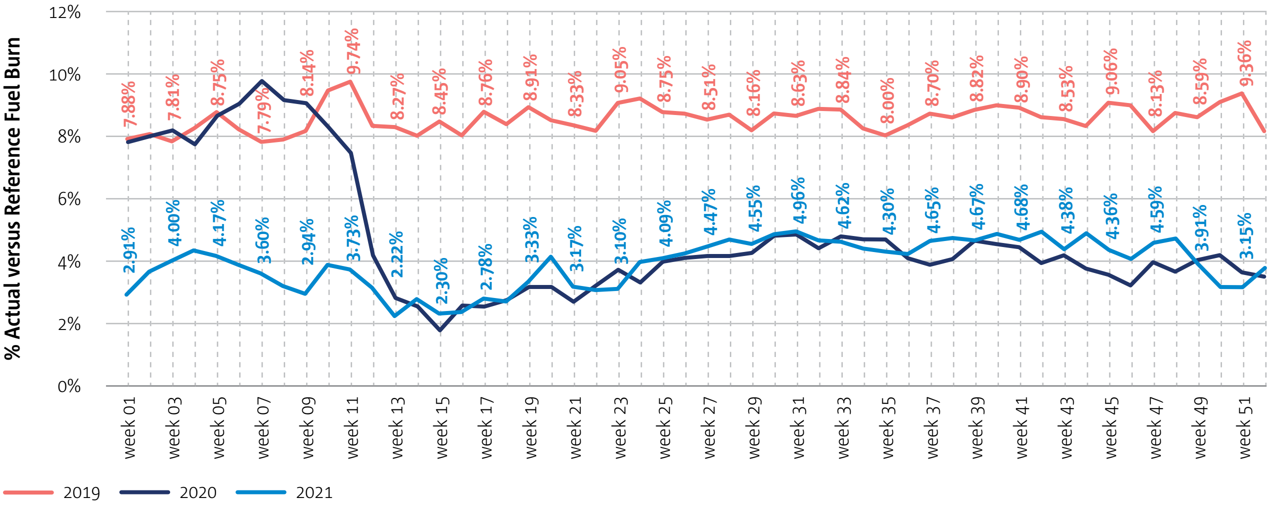
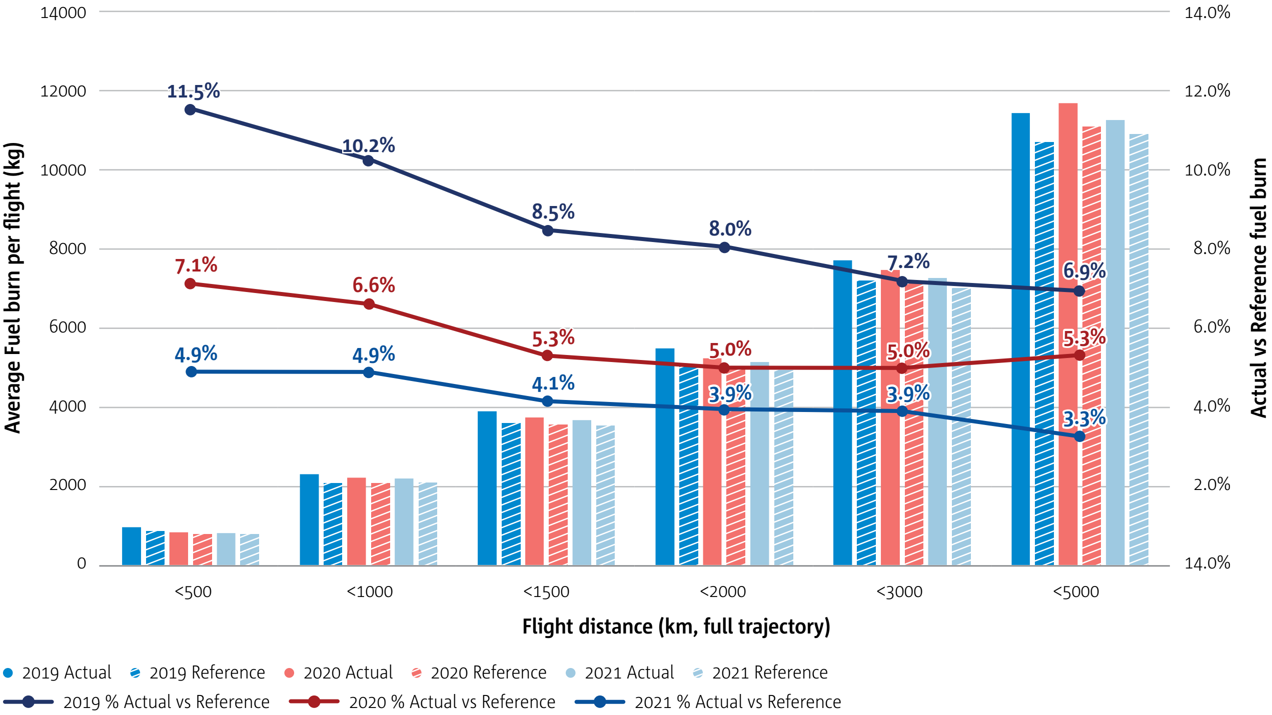


Figure 5.6 Average fuel burn per Intra-NM Area flight (2019-2021) broken down over distance bands and compared with reference fuel burn



indicator measures the system inefficiency linked to all stakeholders such as airports, flight planning processes, aircraft operators, ATC and the network itself. Considerations may still be required to address those situations where optimised flight routings of aircraft operators, may not necessarily align with the NM calculated environmentally optimised trajectory (i.e. modelled lowest fuel burn), and therefore reductions in fuel inefficiency clearly needs further analysis with all involved stakeholders.

Figure 5.5 shows that XFB10 in the Intra-NM Area ranged between 7.8% to 9.8% during 2019. Following the start of the pandemic, the XFB10 fell to between 2 and 5% during 2020 and 2021, finishing at 3.8% at the end of 2021. This demonstrates the network

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[43] Intra-Network Manager (Intra-NM) Area is ECAC plus Morocco and Israel but without Iceland.

Fuel Tankering

Fuel tankering is a practice whereby an aircraft carries more fuel than required for its safe flight in order to reduce or avoid refuelling at the destination airport for subsequent flight(s). It is also referred to as "over tankering".

Fuel tankering can be performed for two reasons:

1. When it is operationally not possible or desirable to refuel at the destination airport due events such as technical failure, fuel contamination, strikes, etc. (about 10% of tankering).

2. To achieve cost savings when the price of fuel and associated services at the departure airport is significantly lower than at the destination airport (about 90% of tankering). This is known as "economic tankering" and falls into two categories:

   (i) Full Economic – additional fuel uplifted at the departure airport that allows for a round trip without intermediate refuelling.

   (ii) Partial Economic – additional fuel uplifted at the departure airport that will only cover part of the fuel requirement for the return flight.

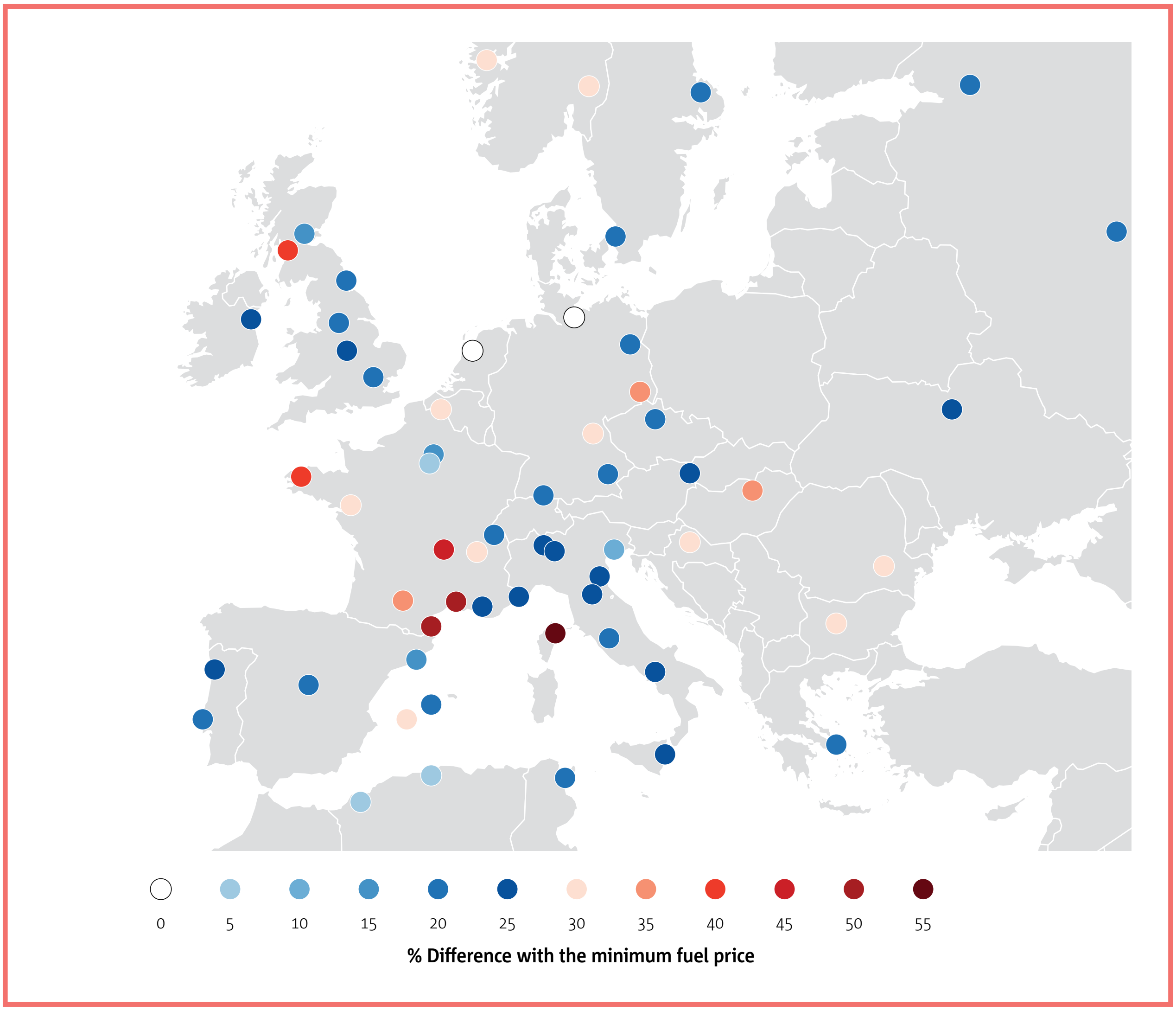
As the use of economic tankering is driven by cost savings, the greater the cost imbalance in fuel and refuelling services between two airports, the more it is likely to be used by airlines.

Economic tankering increases aircraft fuel consumption and results in unnecessary greenhouse gas emissions. A recent study [12] estimated the number of times this practice would offer an economic benefit and the quantity of extra CO_2 emissions which would result. This study was limited to flights of between 1,500 and 2,500 nautical miles (2,780 to 4,630 km), which mainly corresponds to short-haul and medium-haul flights. It was estimated that, in 2018, 21% of ECAC flights performed economic fuel tankering, representing a net saving of €265 million per year for the airlines, but burning an unnecessary 286,000 tonnes of additional fuel (equivalent to 0.54% of ECAC jet fuel used), or 901,000 tonnes of CO_2 per year. The environmental impact of economic tankering is therefore far from negligible and could increase the individual fuel consumption of an aircraft by 5 to 25% depending on the distance flown.

Full and partial economic tankering practices are not limited to short and medium-haul flights. Aircraft fuel tanks are usually designed to allow maximum range, although aircraft do not systematically fly these long distances. As such, it becomes feasible to carry much more fuel than required in order to limit or avoid refuelling at the destination airport.

As part of the 'Fit for 55' package, adopted in July 2021, the Commission proposed a Regulation to boost the uptake of SAF in air transport in the context of the 'ReFuelEU Aviation' initiative [13]. This addresses tankering and ensures a level playing field for sustainable air transport by requiring airlines to uplift from EU airports a certain % of the jet fuel they require to perform flights within and from the EU.

In addition, EASA has published Decision 2022/005/R with an objective to facilitate the implementation of new requirements on fuel/energy planning and management [14, 15]. This applies from 30 October 2022, and will improve efficiency through the introduction of the 'fuel schemes' concept that will, while maintaining a high level of safety, allow operators to optimise and reduce the amount of fuel carried during operations. The potential savings in annual CO_2 emissions are 3 million tonnes.



efficiency improvements that could be achieved in low traffic periods if the large number of current airspace restrictions are removed within the current airspace configuration. The figure also illustrates that there may be system constraints that are challenging to remove even when traffic numbers are at a minimum, such as military areas and airport terminal airspace constraints.

Fuel burn per flight can be broken down to demonstrate the impact that flight distance, aircraft operations or aircraft type have on fuel efficiency. In relative percentage terms, XFB10 is higher for the short-haul flights and reduces as the flight distance increases. This is due to longer flights typically spending a higher proportion of their flight time in the more fuel-efficient cruise phase. Figure 5.6 shows the actual versus reference[44] fuel burn during 2019-2021 for all flights in separate distance bands.

5.4 OPERATIONAL INITIATIVES

This section contains some examples of the numerous operational initiatives being implemented at the network level [16].

Free Route Airspace

Free route airspace (FRA) is a SESAR solution (see section 5.5), that is defined as a volume of airspace within which users may freely plan a route between any defined entry and exit points, subject to airspace availability [17]. This fosters the implementation of more efficient routes and more efficient use of the European airspace. FRA has been implemented in most European airspace already. Since 2018 additional Member States and Area Control Centres reported on FRA implementation, including: Maastricht Upper

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[44] The reference fuel burn is the 10%tile fuel burn

Area Control Centre, Greece, Romania, Bulgaria, Slovakia, Czechia, Poland, Iceland, parts of the United Kingdom and France. In addition, cross-border free-route activities, where the most significant potential benefits lie due to the defragmentation of European airspace, have been implemented in Italy, North Macedonia, Albania, Georgia, Armenia and parts of the United Kingdom and Ukraine. In Europe, according to Common Project 1 regulation [27], mandatory final FRA implementation with cross-border dimension and connectivity to terminal manoeuvring area should be fully implemented by 2025.

The proportion of flight time flown in free route airspace was 68% in 2021, compared to 8.5% in 2014. The Network Manager (NM) estimates that 10 million tonnes of CO_2 have been saved through the implementation of FRA since 2017. This is equivalent to around 170,000 round-trips between Madrid and Riga. In order to advance the roll-out of FRA across borders the NM should increase its efforts in the implementation of cross-border projects by ANSPs. In addition, the implementation of new airspace design projects out to 2030 [18] is expected to provide an additional 2.5-3.5% per flight CO_2 reduction as the flight efficiency of the network is further enhanced.

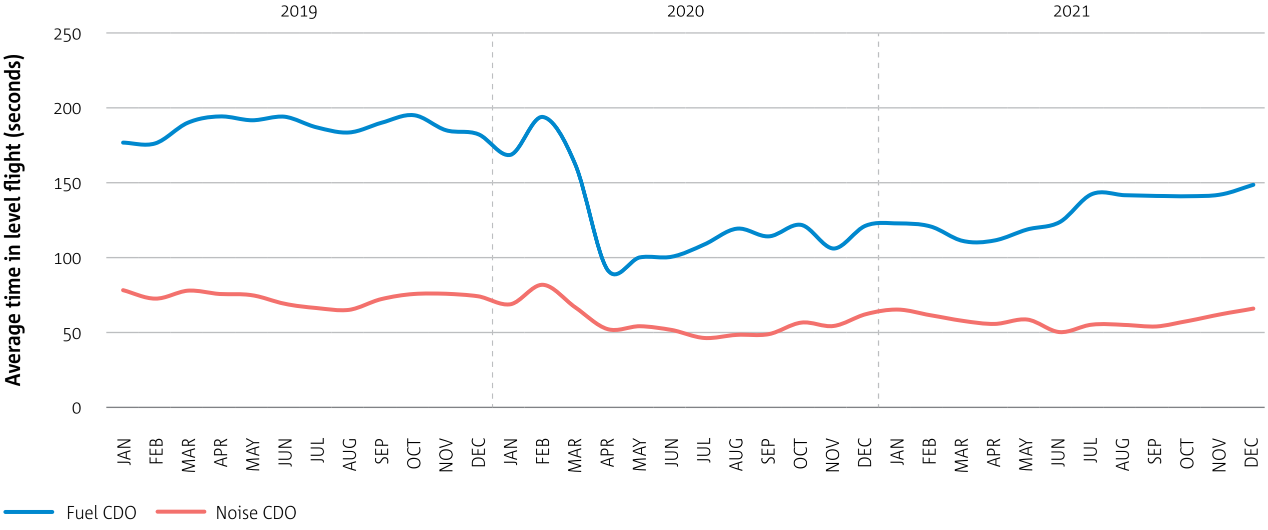
During the peak traffic periods of 2019, the NM also introduced the so-called “file it, fly it” measure to reduce en-route delay in operational airspace sectors which arose due to insufficient staffing levels in Central Europe. Whilst such measures reduced delay from around 4.0 to 2.3 minutes per flight, the corresponding re-routing of flights resulted in additional CO_2 emissions of approximately 60 tonnes per day for the defined traffic period. The measures also resulted in an additional benefit of encouraging aircraft operators to fly the filed flight plan which enabled enhanced predictability and fuel planning.

Continuous Climb Operations / Continuous Descent Operations

Along with Free Route Airspace, Continuous Climb Operations (CCO) and Continuous Descent Operations (CDO) are SESAR solutions often considered to be one of the best options for fuel (CO_2) savings and/or noise reduction in the climb and descent phases. Following an agreement on harmonised definitions of CCO and CDO together with a metric and measurement criteria, their implementation has been supported by the release of the European CCO / CDO Action Plan in 2020 [19].

The CCO / CDO performance dashboard has been measuring fuel and noise benefits at European airports since 2019 [20]. The fuel CCO/CDO measures the vertical flight efficiency, in terms of fuel and CO_2, for the entire climb and descent profile respectively. The noise CCO/CDO measures the vertical flight profile efficiency up to 10,500 ft for CCO and from 7,500 ft for CDO, which are the phases of flight where the major environmental impact is considered to be noise.

Figure 5.7 **Average time in level flight for CDO at 40 busiest airports (in terms of number of movements) during 2019-2021**

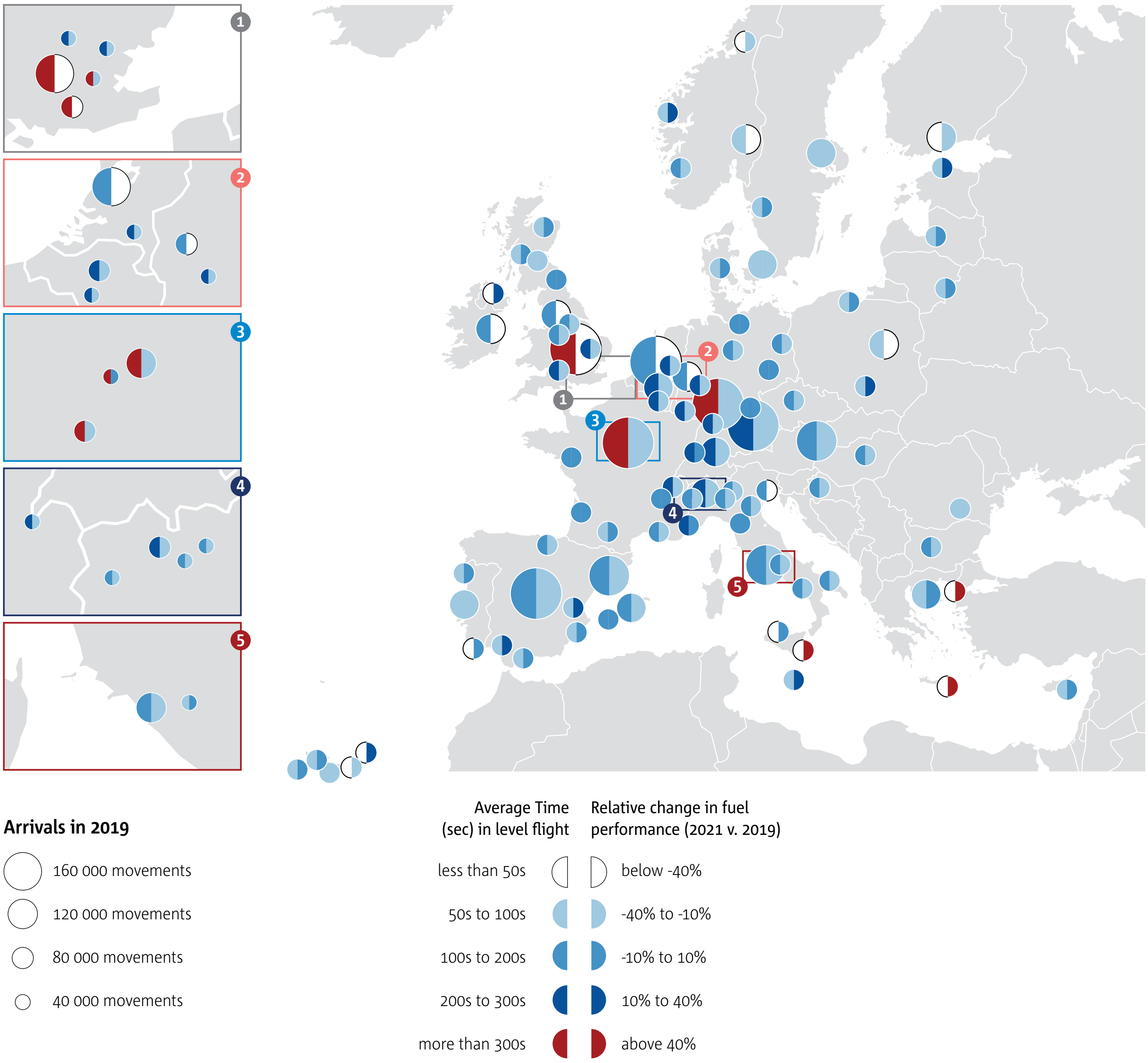


As reported in EAER 2019, there is greater potential for fuel burn and noise reductions in CDO than CCO. Figure 5.7 shows the progression in the 'average time in level flight' for the fuel and noise CDO during 2019-2021. With the removal of network constraints at the height of the COVID pandemic, the average time in level flight for the fuel CDO fell by around 50% from 200 seconds to 100 seconds, only to subsequently slowly increase to around 150 seconds by the end of 2021. The impact on the noise CDO values is not so clear with average time in level flight reducing from around 70 seconds in 2019, to between 50-60 seconds during the pandemic. This suggests that there is an inefficiency captured below 7,500 ft that is less influenced by traffic levels.

In 2021, the average duration of level flight flown at the top 40 airports is 25 seconds for departures (CCO) and 137 seconds for arrivals (CDO), the latter decreasing from a high of 189 seconds in 2019. This compares to 31 seconds across the network for CCO and 135 seconds for CDO. Figure 5.8 indicates that there is a relatively high amount of level flight at airports within the European core area, indicating a link between CCO/ CDO and airspace complexity.

The potential savings in the European Civil Aviation Conference (ECAC) area from the implementation of CCO / CDO are estimated to be up to 320 thousand tonnes of fuel (up to 1 million tonnes of CO_2 emissions) per year based on the peak traffic of 2019. However, it should be noted that it may not be possible to fly

Figure 5.8 Fuel CDO performance at European airports



100% CCO or CDO for a number of reasons such as safety (i.e. time or distance separation), weather or capacity. To realise significant savings, constraints should be minimised, especially in the descent phase, and aircraft should descend from their optimal top of descent points.

The Common Project 1 mandate requires that from 2027 all aircraft must be forward fit with the capability to downlink the Extended Projected Profile (EPP), thereby providing visibility on the ground of the optimum descent profile as calculated by the avionics, including the optimal top of descent point. The SESAR very large demonstration DIGITS (2016-2020) [21] assessed the potential benefits to the descent profiles of making EPP information available to controllers in real time. This work continues in the ADSCENSIO project [29], which is considering potential metrics based on the difference between the EPP and the actual climb/descent profile to detect inefficiencies that may not be captured by the length of level segment metrics, for example in case of a long thrust descent that is continuous but sub-optimal.

Pilot environmental awareness is critical in the implementation of operational initiatives, such as CCO / CDO. In order to support this, the Aircrew Training Policy Group (ATPG) has issued an advisory paper on Environmental Awareness Training for Pilots that calls for mandatory training in all categories of pilot licences through academic knowledge and practical training, thereby integrating it into the established threat and error management philosophy and process. In addition, the European CCO/CDO Task Force has developed training for ATCOs and Flight Crews that detail best practices on how to collaborate in enabling optimum vertical profiles [22].

5.5 SESAR: TOWARDS THE DIGITAL EUROPEAN SKY

The Single European Sky ATM Research and Development (SESAR) innovation cycle has been put in place in support of the EU's aviation strategy and the SES initiative. It pools the resources and expertise of all ATM stakeholders in a coordinated way in order to define, develop and deploy ATM solutions to fulfil the digital European sky vision that meets Europe's policy objectives on aviation and air transport.

The European ATM Master Plan - Setting SESAR's environmental ambition


EUROPEAN ATM MASTER PLAN
Digitalising Europe's Aviation Infrastructure
Executive view
SESAR
2020 edition

The European ATM Master Plan binds together both phases of SESAR research and development, and SESAR deployment. It is the main planning tool that also details the performance goals for key areas, such as the environment where SESAR is targeting a reduction in total gate-to-gate CO_2 emissions of 800-1600 kg (5-10%) by 2035, from a baseline of 16,600 kg for an average European flight in 2012. This includes both airport as well as flight trajectory operational efficiency improvements.

sesar
JOINT UNDERTAKING

The SESAR Joint Undertaking was initially established in 2007 to deliver technological solutions to transform air traffic management in Europe, in line with the vision of the European ATM Master Plan. The newly established SESAR 3 Joint Undertaking has a 10-year mandate (2021-2031) to drive an ambitious programme to make Europe's aviation infrastructure fit for the digital age, while offering quick wins to contribute towards the sector's net zero CO_2 ambitions. The scope has been extended to the provision of support for the market uptake of the output from SESAR research and development through demonstrators. Its aim is to leverage the latest digital technologies to transform Europe's ATM infrastructure, thereby enabling it to handle the future demand and diversity of air traffic safely and efficiently, while minimising its environmental impact in line with the objectives of the European Green Deal.

Improving every stage of the flight

SESAR addresses the whole scope of aviation's environmental footprint, from CO_2 and non-CO_2 emissions to noise and air quality. SESAR Solutions refer to new or improved operational procedures or technologies that are designed to meet the essential operational improvements outlined in the European ATM Master Plan. The SESAR Solutions Catalogue [23] outlines progress in developing the technological and procedural solutions needed for delivering the digital European sky. The fourth edition of the publication contains 101 delivered solutions that have reached the required level of maturity for industrialisation to address key areas of the air traffic management value chain, notably airport operations, air traffic services, network operations and the enabling infrastructure.

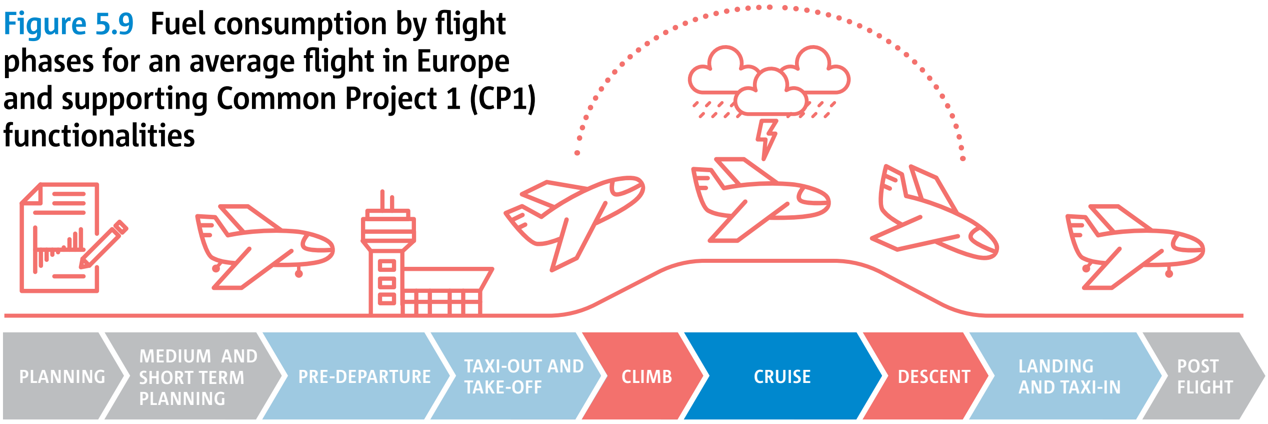
ALBATROSS (2021-2023) is a very large-scale demonstration project that illustrates the potential of the SESAR approach in bridging the gap towards implementation [24]. The objective of the project is to examine the potential for SESAR solutions to realise environmental benefits in real operational environments covering all phases of flight, from flight planning to landing and post-operations feedback. The demonstration concepts include dynamic Route Availability Document (RAD) restrictions, semi-robotic towing vehicle / one-engine taxiing, optimised descent operations, initial trajectory information sharing, slot swapping or re-routing in support of environmental objectives, enhanced civil-military coordination, cross-border free route airspace and use of clean energy to power ATC equipment.

Accelerating market uptake of aviation green deal solutions

A significant portion of SESAR 3 Joint Undertaking's budget of €1.6 billion will be dedicated to a flagship programme on the Aviation Green Deal, as outlined in the SESAR multi-annual work programme [25]. Innovative work streams include:

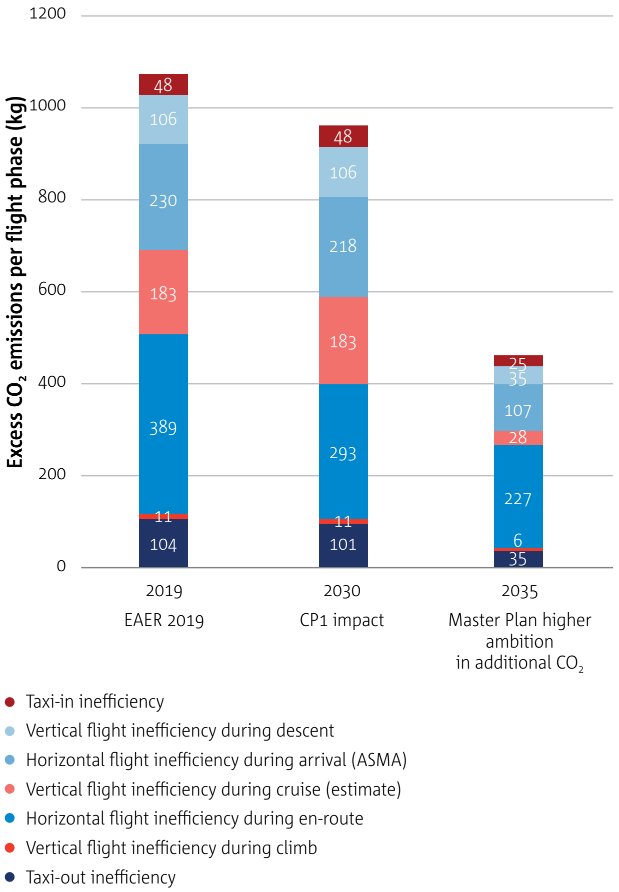
- Wake energy retrieval when two aircraft fly approximately 3 kilometres apart during the cruise flight phase.
- Green taxi solutions such as one engine taxiing and semi-robotic towing vehicles.
- Enhanced understanding of the climate impact of aviation non-CO_2 emissions.
- Environmental dashboards to support ATM decision-makers in making informed decisions and improve communication on ATM efforts on environmental sustainability.
- Ensuring the ATM system is ready to support new types of aircraft, such as hybrid-electric, hydrogen, electric, drones/UAVs or super/hypersonic aircraft.

Figure 5.9 **Fuel consumption by flight phases for an average flight in Europe and supporting Common Project 1 (CP1) functionalities**



Average fuel burn during flight phase (Total 5.7 Tonnes)	130 kg 10 kg/min	660 kg 60kg/min	4260 kg 60 kg/min	600 kg 40 kg/min	60 kg 8kg/min
CP1 supporting functionalities	• DMAN • AMAN DMAN Integration • AOP • Airport Safety Nets		• FUA • Management of predefined airspace configuration • FRA	• AMAN • XMAN • AMAN/ DMAN-integration	• AOP • Airport Safety Nets

Figure 5.10 Excess CO_2 emissions for an average flight in Europe



SESAR Deployment

The SESAR Deployment Manager (SDM) [26] plans, synchronizes, coordinates and monitors the implementation of the SESAR 'Common Projects' (CPs) that drives the modernisation of ATM in Europe. The current Common Project 1 (CP1) [27] has various ATM functionalities, deriving from SESAR solutions, that reduce inefficiencies and generate fuel and CO_2 savings in different phases of the flight, especially the cruise phase (Figure 5.9).

Figure 5.10 provides a breakdown of CO_2 emissions inefficiencies per phase of flight for the average flight in the ECAC area during 2019, predicted improvements by 2030 due to CP1 projects and Master Plan target for 2035.

When comparing the gate-to-gate actual trajectories of European flights against unimpeded trajectories, there is an additional 6% of CO_2 emissions in 2019 (around 1 tonne of excess CO_2 emissions against 17 tonnes of CO_2 emissions for the average flight). The contribution of CP1 projects represent around 20% towards the Master Plan's performance ambition in 2035.

STAKEHOLDER ACTIONS

Zero Emission Regional Aviation

Avinor is responsible for air navigation services in the Norwegian airspace and operates Norway's 43 state-owned airports. Its vision is that all domestic flights are electrified by 2040. In view of this, the Norwegian Association of Air Sports and Avinor established a project in 2015 to promote and demonstrate electrification of aviation. Aircraft such as the Pipistrel Alpha Electro and Velis Elector have proven to be effective in communicating climate solutions, not only electrification, but also Sustainable Aviation Fuels (SAF) and hydrogen. In parallel to promoting zero emission aviation, Avinor has carried out a thorough mapping of electricity supply and consumption at all its airports to ensure adequate charging capability. The network of airports in Scandinavia, and in Norway in particular, is well suited for electrified passenger flights due to an already established market with several relatively short flights and thin routes.

Optimisation of runway usage on single and multiple runway airports

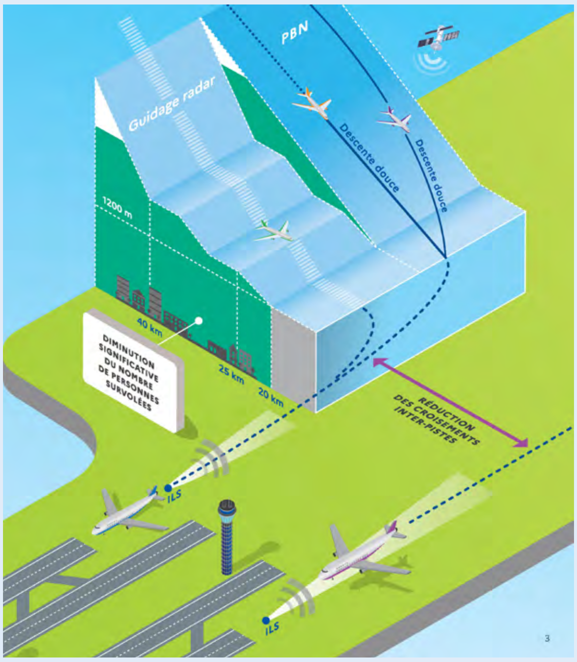
Multi-runway airports often have dedicated arrival and departure runways. This facilitates ATC management but, depending on the arrival-departure balance, may lead to sub-optimal runway utilisation and increased fuel burn. The SESAR *'sequence-based integration of arrival and departure management'* solution addresses this problem. Validation trials at Stockholm Arlanda airport in 2019 demonstrated a potential to reduce departure CO_2 emissions by an average of 3.45 kg per flight, and arrival CO_2 emissions by as much as 23.45 kg. This solution is moving to pre-industrialisation at Stockholm Arlanda in 2022-2023 as part of the SESAR large-scale demonstration project SORT [28].

Tackling early descent at Maastricht Upper Area Control Centre

In the core area of Europe airspace, aircraft are often required to initiate descent before the optimum point in their flight trajectory, resulting in an overconsumption of fuel. An analysis of over 2500 European flights in 2019 found that descent was initiated on average 33km before the optimum point, leading to a potential to 3 to 10 kg fuel burn penalty even if the aircraft did not level-off at any time during the descent. The availability of *Automatic Dependent Surveillance - Contract Extended Projected Profile (ADS-EPP)* information on the air traffic controller's screen provides new information that results in fewer instances of early descent. The ongoing work of the SESAR demonstration project ADSCENSIO (2021-2023) [29] is further investigating the environmental benefits of the availability of EPP information on the ground.

Round-the-clock Continuous Descent Operations (CDO) at Paris-CDG

Since 2016, the French ANSP DSNA has carried out continuous descent operations (CDO) for night flights on a single runway pair at Paris-CDG airport. CDO enables incoming aircraft to approach their landing in a continuous diagonal movement rather than a traditional phased landing of several downward steps. The challenge of expanding this concept to round-the-clock operations at Paris-CDG airport, including at peak traffic times, is tied to the complexity of feeding the airport's two parallel runway pairs and the need for major airspace changes to create a new air traffic pattern. Live trials in 2021 demonstrated a 7% fuel burn saving from top of descent and a 70% reduction in population overflown. Full scale implementation is now due to start in 2023.



Fello'fly – Flying in formation to reduce emissions

In 2021, Airbus performed the first long-haul demonstration of formation flight in general air traffic (GAT) regulated transatlantic airspace with two A350 aircraft flying at three kilometres apart from Toulouse, France to Montreal, Canada [30]. Over 6 tonnes of CO_2 emissions were saved on the trip, confirming the potential for more than a 5% fuel saving on long-haul flights. A key SESAR 3 JU goal is to develop and validate an ATM concept to support the wide application of this principle; in a first step, lower density environments will be addressed, but the ultimate goal is to enable wake energy retrieval to be applied routinely in the core European area, which is the most dense en-route airspace in the world.

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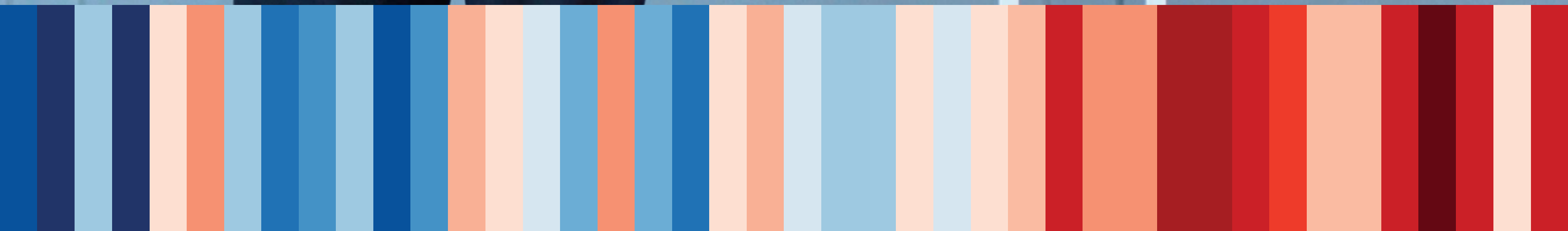


AIRPORTS

- **In 2020, EASA launched the Environmental Portal to facilitate sharing of Aircraft Noise Certificate information together with the ANP Database for sharing Aircraft Noise and Performance data.**
- **During 2020, approximately 50% of operations in Europe were by aircraft compliant with the latest Chapter 14 noise standard.**
- **There are significant delays in approving and implementing the Performance Based Navigation transition plans, which in turn delays the achievement of environmental benefits.**
- **Collaboration of all relevant stakeholders is critical in identifying optimum solutions to mitigate environmental impacts around airports, while accounting for system constraints.**
- **As the aviation sector evolves to respond to environmental challenges, and new market segments are created, airport infrastructure also needs to adapt accordingly.**
- **By 2030, the European Green Deal's Zero Pollution Action Plan aims to reduce the share of people chronically disturbed by transport noise by 30% and improve air quality to reduce the number of premature deaths caused by air pollution by 55% (compared to 2017).**
- **In 2020, the Airport Carbon Accreditation Programme added Levels 4 (Transformation) and 4+ (Transition) to support airports in achieving net zero CO_2 emissions and to align it with the objectives of the Paris Agreement.**
- **More than 90 European airports are already set to achieve net zero CO_2 emissions by 2030, with 10 airports managed by Swedavia having already achieved this target.**

6.1 MANAGING ENVIRONMENTAL IMPACTS AROUND AIRPORTS

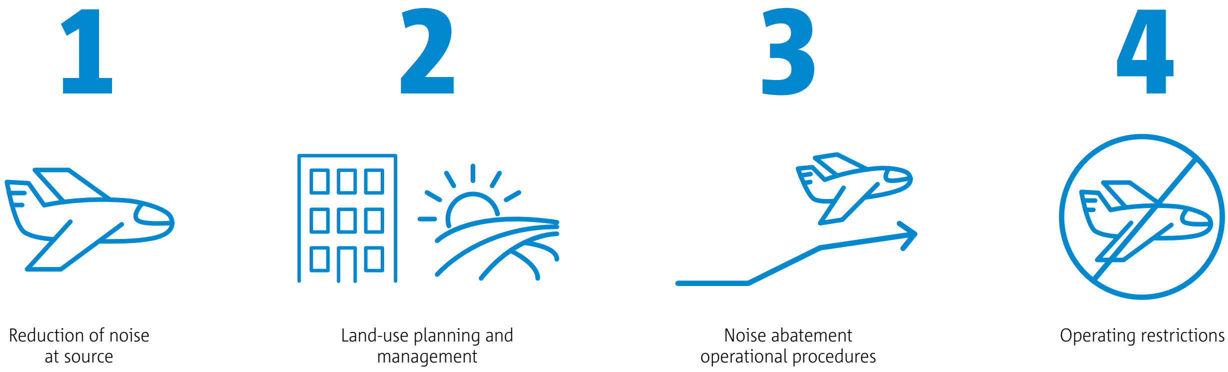
Noise regulatory measures

There are two main European regulatory measures for managing the impact of aircraft noise around airports. The first is the Environmental Noise Directive [1] that promotes effective monitoring and management of noise impacts alongside national and local initiatives. The other is the Balanced Approach Regulation [2, 3] that establishes airport noise management elements, including rules and procedures on the introduction of noise-related operating restrictions (Figure 6.1).

EASA performs two specific roles in support of the above regulatory measures. The first is to verify and publish aircraft noise and performance data, which is used in models to calculate airport noise contours and assess the surrounding noise impact. This dataset ensures that airport noise modelling in Europe is robust and harmonised. The second role is to collect noise certificate documentation from aircraft with a maximum take-off mass greater than 34,000 kg, or 19 passenger seats or more, operating at European airports. To fulfil these roles, the Agency has launched the Aircraft Noise and Performance (ANP) database and the Environmental Portal [4] through which appropriate stakeholders can submit and share information.

In line with the Environmental Noise Directive, aircraft noise management at airports involves monitoring and assessing the situation, and then defining a baseline, future objectives and an associated noise action plan. The Balanced Approach plays a key role in this action plan and consists of the following core elements:

Figure 6.1 Balanced Approach to airport noise management



1. Reduction of noise at source involving research programmes aiming at reducing aircraft noise through technology and design.

2. Land-use planning and management policies to avoid incompatible developments such as residential buildings in noise-sensitive areas.

3. Noise abatement operational procedures [5] to enable the reduction or redistribution of noise around the airport and make full use of modern aircraft and air navigation capabilities.

4. Operating restrictions on aircraft that limit access to or reduce the operational capacity of an airport, for instance noise quotas or flight restrictions.

Greater emphasis may be placed on certain elements of the Balanced Approach compared to others, depending on the airport noise abatement objectives and the cost of mitigation measures [6, 7]. Whilst recognising that operational restrictions should be used only after consideration of all other elements of the Balanced Approach, 79% of European airports recently surveyed by Airport Council International Europe (ACI-E) indicated that they employ various measures (e.g. restrictions on noisier aircraft, night flight restrictions, runway restrictions, noise budgets and movement caps). The scope of operating restrictions varies on an airport-by-airport basis and the aircraft noise certification basis. Unlike for aircraft compliant with Chapter 3 of ICAO Annex 16 Volume I, restrictions of Chapter 4 and 14 aircraft should be of a partial nature and not totally prohibit access of these aircraft to the airport concerned.

A recent study for the European Commission on the application of the Balanced Approach Regulation concluded that some Member States have the same competent authority for this Regulation and the Environmental Noise Directive, whereas others have different authorities. While the Regulation is considered to have clear and accountable processes to engage and consult stakeholders, the study noted that it would be beneficial to clarify objectives and procedures by means of best practice guidance to follow when selecting and implementing noise reduction measures.

Collaborative Environmental Management

The consultation and collaboration of stakeholders (e.g. airports, airlines, air navigation service providers, local authorities, local communities) is critical in order to identify optimum solutions to mitigate environmental impacts around airports while taking into account potential system constraints. The EUROCONTROL 'Collaborative Environmental Management' (CEM) specification was initially developed in 2014 to facilitate these discussions and can be adapted to suit local needs.

The CEM specification [8] was updated in 2021 in order to meet the growing sustainability challenges that the aviation sector is facing. This update included:

- enabling the implementation of the new measures that may be initiated in response to the EU Green Deal (e.g. use of SAF and inclusion of SAF providers);
- strengthening the local community engagement and the collaboration with local authorities (e.g. through support from the Airport Regions Council);

- references to new legislation and voluntary industry schemes (e.g. Airport Carbon Accreditation);
- reflecting the growing importance of new markets (e.g. Drones, Urban Air Mobility); and
- case studies featuring best practices in stakeholder engagement and noise abatement from operational initiatives.

The CEM specification has been endorsed by ACI-E as an industry recommended practice, and greater coordination with the Airports Regions Council is foreseen to reinforce the exchange of environmental technical information and extend the cooperation on good practices.

Building on CEM, the SESAR Total Airport Management project is working on bringing collaboration in airport management to the next level by developing active real-time airport environmental performance management tools that incorporate key parameters into the Airport Operations Plan (AOP), which integrates with the Network Manager. Performance dashboards combine fuel burn / CO_2 emission metrics with air quality and noise indicators to enable trade-off assessments. They will be able to support, for example, runway configuration management, optimisation of gate or taxi route allocation, arrival/departure route allocation and conformance to agreed noise and air quality levels at specific monitoring stations [9, 10].

Performance Based Navigation

Conventional navigation places limitations on a more efficient use of the airspace and can result in an unnecessary environmental impact. The use of Performance Based Navigation (PBN) enables an optimum aircraft flight path trajectory to mitigate environmental impacts, particularly in the vicinity of airports, without having to overfly ground-based navigation aids. This means that PBN routes and procedures can be placed:

- to avoid noise-sensitive areas around an airport. The concentration of flight paths, and thus aircraft noise, can be a benefit if these flights avoid densely populated residential areas [11]. Alternating flight paths through an area may also be possible to provide predictable respite for affected communities;
- to enhance vertical profiles (e.g. Continuous Descent Operations and Continuous Climb Operations) in terminal airspace, whereby more efficient vertical profiles can be flown, resulting in lower emissions and noise [12]; and
- to enable shorter routes between origin and destination airports to reduce overall fuel burn.

Regulation (EU) 2018/1048 [13] requires the gradual implementation of PBN routes and approach procedures by 6 June 2030 to replace existing conventional navigation procedures in the Single European Sky. Two interim deadlines of December 2020 and January 2024 have also been set to prioritise the publication of new PBN routes and approach procedures [14]. The Regulation 2018/1048 also requires coordination with all affected stakeholders and the approval of transition plans to detail what will be implemented and by when. In order to avoid potential negative impacts during the airspace redesign, it is important to follow a CEM approach as the scope of the environmental benefits will be dependent on the local airport circumstances. With the data available in mid 2022, PBN implementation is, in most cases, subject to a significant delay.

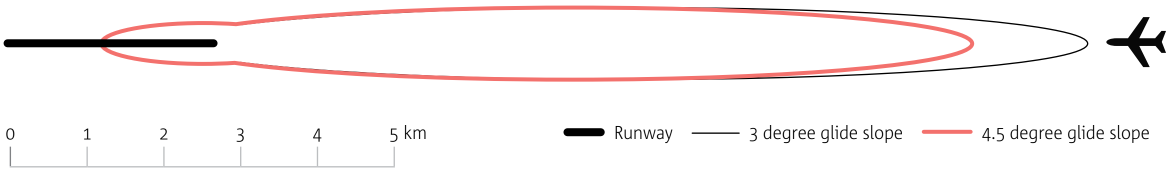
In 2019, a partial assessment of environmental benefits from PBN was performed by the SESAR Deployment Manager covering certain operational initiatives at 18 airports. These PBN operations noted a reduction in the “Arrival Sequencing and Metering Area (ASMA)” time, which measures the delay in the arrival flow of air traffic, thereby enabling significant savings in time, fuel and CO_2 emissions (2.6 million tonnes between 2014-2030). This CO_2 saving is significant and represents about 20% of the total expected CO_2 savings from future SESAR operational initiatives out to 2030.

Increased flexibility in the vertical flight path

SESAR has defined and validated a concept for the use of a Second (alternative) Runway Aiming Point (SRAP) on approach in place of the runway threshold [15]. Aircraft are cleared to land using this second aiming point depending on their wake turbulence category and their need for more or less runway length, thereby enabling the inbound aircraft to reduce noise footprint and possibly reduce runway occupancy time and/or taxi-in time depending on the local airport layout. In addition, SESAR has developed the Increased Glide Slope (IGS) concept, which facilitates a steeper 4.5 degree approach (instead of the usual 3 degree) to the airport runway threshold that helps to reduce noise (Figure 6.2).

These innovative procedures can be combined to further increase benefits and are already in the pre-industrialisation stage. Following extensive simulations, the SESAR large scale demonstration DREAMS conducted a live trial campaign in 2021 and 2022 in Germany, Italy and the Netherlands [16].

Figure 6.2 **Single landing 60 dB L_{night} noise contours for aircraft flying a baseline 3 degree glide slope and an increased 4.5 degree glide slope**



Phenomena Study

The objective of this study [17] was to support the European Commission in defining potential measures to significantly reduce (20-50%) the impact on human health due to environmental noise by 2030, and to assess how noise legislation could enhance the implementation of measures. For aviation, airports with more than 50,000 movements per year were considered, and potential noise abatement solutions were focused on existing and broadly available measures.

The study concluded that more efficient coordination between different policy areas and stakeholders would help to align with the European Green Deal ambitions in pursuing Sustainable Development Goals. The scenario that offered the best potential for health burden reduction (44-46%) combined improved take-off procedures, precision-area navigation, phase-out of older aircraft and acquisition of new quieter aircraft. It was also noted that this scenario could be augmented by selective night curfews. In order to avoid future noise issues at small, but fast-growing airports, often situated close to residential areas, changing the definition of airports to be included in the Environmental Noise Directive from 50,000 down to 30,000 movements a year was also noted as something that should be considered.

Zero Pollution Action Plan

The output of the Phenomena study informed the European Green Deal's Zero Pollution Action Plan [18], which aims to reduce air, water and soil pollution to levels no longer considered harmful to health and natural ecosystems. This translates into 2030 targets, compared to a 2017 baseline, to accelerate the reduction of pollution at source, including:

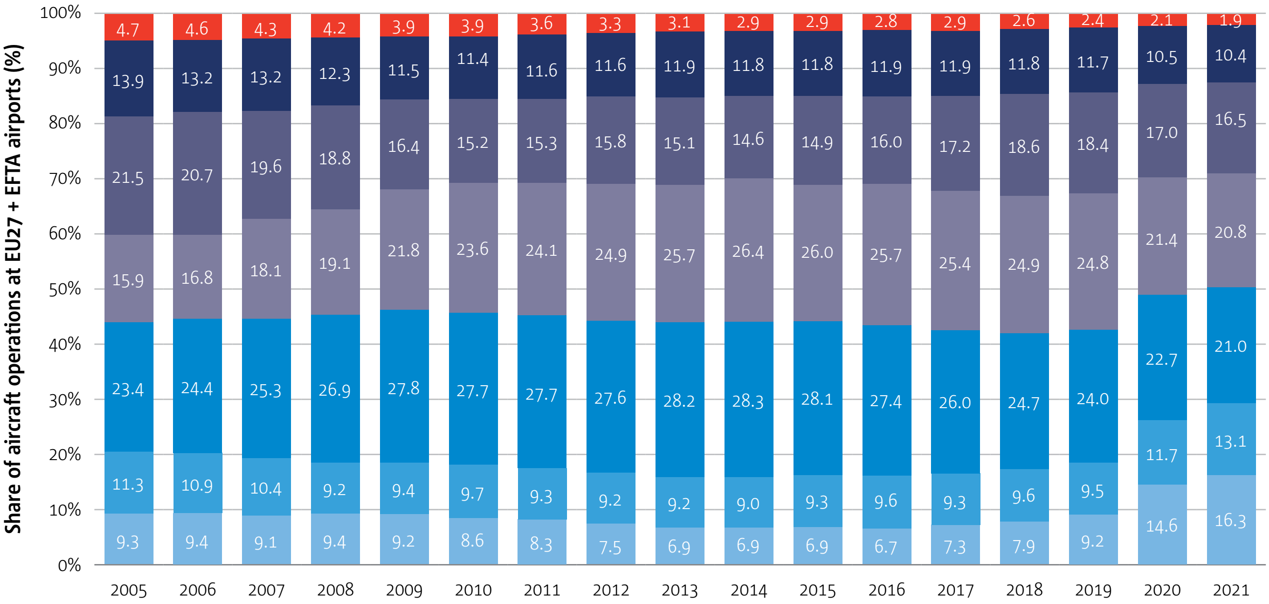
- reducing the share of people chronically disturbed by transport noise by 30%; and
- improving air quality to reduce the number of premature deaths caused by air pollution by 55%.

The aviation sector will have to play its role in the establishment of measures and actions to achieve these goals.

6.2 AIRCRAFT NOISE PERFORMANCE AT EUROPEAN AIRPORTS

As the latest aircraft technology gradually penetrates the European fleet, its environmental performance is expected to improve over time. Figure 6.3 shows the share of EU27+EFTA operations by aircraft cumulative margin[45] to Chapter 3 noise limits. During 2021, only 1.9% of operations were by marginally compliant Chapter 3 aircraft, while 50% of operations were by Chapter 14 compliant aircraft.

Figure 6.3 **Share of operations by cumulative margin to Chapter 3 limits at EU27+EFTA airports**



● 0 to 10 EPNdB – "Marginally compliant" aircraft that meet Chapter 3 but not Chapter 4 limits

10 to 17 EPNdB – Aircraft that meet Chapter 4 but not Chapter 14 limits, split into the following bands:

● 10 to 13 EPNdB ● 13 to 15 EPNdB ● 15 to 17 EPNdB

≥ 17 EPNdB – Aircraft that meet Chapter 14 limits, split into the following bands:

● 17 to 22 EPNdB ● 22 to 27 EPNdB ● > 27 EPNdB

6.3 GREEN AIRPORT INFRASTRUCTURE

As the aviation sector evolves in order to respond to environmental challenges and new market segments, airport infrastructure also needs to adapt accordingly. The trans-European transport network (TEN-T) regulation promotes the interconnection, multimodal mobility and interoperability of national networks. It is currently being reviewed to ensure that transport infrastructure development is aligned with the European Green Deal and the Strategy on Sustainable and Smart Mobility [19].

Sustainable Aviation Fuels (SAF)

The use of 'drop-in' sustainable aviation fuels (SAF) in the current global fleet can reduce aviation emissions on a life-cycle basis in the short term. Structured development and documentation of all relevant elements for introducing SAF into the airport fuel supply system is critical to ensure efficient and cost-effective operational logistics. This includes product registration, sampling and probing of SAF, assignment of customs tariff number as well as the delivery and storage at the airport's fuel farm.

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[45] 'Cumulative margin' is the figure expressed in EPNdB obtained by adding the individual margins (i.e. the differences between the certificated noise level and the maximum permitted noise level) at each of the three reference noise measurement points in Chapter 3. See also figure 3.3 in Technology and Design chapter.

While airports are not usually involved in the fuel supply chain, they can be a key enabler in bringing parties together (e.g. fuel producers, users, suppliers, fuel farm operators) and facilitating the process of SAF uptake by airlines [20].

Hydrogen

Unlike with the use of drop-in SAF, which can be blended with fossil-based fuel, airports will require time to prepare for novel hydrogen aircraft and their associated fuelling infrastructure [21], which could take various forms depending on the demand for hydrogen, the airport's location and distance to the hydrogen source, the space available at the airport and the accessibility to the feedstock for producing hydrogen. Potential supply chains include:

- manufacturing hydrogen on site;
- importing hydrogen in its gaseous form and liquefying on site;
- importing hydrogen in its liquid form; or
- importing hydrogen in exchangeable tanks.

The Airbus "Hydrogen Hub at Airports" concept brings together key airport stakeholders to better understand hydrogen infrastructure needs for future aircraft and to develop a stepped approach to decarbonise all airport-associated infrastructure. Each supply chain will have different infrastructure, operations, safety, efficiency and costs implications. While it is more favourable to transport hydrogen within the airport via a fuel supply system directly to the gate, this might only happen once the economies of scale justify the required investment in infrastructure. The physical properties of hydrogen make it at least as safe as normal Jet A-1 fuel, but with different safety risks and challenges that will require specialised procedures to handle the fuel safely.

Hydrogen Hub at Airports by Airbus

This concept involves collaborating with airports to develop a stepped approach to decarbonise airport facilities, ground operations and transportation using hydrogen

2020 Launch of preliminary studies into airport infrastructure and energy production needs

2023 Start of concept deployment at airports worldwide

2030 Ramp up of hydrogen infrastructure deployment worldwide

2035 Entry-into-service of ZEROe hydrogen aircraft at airports

A large supply of green hydrogen[46] at an airport could support new hydrogen fuelled aircraft that are aiming to enter service in the 2035 timeframe, while also helping to decarbonise other airport or local community activities (e.g. ground support equipment, buses).

Sustainable Taxiing

During 2020 Schiphol airport initiated a trial under SESAR on sustainable taxiing using a 'Taxibot' [22]. The trial confirmed a 50% fuel / CO_2 emissions saving compared to standard taxi procedures, while also helping to reduce NO_X emissions and noise. Various operational, infrastructure and technical challenges need to be addressed, but the use of fully electric sustainable taxiing is expected to become the standard procedure by 2030.

6.4 NET ZERO CO_2 EMISSIONS

In June 2019, a Sustainability Strategy for Airports was launched in Europe with a systematic approach containing practical guidance on how to achieve it [23]. As part of this strategy, over 500 European airports committed to net zero CO_2 emissions[47] from airport operations fully within its own control by 2050 at the latest, reducing absolute emissions to the furthest extent possible and addressing any remaining emissions through carbon removal and storage.

Airports are drafting roadmaps to identify and implement the measures and actions needed to reach net zero CO_2 emissions [24]. More than 90 airports are already set to achieve net zero CO_2 emissions by 2030, with 10 airports managed by Swedavia having already achieved this target.

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[46] The 'colours' of hydrogen refer to how it is produced and its carbon footprint. 'Green' hydrogen is produced in a climate neutral manner. 'Blue' hydrogen is produced from natural gas but the CO_2 produced is captured and stored rather than being released to the atmosphere as with 'Grey' hydrogen. 'Brown' and 'pink' hydrogen are produced from coal and nuclear energy respectively.

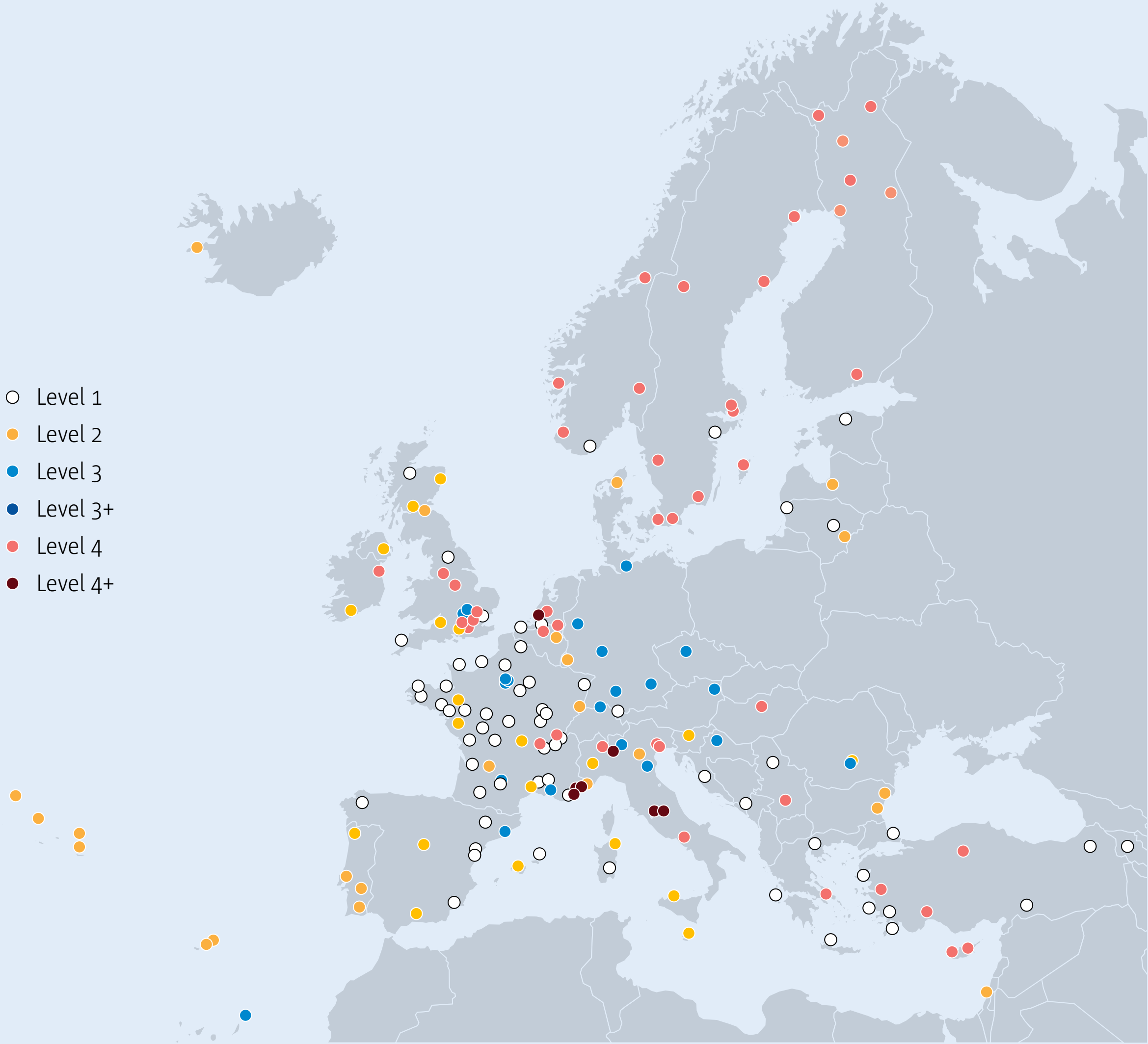
[47] Net zero carbon dioxide (CO_2) emissions are achieved when CO_2 emissions from human activities are balanced globally by CO_2 removals from human activities over a specified period. Net zero CO_2 emissions are also referred to as carbon neutrality.

STAKEHOLDER ACTIONS

AIRPORT CARBON ACCREDITATION PROGRAMME

The Airport Carbon Accreditation (ACA) programme [25] was launched in 2009 by the Airports Council International Europe and, as of November 2021, includes 362 airports on a global basis. The ACA is a voluntary industry led initiative, overseen by an independent Administrator and Advisory Board, that provides a common framework for carbon management with the primary objective to encourage and enable airports to reduce their CO_2 emissions. All data submitted by airports is externally and independently verified. As of the latest mid 2019 to mid 2021 reporting period, there were 155 European airports participating in the programme corresponding to 65.2% of European passenger traffic (Figure 6.4).

Figure 6.4 **European airports participating in the ACA programme**



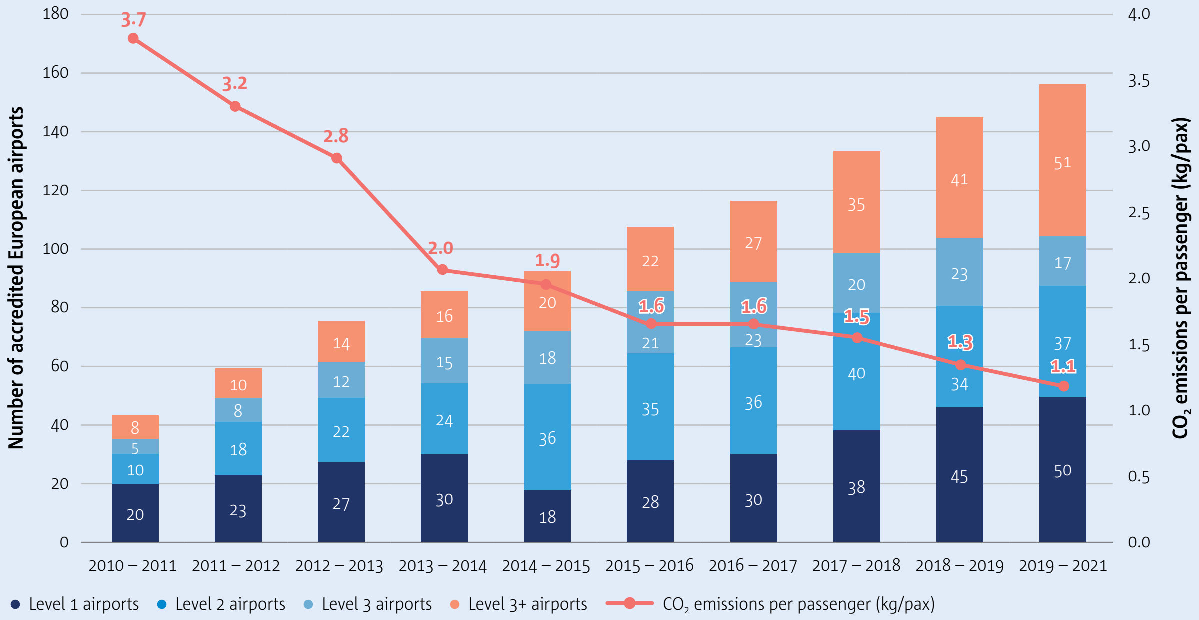
The ACA programme was initially structured around four levels of certification (Level 1: Mapping, Level 2: Reduction, Level 3: Optimisation; Level 3+: Neutrality) with increasing scope and obligations for carbon emissions management (Scope 1: direct airport emissions, Scope 2: indirect emissions under airport control from consumption of purchased electricity, heat or steam and Scope 3: emissions by others operating at the airport such as aircraft, surface access, staff travel).

In 2020, Levels 4 (Transformation[48]) and 4+ (Transition[49]) have been added as interim steps towards the long-term goal of achieving net zero CO_2 emissions and to align it with the objectives of the Paris Agreement. Guidelines were also published to inform airports about offsetting options, requirements and recommendations, as well as dedicated guidance on the procurement of offsets [26]. When applying for Levels 4 and 4+ airports are required to develop both a Carbon Management Plan and a Stakeholder Partnership Plan in order to formulate a long-term absolute reduction trajectory and target for all Scope 1 & 2 emissions, and possibly also Scope 3 emissions. A carbon footprint for the airport's emissions shall include additional emissions sources compared to the requirements of Levels 3 and 3+ (e.g. deicing substances, refrigerant losses, third non-road emissions, aircraft full flight emissions and offsite emissions such as waste incineration).

As of November 2021, 7 European airports have already achieved accreditation at the highest Level 4+ (Milan Linate Airport, Cannes-Mandelieu Airport, Nice Côte d'Azur Airport, La Môle-Saint-Tropez Airport, Rome-Fiumicino International Airport, Rome-Ciampino International Airport and Rotterdam The Hague Airport).

Due to the impact of COVID-19, the ACA programme decided to merge Years 11 and 12 and treat them as a single reporting year covering mid 2019 to mid 2021. Consequently, each airport submitted one 12 month carbon footprint at different moments during this two year period. Total direct CO_2 emissions which were under the full control of accredited European airports (Scope 1 and 2) were reported as 1.845 million tonnes of CO_2. The carbon emission per passenger travelling through European airports at all levels of Airport Carbon Accreditation was 1.14 kg CO_2/passenger (Figure 6.5).

Figure 6.5 Increasing number of accredited European airports and decreasing CO_2 emissions per passenger (as of mid 2021)



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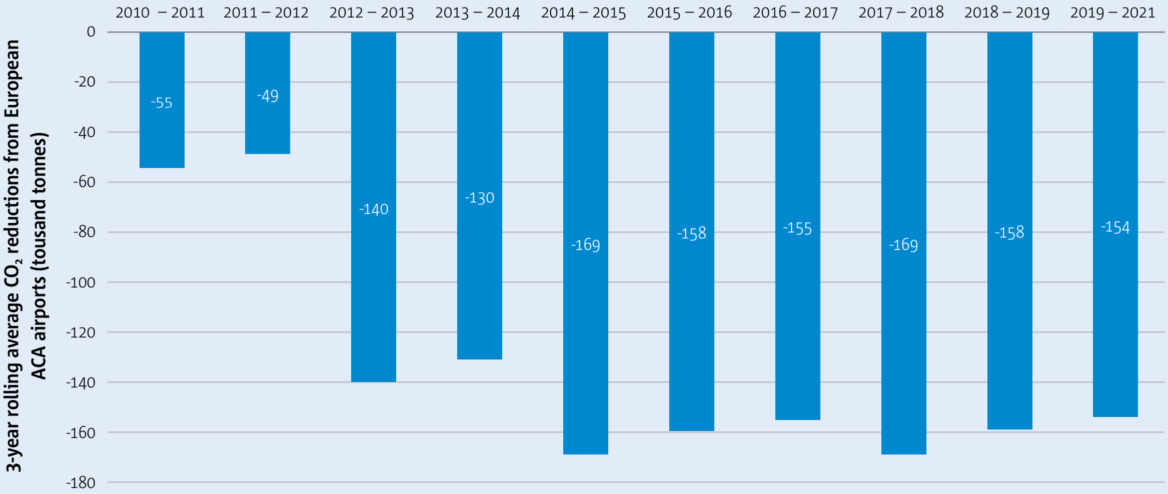
[48] Definition of a long-term carbon management strategy oriented towards absolute emissions reductions and aligned with the objectives of the Paris Agreement. Demonstration of actively driving third parties towards delivering emissions reductions.

[49] All Levels 1 to 4 plus offsetting of the residual carbon emissions over which the airport has control.

A total reduction in Scope 1 and 2 emissions compared to a three year rolling average[50] of 0.154 million tonnes of CO_2 for all accredited airports in Europe was also reported (Figure 6.6). This represents about 7.9% reduction compared to the three-year rolling average. The Scope 3 emissions showed a smaller increase of 0.679 million tonnes of CO_2 compared to an increase by 1.159 million tonnes of CO_2 in 2017-2018 reporting period.

Figure 6.6 Reductions in airport Scope 1 and 2 CO_2 emissions



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[50] Emissions reductions have to be demonstrated against the average historical emissions of the three years before year 0. As year 0 changes every year upon an airport's renewal/upgrade, the three years selected for the average calculation do so as well. Consequently, airports have to show emissions reductions against a three-year rolling average.

STAKEHOLDER ACTIONS

AIRPORT COUNCIL INTERNATIONAL EUROPE (ACI EUROPE)

ACI EUROPE represents over 500 airports in 55 countries, which accounts for over 90% of commercial air traffic in Europe. It works to promote professional excellence and best practice amongst its members, including in the area of environmental protection.

AIRPORTS COUNCIL INTERNATIONAL

Paving the way for Green Hydrogen

In September 2021, Lyon-Saint Exupéry airport launched a partnership with Airbus and Air Liquide to promote the use of hydrogen at airports, which will unfold in three stages:

1. 2023: A 'green' hydrogen gas distribution station, produced from renewable energy, will be deployed to supply airport ground vehicles (airside buses, trucks, handling equipment, etc.) and heavy goods vehicles that drive around the airport.

2. 2023 to 2030: Green liquid hydrogen infrastructure will be installed at the airport to allow future aircraft to be fuelled with liquid hydrogen.

3. 2030 onwards: Green liquid hydrogen infrastructure, from production to mass distribution, will be deployed at the airport.

This project will serve as a preparatory project to roll-out similar infrastructure across Europe.

Net zero CO_2 emissions

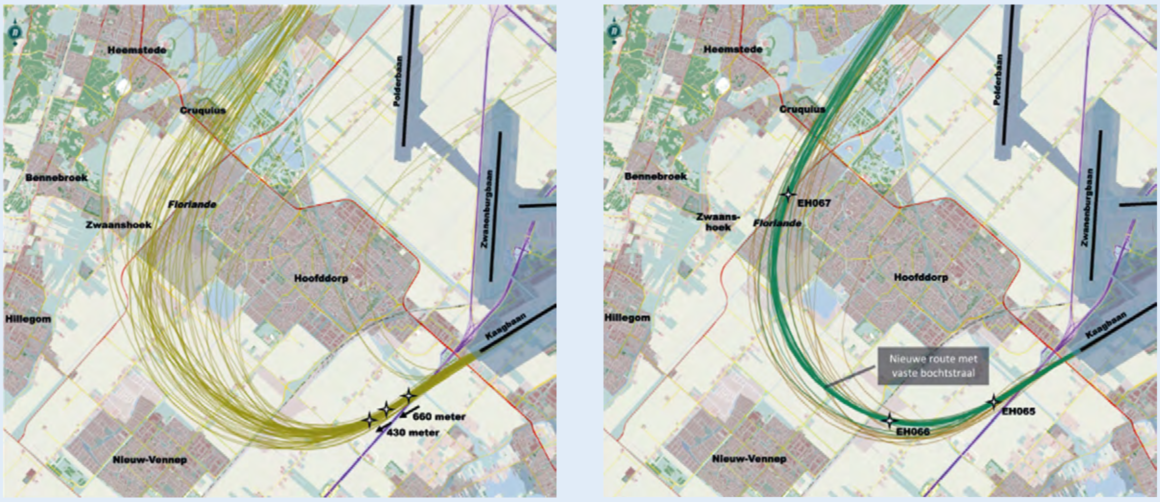
More than 10 years ago, Swedavia decided that its 10 airports should be fossil-free.

To achieve the long-term target of zero CO_2 emissions by 2020, Swedavia uses green electricity (e.g. wind, solar, biofuel in combined heat and power plants) and has implemented extensive conversions and investments in both vehicles and energy-efficiency improvements. Collaboration and innovation have been key to finding solutions, with goals to drive development. Robust measurement systems and data management have also created new insights and new possibilities in terms of optimising operations and reducing fuel consumption. Finally, the last key to success has been the commitment shown by Swedavia's leaders and employees.

This is just one intermediate goal to help achieve the overarching objectives agreed on by the Swedish aviation industry: that domestic aviation ends its reliance on fossil fuels by 2030 and that by 2045 no flights taking off from Swedish airports use fossil fuels.

Departure optimisation in Amsterdam

Since 2008, an alternative PBN based Standard Instrument Departure (SID) route (green tracks) has been used at Amsterdam Schiphol Airport with a Fixed Radius (FR) turn. The FR turn allows aircraft to navigate more accurately in the first turning part of the departure between the residential areas of Hoofddorp and Nieuw-Vennep, thereby reducing the spread in flown tracks (yellow tracks). While the noise is concentrated around the trajectory of the RF turn, the overall resulting nuisance is reduced, and while this leads to concentration of noise over Floriande, the noise impacts are smaller because aircraft fly higher over this area. This PBN was designed using Collaborative Environmental Management and led to a reduction of noise complaints.



Credit: LVNL Netherlands

AIRPORT REGIONS COUNCIL (ARC)

ARC is an association of local and regional authorities with an international airport on their territories. It has over 30 members, representing nearly 70 million European citizens. More than half of European air traffic goes through an ARC airport. ARC Members are dedicated to balancing the economic benefits generated by the airport with their environmental impact.

Cycle Express Highways

Airport inter-modality with public transport and accessibility via cycle lanes are critical to mitigate air pollution from surface access traffic. In the Frankfurt-Rhein-Main region, cycle express highways are planned to augment the existing cycle path network and Frankfurt International airport will be part of that network. These dedicated expressways are direct routes with limited inclines to facilitate quicker and longer journeys by bike, as well as being wider in order to provide more space and greater safety. It facilitates commuting by bike which benefits the health of citizens and has a positive impact on air quality by reducing commuter traffic [27].

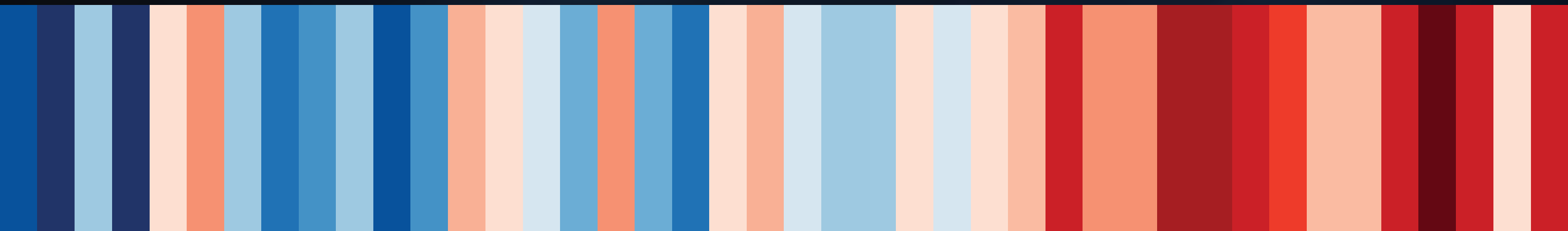
NON-GOVERNMENTAL ORGANISATIONS (NGOs)

Environmental NGOs in Europe are actively involved in policy-making discussions to address the increasing environmental impacts of aviation. They communicate wider civil society views on concerns and positions associated with noise, air pollution, climate change and social justice [28]. They also contribute to raising awareness on aviation's environmental impact through transparency of data.

Tracking emissions of flights from airports

For the first time in 2020, European airlines were requested to comply with the Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA) and to report on all their CO_2 emissions during 2019, including flights entering and exiting Europe, not only on intra-European flights. Based on data requests from national governments, it was found that some airlines had over 80% of their CO_2 emissions linked to long haul flights. An Airport Tracker was subsequently released in 2021 to visualize the emissions from these flights [29]. Passenger flights departing Europe's five major airports: London Heathrow, Paris Charles de Gaulle, Frankfurt, Amsterdam Schiphol and Madrid Barajas emitted 53 million tonnes of CO_2 in 2019 – similar to the Swedish economy.

7



MARKET-BASED MEASURES

- **Market-based measures address aviation's climate impact beyond what is achieved by technology, operational measures and sustainable aviation fuels while also incentivising such measures.**
- **During 2013-2020, the EU Emissions Trading System (ETS) led to a total reduction in aviation net CO_2 emissions of 159 Mt (approximately equivalent to the annual emissions of the Netherlands in 2018) through funding of emissions reductions in other sectors.**
- **Monitoring, reporting and verification of CO_2 emissions under the ICAO Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA) began in 2019. 88 States volunteered to participate in the CORSIA offsetting pilot phase from 2021, including all EU and EFTA States. This has increased to 107 States in 2022 and represents a majority of ICAO Member States.**
- **Emissions trading systems (e.g. EU ETS) have a greenhouse gas emissions cap covering sectors of the economy, while offsetting schemes (e.g. CORSIA) compensate for emissions through reductions in other sectors but without an associated emissions cap.**
- **The environmental integrity of offsets depends on their ability to demonstrate that the emissions reductions would not have occurred in the absence of the market mechanism that funds the offset.**
- **At COP26 in 2021, accounting rules under the Paris Agreement were agreed for international transfers of carbon market units, including the avoidance of double-counting of emission reductions in respect of CORSIA and nationally determined contributions by countries under the Climate Change Convention.**
- **International cooperation is key in building capacity to address the global environmental and sustainability challenges facing the aviation sector. EU funded action has enhanced the relationship with partner States on implementing CORSIA and other areas of environmental protection.**
- **Other measures linked to carbon pricing initiatives that are relevant for the aviation sector are being discussed in Europe.**

Market-based measures complement other measures in addressing the climate change impact of the aviation sector. This chapter provides an overview of two such measures, namely the EU's Emissions Trading System (ETS) and ICAO's Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA), as well as some insights on emerging carbon pricing instruments and international cooperation activities.

7.1 EU EMISSIONS TRADING SYSTEM

The EU Emissions Trading System (EU ETS) [1] is the cornerstone of the EU's policy to combat climate change. Through the inclusion of multiple economic sectors (e.g. power, heat, manufacturing industries, aviation), this cap and trade system incentivises CO_2 reduction within each sector, or through trading of allowances with other sectors of the economy where emission reduction costs are lower.

Aviation and the EU ETS

In 2008, the EU decided to include aviation activities in the EU ETS [2], and they are thus subject to the EU's greenhouse gas emissions reduction target of at least minus 55% by 2030 compared to 1990. The initial scope of the EU ETS covered all flights arriving at, or departing from, airports in the European Economic Area (EEA). However, flights to and from airports in non-EEA countries or in the outermost regions were subsequently excluded until the end of 2023 through a temporary derogation. This exclusion [3, 4], facilitated negotiation of a global market-based measure for international aviation emissions at the International Civil Aviation Organisation (ICAO).

It is permitted to link the EU ETS with other emissions trading systems, provided that these systems are compatible, mandatory and have an absolute emission cap. An agreement to link the systems of the EU and Switzerland entered into force on 1 January 2020 [5]. Accordingly, flights from the EEA area to Switzerland are subject to the EU ETS, and flights from Switzerland to the EEA area fall under the Swiss ETS [6]. Allowances from both systems can be used to compensate for emissions occurring in either system.

The EU ETS Support Facility [7] continues to provide 26 States with access to ETS-related data, as well as traffic and emissions data to over 300 aircraft operators.

In July 2021, the European Commission adopted the 'Fit for 55' Legislative Package to make the EU's climate, energy, transport and taxation policies fit for achieving the 2030 greenhouse gas emissions reduction target. This included proposed amendments to the EU ETS Directive for aviation activities [8] that covered:

- Consolidating the total quantity of aviation allowances at current levels;
- Applying a higher linear reduction factor of 4.2% per year to the aviation cap, instead of the current 2.2%;
- A gradual phase out of the free allocation of EUAAs (EU Aviation Allowances) to aircraft operators by 2027;
- Continuation of the intra-EEA application of the EU ETS, as well as flights to Switzerland and the UK[51];
- Implementing CORSIA appropriately to extra-EEA flights; and
- Ensuring that airlines are treated equally on the same routes with regard to their obligations and economic impacts.

In addition, the Commission is proposing to adjust the EU ETS Directive to implement Member States' notification to EU-based airlines of the offsetting requirements for the year 2021 [9].

Aviation emissions under EU ETS third phase (2013-2020)

An initial cap for aviation in the EU ETS was based on average emissions between 2004 and 2006 of flights within the initial ETS applicability scope, representing 221.4 million tonnes (Mt) of CO_2 per year. The cap for aviation activities in the ETS's third phase (2013-2020) amounts to 95% of the initial cap, adjusted for the change in applicability scope. While aircraft operators may use EU Aviation Allowances (EUAAs) as well as EU Allowances (EUAs) from the stationary sectors, stationary installations are not permitted to use EUAAs. In addition, aircraft operators were entitled to use certified emission reduction credits (CERs) up to a maximum of 1.5% of their verified emissions. In

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[51] In the EU-UK Trade and Cooperation Agreement reached in December 2020, the EU ETS will continue to apply to departing flights from the EEA to the UK, while a UK ETS will apply effective carbon pricing on flights departing from the UK to the EEA, starting in 2021. See also Commission Delegated Regulation (EU) 2021/1416 of 17 June 2021.

2019, 611 aircraft operators were reported as having a monitoring plan (7% fewer than in 2018) of which 308 were commercial and 303 were non-commercial [11].

Aircraft operators are required to report verified emissions data from flights covered by the scheme on an annual basis. As is shown in Figure 7.1, total verified CO_2 emissions from aviation covered by the EU ETS increased from 53.5 Mt in 2013 to 68.2 Mt in 2019. This implies an average increase of CO_2 emissions of 4.15% per year. The impact of the COVID-19 pandemic on international aviation saw this figure fall to 24.9 Mt in 2020, representing a decrease of 63.5% from 2019 levels. Since 2013, the amount of annual EUAAs issued is around 38.3 Mt of which about 15% have been auctioned by the States, while 85% have been allocated for free. The purchase of EUAs by the aviation sector for exceeding the aviation cap has gone up from 21.4 Mt in 2013 to 32.5 Mt in 2019 contributing thereby to a reduction of around 159 Mt of CO_2 emissions from other sectors during this period. As a result of the COVID-19 pandemic, the verified emissions of 24.9 Mt in 2020 were below the freely allocated allowances for the first time – see the dotted line for year 2020 in Figure 7.1.

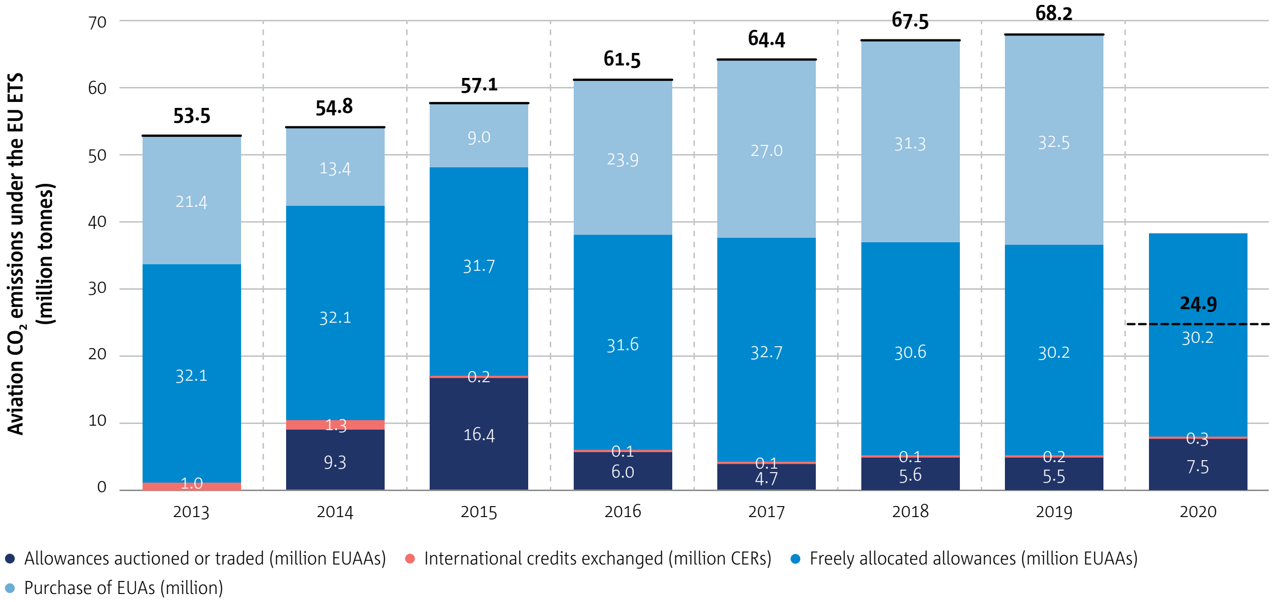
As shown in Figure 7.2, the annual average EU ETS carbon price varied between €4 and €25 per tonne of CO_2 during the 2013-2020 period. Consequently, total aircraft operator costs linked to purchasing EU Allowances (EUAs) have gone up from around €84 million in 2013 to around €955 million in 2019. For 2019, it is estimated that the ETS costs represented about 1.5% of total operating costs for aircraft operators on flights within the scope of the EU ETS[52].

Aviation emissions under EU ETS fourth phase (2021-2030)

The ETS has seen a number of modifications which will affect the aviation sector [14], including the linear reduction factor of 2.2% per year that is applied to the aviation cap since 2021. In addition, the emission reductions will need to be exclusively within the EEA, therefore only EU Aviation Allowances (EUAAs) and EU Allowances (EUAs) are eligible for compliance as is the case for all other sectors under the EU ETS. Once agreed, changes to the EU ETS under the Fit for 55 Legislative Package will apply to the fourth phase.

During 2021, the EU ETS carbon prices have further increased, and record-high EUA prices exceeding €90 per tonne of CO_2 were observed in early 2022 [13]

Figure 7.1 **Aviation CO_2 emissions under the EU ETS in 2013-2020 where 1 EUAA / EUA equals 1 tonne of CO_2 emissions [12].**



Note: Since the publication of the 2019 EAER, there has been a change in the methodology of allocating the auctioned EUAAs between different years. Data in Figure 7.1 reflects the years in which the EUAAs were effectively released to the market. This applies especially for allowances attributable to years 2013, 2014 and 2015, which were all auctioned in 2015. The 2014 auctions of EUAAs relate to auctioning of EUAAs due to the postponement of 2012 auctions.

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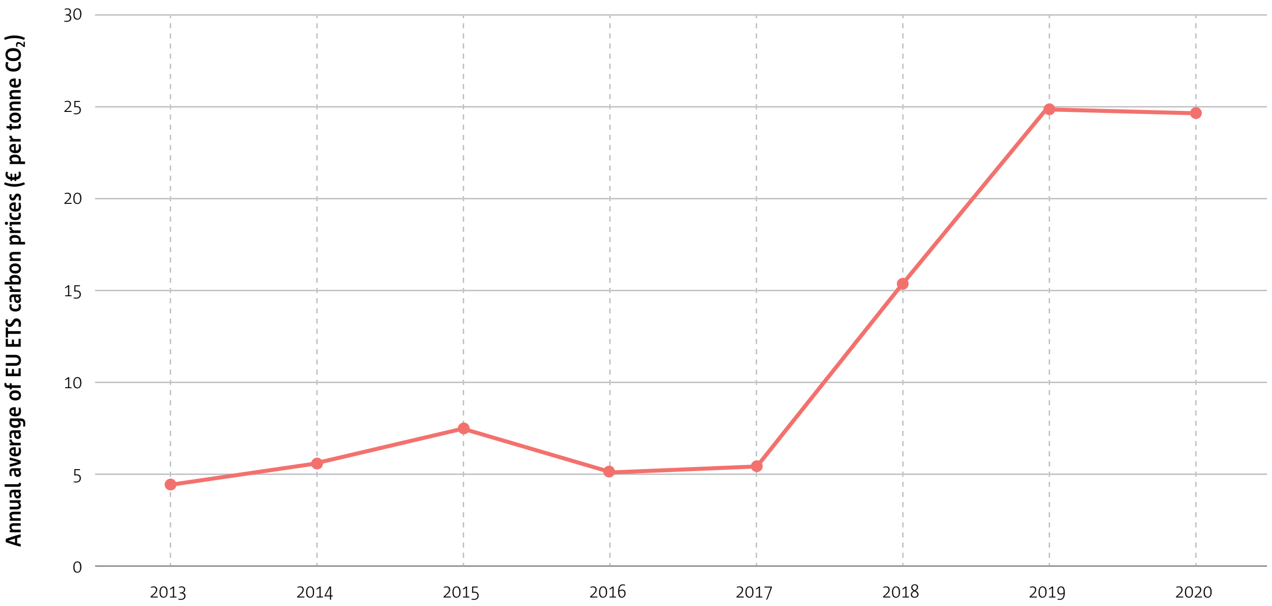
[52] Estimation from EASA AERO-MS model.

Figure 7.2 **EU ETS Carbon Prices in 2013-2020 [13]**



7.2 CARBON OFFSETTING AND REDUCTION SCHEME FOR INTERNATIONAL AVIATION (CORSIA)

Background

CORSIA

The 39th ICAO General Assembly in October 2016 reconfirmed the 2013 aspirational objective of stabilising CO_2 emissions from international aviation at 2020 levels. In light of this, ICAO States adopted Resolution A39-3 [15] which introduced a global market-based measure called the 'Carbon Offsetting and Reduction Scheme for International Aviation' (CORSIA).

This outcome came as a result of sustained support by European States and industry to address international aviation emissions at the global level.

In June 2018, the ICAO Council approved the associated Standards and Recommended Practices (SARPs) for CORSIA implementation, which are included in the ICAO Annex 16, Volume IV to the Chicago Convention. The SARPs are supported by guidance material included in the Environmental Technical Manual (Doc 9501), Volume IV and so called 'Implementation Elements' which are directly referenced in the SARPs. ICAO Contracting States will need to adopt the necessary national law to implement the provisions of CORSIA SARPs.

In October 2019, the 40th ICAO General Assembly recalled the decision from the previous Assembly to implement CORSIA, welcomed the progress achieved, and adopted Resolution A40-19 [16] reconfirming the goal of stabilising CO_2 emissions at 2020 levels.

Europe's participation in CORSIA

In line with the 'Bratislava Declaration' signed on 3 September 2016, and following the adoption of the CORSIA SARPs by the ICAO Council, EU Member States and the other Member States of the European Civil Aviation Conference (ECAC) notified ICAO of their intention to voluntarily participate to CORSIA offsetting from the start of the pilot phase in 2021, provided that certain conditions were met, notably on the environmental integrity of the scheme and global participation.

Implementation of CORSIA's monitoring, reporting and verification rules within the EU has been through the relevant ETS Regulations [17, 18].

CORSIA scope and timeline

CORSIA operates on a route-based approach and applies to international flights, i.e. flights between two ICAO States. A route is covered by CORSIA offsetting requirements if both the State of departure and the State of destination are participating in the scheme, and is applicable to all aeroplane operators (i.e. regardless of the administering State) on the route.

All aeroplane operators with international flights producing annual CO_2 emissions greater than 10,000 tonnes from aeroplanes with a maximum take-off mass greater than 5,700 kg, are required to monitor, verify and report their CO_2 emissions on an annual basis from 2019. The average CO_2 emissions reported during 2019 and 2020 represents the baseline for carbon neutral growth from 2020, and so the aviation sector is required to offset any international CO_2 emissions above that level.

CORSIA includes three implementation phases. During the pilot and first phases, offsetting requirements will only be applicable to flights between States which have volunteered to participate in CORSIA offsetting. As of 1 January 2022, 107 States have volunteered representing an increase of 19 States from 2021 (Figure 7.3). The second phase applies to all ICAO Contracting States, with certain exemptions.

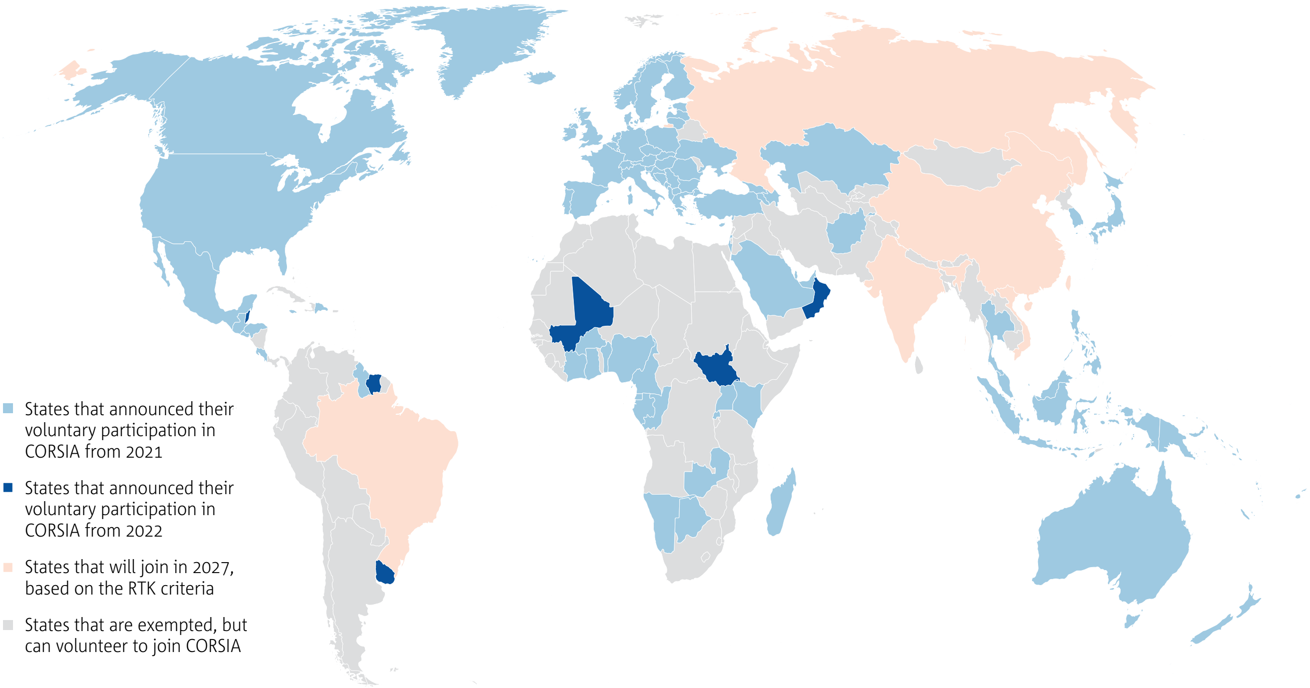
3 PHASES OF IMPLEMENTATION

PILOT PHASE 2021 – 2023	FIRST PHASE 2024 – 2026	SECOND PHASE 2027 – 2035

- Participation of States in the pilot phase (2021 to 2023) and the first phase (2024 to 2026) is voluntary.
- For the second phase from 2027, all States with an individual share of international aviation activity in year 2018 above 0.5% of total activity or whose cumulative share reaches 90% of total activity, are included. Least Developed Countries, Small Island Developing States and Landlocked Developing Countries are exempt unless they volunteer to participate.

In June 2020, the ICAO Council decided that the baseline during the pilot phase of CORSIA (2021-2023) would be 2019 emissions only. This decision was made to safeguard the aviation industry against inappropriate economic burden resulting from an unexpected lower baseline caused by the COVID-19 pandemic that saw an approximate 56% decline in aviation emissions in 2020 compared to 2019. It is expected that, due to the change of baseline and the foreseen recovery scenario of international aviation after the COVID-19 pandemic, there will be no offsetting requirements for airlines during the pilot phase of the scheme.

Figure 7.3 **ICAO Member States participation in CORSIA offsetting in various phases [19]**



CORSIA in practice

International flights within the scope of CORSIA are attributed to an aeroplane operator, and each operator is attributed to an administrating State to which it must submit an Emissions Monitoring Plan. Since 1 January 2019, an aeroplane operator has been required to report its annual CO_2 emissions to the State to which it has been attributed, irrespective of whether it has offsetting obligations. As of 1 January 2021, the State will calculate annual offsetting requirements for each operator that has been attributed to it by multiplying the operator's CO_2 emissions covered by CORSIA offsetting obligations with a Growth Factor. For years 2021-2029, the Growth Factor represents the percentage growth of the aviation sector's international CO_2 emissions in a given year compared to the sector's baseline emissions. From 2030 onwards, a component will be introduced into the Growth Factor to account for the individual aeroplane operator's growth against its baseline.

At the end of the 3-year compliance period, an aeroplane operator must meet their offsetting requirements by purchasing and cancelling certified CORSIA eligible emissions units. Each emissions unit represents a tonne of CO_2 reduced, or avoided, as compared to a scenario without the CORSIA eligible emissions unit. In order to safeguard the environmental credibility of offset credits used under CORSIA, the emission units must comply with the Emission Unit Criteria approved by the ICAO Council (Figure 7.4). Aeroplane operators can also reduce their offsetting requirements by using CORSIA eligible fuels that meet CORSIA sustainability criteria in proportion to their life-cycle CO_2 savings above a minimum threshold of 10% [20].

ICAO has established a Technical Advisory Body (TAB) to undertake the assessment of Emissions Unit Programmes against the approved Emissions Units Criteria, and to make recommendations on their use within CORSIA. To date, the ICAO Council has approved

Figure 7.4 CORSIA Emissions Unit Eligibility Criteria [21]

	On an emissions unit level, offset credit programs should deliver credits that represent emissions reductions, avoidance, or sequestration that:	At the program level, the eligible offset credit programs should meet the following design elements:
1	Are additional	Clear Methodologies and Protocols, and their Development Process
2	Are based on realistic and credible baseline	Scope Considerations
3	Are quantified, monitored, reported, and verified	Offset Credit Issuance and Retirement Procedures
4	Have a clear and transparent chain of custody	Identification and Training
5	Represent permanent emissions reductions	Legal Nature and Transfer of Units
6	Assess and mitigate against potential increase in emissions elsewhere	Validation and verification procedures
7	Are only counted once towards a mitigation obligation	Program Governance
8	Do no net harm	Transparency and Public Participation Provisions
9		Safeguards System
10		Sustainable Development Criteria
11		Avoidance of Double Counting, Issuance and Claiming

eight emissions unit programmes to supply CORSIA Eligible Emissions Units [22].

Projects that are designed to remove carbon from the atmosphere can include both natural and technological carbon removal processes (e.g. planting trees, Direct Air Capture), and have a potential to produce high-quality carbon offsets in the future.

The adoption of rules for international carbon markets under Article 6 of the Paris Agreement was completed at the COP26 meeting in Glasgow during November 2021 [23]. These rules require a host country to authorize carbon credits for 'international mitigation purposes', such as CORSIA, and to ensure that these emission reductions are not used to achieve its National Determined Contribution (NDC) under the UNFCCC process. Both sides of the adjustments (the seller and the buyer) must occur within the same NDC period. These rules are designed to guarantee that corresponding adjustments take place prior to these emission reductions being used to demonstrate compliance with CORSIA, thereby avoiding double-counting.

What are the differences and similarities between the EU ETS and CORSIA?

The EU ETS is a cap-and-trade system, which sets a limit on the number of emissions allowances issued, and thereby constrains the total amount of emissions of the sectors covered by the system. In the EU ETS, these comprise operators of stationary installations (e.g. heat, power, industry) and aircraft operators. The cap for aviation in the EU ETS is 95% of the average emissions between 2004 and 2006, adjusted for the changes in the applicability scope. The total number of emissions allowances is limited and reduced over time, thereby driving operators in need of additional allowances to buy these on the market from other sectors in the system – hence 'cap-and-trade'. This ensures that the objective of an absolute decrease of the level of CO_2 emissions is met at the system level. In the case of the ETS, the European Commission proposal [8] is expected to lead to emission reductions of 61% in 2030 compared to 2005 levels for the sectors covered by the EU ETS. The supply and demand for allowances establishes their price under the ETS, and the higher the price, the higher the incentive to reduce emissions in order to avoid having to buy allowances.

The ICAO CORSIA is an offsetting scheme with an objective of carbon neutral growth designed to ensure CO_2 emissions from international aviation do not exceed 2020 levels. To that end, aeroplane operators will be required to purchase offset credits to compensate for emissions above the CORSIA baseline or use CORSIA Eligible Fuels. The observed spread of the cost of CORSIA eligible emission units has been high and dependent on the project category [24].

EU ETS allowances are not accepted under CORSIA, and international offset credits, including those deemed eligible under CORSIA, are not accepted under the EU ETS as of 1 January 2021.

Both the EU ETS and CORSIA include similar Monitoring, Reporting and Verification (MRV) systems, which are aimed to ensure that the CO_2 emissions information collected through the scheme is robust and reliable. The MRV system consists of three main components: first, an airline is required to draft an Emissions Monitoring Plan, which needs to be approved by a relevant Competent Authority. After the Plan has been approved, the airline will monitor its CO_2 emissions either through a fuel burn monitoring method or an estimation tool. The necessary CO_2 information will be compiled on an annual basis and reported from airlines to their Competent Authorities by using harmonised templates. A third-party verification of CO_2 emissions information ensures that the reported data is accurate and free of errors. A verifier must be independent from the airline, follow international standards in their work and be accredited to the task by a National Accreditation Body.

7.3 CAPACITY BUILDING ACTIVITIES

International cooperation and capacity building activities are a key element in achieving a sustainable aviation sector within Europe and worldwide.

Several EU initiatives, managed by EASA on behalf of the European Commission, have been launched in different regions with the objective to support States in aviation environmental protection activities. The two main on-going CORSIA capacity building initiatives include the €4 million EU-South East Asia 'Cooperation on Mitigating Climate Change impact from Civil Aviation' project launched in 2019, and the €5 million 'Capacity Building Project for CO_2 Emissions Mitigation in the African and Caribbean Region' launched in 2020. Various EU Aviation Partnership Projects (APPs) covering the regions of Latin America, South Asia, and North Asia also include environmental components (Figure 7.5).

The overall objective of these projects is to enhance the partnership between the EU and partner States in the areas of civil aviation environmental protection and climate change, and to achieve long-lasting results beyond the duration of the projects. The specific aims of the CORSIA projects are to support policy dialogues with partner States on mitigating GHG emissions from civil aviation and to help enable partner States to implement CORSIA in line with the agreed international schedule. This includes consideration of joining the voluntary offsetting phase that started in 2021 at the earliest possible time. The results from these past and ongoing international cooperation and capacity building activities have been positive in achieving the above objectives.

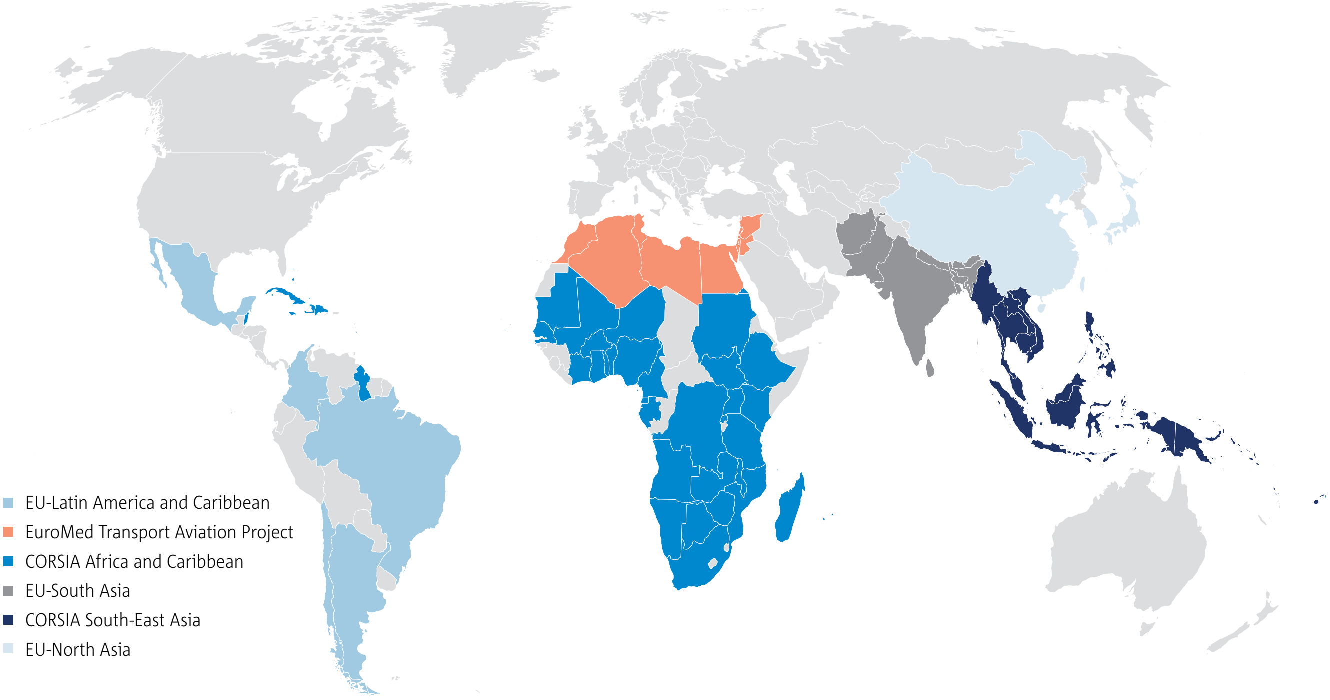
In order to facilitate coordination between European international cooperation projects that are initiated by the EU, EU Member States, industry and NGOs, an Aviation Environmental Projects Coordination Group (AEPCG) was established by EASA in 2020.

7.4 OTHER CARBON PRICING INITIATIVES

In addition to the EU ETS and CORSIA, there are several carbon pricing initiatives being implemented or planned that are relevant for the aviation sector.

In recent years, several airlines have introduced voluntary offsetting initiatives aimed at compensating, partly or in full, those CO_2 emissions caused by their operations that are not mitigated by in-sector

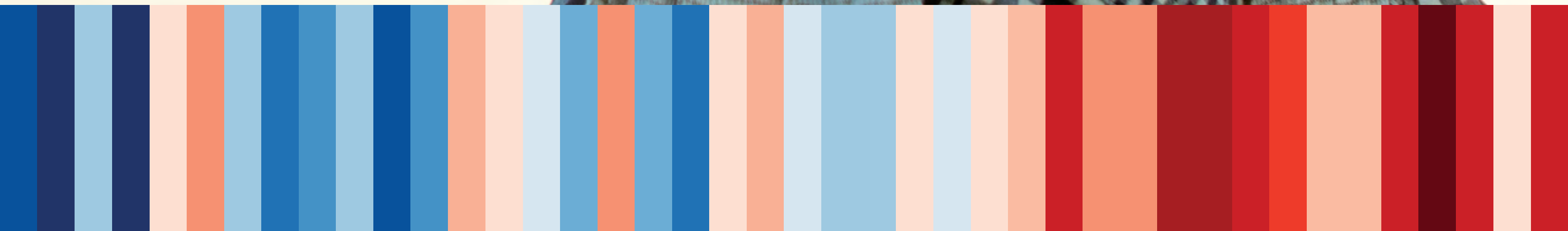
Figure 7.5 EASA-managed international cooperation projects with environmental components [25]



measures. Such voluntary initiatives have the potential to contribute to a more sustainable aviation sector, assuming that investments are channelled to high quality offset credits. However, there has been some criticism of the quality of offset credits in this unregulated market [26].

In order to direct investments towards sustainable projects and activities, the EU has also introduced a classification system, or “taxonomy” [27]. This taxonomy is expected to play an important role in scaling up sustainable investment and implementing the European Green Deal by providing companies, investors and policymakers with definitions of which economic activities can be considered environmentally sustainable. Technical screening criteria for aviation activities that fall under the sustainable investment taxonomy are currently being developed and are foreseen to be adopted during 2022.

Aviation fuel is currently exempted from taxation under the EU Energy Taxation Directive. EU Member States could in theory tax fuel on a bilateral basis, although none currently do so [28]. As part of the ‘Fit for 55’ Legislative Package, the European Commission has proposed to introduce minimum rates of taxation that would encourage a switch to sustainable fuels as well as more fuel-efficient aircraft [29]. According to the proposal, the tax for fossil based aviation fuel would be introduced gradually from 2023 before reaching the final minimum rate of €10.75/Gigajoule (approximately €0.38 per litre compared to an average price of aviation fuel in 2021 of €0.46 per litre [30]) after a transitional period of ten years. In comparison, sustainable aviation fuels would incur a zero tax rate during this same period and after that benefit from a much lower minimum tax rate.



APPENDIX A: LIST OF RESOURCES

INTRODUCTION

[1] EIB (2022), The EIB Climate Survey.
[2] EC (2021), Eurobarometer survey on climate change.
[3] McKinsey (2002), Opportunities for industry leaders as new travellers take to the skies.
[4] Klöwer, M., Allen, M. R., Lee, D.S., Proud, S.R., Gallagher, L. and Skowron A. (2021) Quantifying aviation's contribution to global warming. Environmental Research Letters, Volume 16, Number 10.
[5] University of Reading (2018), Warming Stripes.
[6] COP 26 declaration: International Aviation Climate Ambition Coalition.
[7] Toulouse Declaration on future sustainability and decarbonisation of aviation.
[8] EC (2022), Zero Pollution Action Plan: Towards Zero Pollution for Air, Water and Soil.
[9] EC (2002), Directive 2002/49/EC of the European Parliament and of the Council of 25 June 2002 relating to the assessment and management of environmental noise.
[10] EU (2014), Regulation (EU) 598/2014 of the European Parliament and the Council of 16 April 2014 on the establishment of rules and procedures with regard to the introduction of noise related operating restrictions at Union airports within a Balanced Approach and repealing Directive 2002/30/EC.
[11] EEA (2021), Air quality in Europe – 2021 report, EEA Report No 15/2021.
[12] EC (2008), Directive 2008/50/EC of the European Parliament and of the Council of 21 May 2008 on ambient air quality and cleaner air for Europe.
[13] EU (2016), Directive (EU) 2016/2284 of the European Parliament and of the Council of 14 December 2016 on the reduction of national emissions of certain atmospheric pollutants, amending Directive 2003/35/EC and repealing Directive 2001/81/EC new National Emission Ceilings Directive 206/2284.
[14] EU (2019), European Green Deal.
[15] EU (2021), Regulation (EU) 2021/1119 of the European Parliament and of the Council of 30 June 2021 establishing the framework for achieving climate neutrality and amending Regulations (EC) No 401/2009 and (EU) 2018/1999 ('European Climate Law').
[16] EC (2020), Sustainable and Smart Mobility Strategy.
[17] EC (2021), Fit for 55. Delivering the Green Deal.
[18[UN (2022), Sustainable Development Goals.
[19] EU (2022), EU and the UN Sustainable Development Goals.
[20] A4E; ACI-E; ASD; CANSO; ERA (2021), Destination 2050 Report.
[21] ATAG (2020), Waypoint 2050 Report.
[22] IATA (2021), Fly Net Zero commitment.

OVERVIEW OF AVIATION SECTOR

[1] WHO Europe (2018), Environmental noise guidelines for the European region, World Health Organization Regional Office for Europe, Copenhagen.
[2] EEA (2021), Reported data on noise exposure covered by Directive 2002/49/EC.
[3] EEA (2021), National emissions reported to the UNFCCC and to the EU Greenhouse Gas Monitoring Mechanism.
[4] EEA (2021), National emissions reported to the Convention on Long-range Transboundary Air Pollution (LRTAP Convention).
[5] UNEP (2020), Emissions Gap Report 2020,
[6] EC, 2019, Handbook on the external costs of transport, version 1.1.
[7] World Wide Fund for Nature (WWF), 2021, Science-based Target Setting for the Aviation Sector, Version 1.0.
[8] ICAO CAEP, 2022, Report on the feasibility of a Long-Term Aspirational Goal (LTAG) for international civil aviation CO_2 emission reductions.
[9] EUROCONTROL, 2022, Aviation Outlook 2050.
[10] Ivan Jakovljević, Radomir Mijailović, Petar Mirosavljević, Carbon dioxide emission during the life cycle of turbofan aircraft, Energy, Volume 148, 2018, Pages 866-875, ISSN 0360-5442.

AVIATION ENVIRONMENTAL IMPACTS

[1] WHO Europe (2018), Environmental noise guidelines for the European region.
[2] EEA (2021), Reported data on noise exposure covered by Directive 2002/49/EC.
[3] EC (2021), Assessment of potential health benefits of noise abatement measures in the EU. Phenomena project.
[4] EIONET (2021), ETC/ATNI Report 07/2020: Noise Action Plans. Impact of END on managing exposure to noise in Europe. Update of Noise Action Plans 2019.
[5] EU (2021), Aviation Noise Impact Management through Novel Approaches (ANIMA).
[6] EU (2021), ANIMA Noise Management Toolset (NMT).
[7] Müller, U. (2021), ANIMA D3.2 - Development of indicators for night noise protection zones.
[8] EEA (2021), Air quality in Europe – 2021 report.
[9] EC (2008), Directive 2008/50/EC of the European Parliament and of the Council of 21 May 2008 on ambient air quality and cleaner air for Europe.
[10] WHO (2021), WHO global air quality guidelines: particulate matter (PM2.5 and PM10), ozone, nitrogen dioxide, sulphur dioxide and carbon monoxide.
[11] Yim et al. (2015), Global, regional and local health impacts of civil aviation emissions.
[12] Jonsdottir, H.R., Delaval, M., Leni, Z. et al. (2019), Non-volatile particle emissions from aircraft turbine engines at ground-idle induce oxidative stress in bronchial cells.
[13] European Commission (2020), Updated analysis of the non-CO2 climate impacts of aviation and potential policy measures pursuant to EU Emissions Trading System Directive Article 30 (4).
[14] Hudda, N., Simon, M. C., Zamore, W., & Durant, J. L. (2018), Aviation-Related Impacts on Ultrafine Particle Number Concentrations Outside and Inside Residences near an Airport.
[15] Kapadia, Z. Z., Spracklen, D. V., Arnold, S. R., Borman, D. J., Mann, G. W., Pringle, K. J., Monks, S. A., Reddington, C. L., Benduhn, F., Rap, A., Scott, C. E., Butt, E. W., and Yoshioka, M. (2016), Impacts of aviation fuel sulphur content on climate and human health.
[16] Climate and Clean Air Coalition (2021), Tropospheric ozone.
[17] Riley, K., Cook, R., Carr, E., & Manning, B. (2021), A systematic review of the impact of commercial aircraft activity on air quality near airports.
[18] Stacey, B. (2019), Measurement of ultrafine particles at airports: A review.
[19] Keuken et al. (2015), Total and size-resolved particle number and black carbon concentrations in urban areas near Schiphol airport (the Netherlands).

[20] Austin, E., Xiang, J., Gould, T. R., Shirai, J. H., Yun, S., Yost, M. G., Larson, T. V., Seto E. (2021), Distinct Ultrafine Particle Profiles Associated with Aircraft and Roadway Traffic.

[21] Fleuti, E. (2020), Effects of COVID-19-related air traffic restrictions on local air quality at Zurich airport.

[22] Venter, Z. S., Aunan, K., Chowdhury, S., Lelieveld, J. (2020), COVID-19 lockdowns cause global air pollution declines.

[23] Kroll, J.H., Heald, C.L., Cappa, C.D. et al. (2020), The complex chemical effects of COVID-19 shutdowns on air quality.

[24] IPCC (2018), Global Warming of 1.5 °C. An IPCC Special Report on the impacts of global warming of 1.5 °C above pre-industrial levels and related global greenhouse gas emission pathways.

[25] IPCC (2022), Sixth Assessment Report.

[26] WMO (2022), State of the Global Climate 2021.

[27] IPCC (1999), IPCC Special Report: Aviation and the Global Atmosphere.

[28] M Klöwer et al (2021), Quantifying aviation's contribution to global warming.

[29] Gierens. K, Matthes. S and Rohs. S (2020), How Well Can Persistent Contrails Be Predicted?.

[30] Shine, K. And Lee, D.S. (2021), COMMENTARY: Navigational avoidance of contrails to mitigate aviation's climate impact may seem a good idea – but not yet.

[31] Lee, D. S., Pitari, G., Grewe, V., Gierens, K., Penner, J. E., Petzold, A., et al. (2010), Transport impacts on atmosphere and climate: Aviation.

[32] Voigt, C., Kleine, J., Sauer, D. et al. (2021), Cleaner burning aviation fuels can reduce contrail cloudiness.

[33] Lee D. S., Fahey D. W., Skowron A., Allen M. R., Burkhardt U., Chen Q., Doherty S. J., Freeman S., Forster P. M., Fuglestvedt J., Gettelman A., DeLeon R. R., Lim L. L., Lund M. T., Millar R. J., Owen B., Penner J. E., Pitari G., Prather M. J., Sausen R. and Wilcox L. J. (2020), The contribution of global aviation to anthropogenic climate forcing for 2000 to 2018.

[34] SESAR (2018), Air Traffic Management for Environment.

[35] Maastricht Upper Area Control (2021), Reducing the impact of non-CO_2 climate impact through contrail prevention.

[36] Grewe, V. et al (2021), Evaluating the climate impact of aviation emission scenarios towards the Paris agreement including COVID-19 effects.

[37] Matthes S., Malte N., Linke F. (2022), Testing of a Monitoring Reporting & Verification (MRV) Scheme for non-CO_2 aviation effects.

[38] ACI World (2020), Climate Change Resilience and Adaptation Survey Report.

[39] Joint Research Centre (2018), Impacts of climate change on transport - A focus on airports, seaports and inland waterways.

[40] EUROCONTROL (2021), EUROCONTROL study on climate change risks for European aviation.

[41] Gratton G., Padhra A., Rapsomanikis S., Williams P.D. (2021), The impacts of climate change on Greek airports.

[42] ICAO (2020), Climate Adaptation Synthesis Report.

[43] European Commission (2021), EU Climate Adaptation Strategy.

[44] European Commission (2020), Sustainable and Smart Mobility Strategy.

[45] EEA (2018), National climate change vulnerability and risk assessments in Europe.

[46] European Commission (2021), Commission Notice — Technical guidance on the climate proofing of infrastructure in the period 2021-2027.

[47] UNDRR (2018), Making critical infrastructure resilient. Ensuring continuity of service. Policy and regulations in Europe and Central Asia.

TECHNOLOGY AND DESIGN

[1] EU (2018), Regulation (EU) 2018/1139 of the European Parliament and of the Council of 4 July 2018 on common rules in the field of civil aviation and establishing a European Union Aviation Safety Agency.

[2] ICAO (2020), Annex 16 to the Convention on International Civil Aviation — Environmental Protection, Volume I, 8th Edition, Amendment 13 — Aircraft Noise.

[3] ICAO (2020), Annex 16 to the Convention on International Civil Aviation —Environmental Protection, Volume II, 4th Edition, Amendment 10 — Aircraft Engine Emissions.

[4] ICAO (2020), Annex 16 to the Convention on International Civil Aviation —Environmental Protection, Volume III, 1st Edition, Amendment 1 — Aeroplane CO2 Emissions.

[5] EASA (2022), EASA Certification Noise Levels.

[6] ICAO (2019), Independent Expert Integrated Technology Goals Assessment and Review for Engines and Aircraft, Doc 101277.

[7] ICAO (2022) ICAO Aircraft Engine Emissions Databank – approved emissions levels.

[8] ICCT (2020), Fuel Burn of new Commercial Jet Aircraft: 1960 to 2019.

[9] EASA (2021), Study on the societal acceptance of Urban Air Mobility in Europe.

[10] EASA (2022), Civil drones (unmanned aircraft).

[11] SESAR (2022), Smart ATM - U Space.

[12] Çetin, E.; Cano, A.; Deransy, R.; Tres, S.; Barrado, C. (2022), Implementing Mitigations for Improving Societal Acceptance of Urban Air Mobility.

[13] ICCT (2022), Environmental Limits on Supersonic Aircraft in 2035.

[14] Matthes, S.; Lee, D.S.; Rodriguez de Leon, R.; Lim, L.; Owen, B.; Skowron, A.; Thor, R.N.; Terrenoire, E. (2021), Review: the effects of supersonic aviation on ozone and climate.

[15] NASA (2021), Low-Boom Flight Demonstration.

[16] EU (2022), Horizon 2020 RUMBLE research and innovation project.

[17] EU (2022), SENECA – (LTO) noiSe and EmissioNs of supErsoniC Aircraft.

[18] EU (2022), More and Less.

[19] EASA (2022), NPA 2022-04 Regular update of the SERA regulatory framework and A-NPA 2022-05 Environmental protection requirements for supersonic transport aeroplanes.

[20] Clean Sky 2 and Fuel Cells & Hydrogen 2 Joint Undertakings (2020), Hydrogen Powered Aviation.

[21] ICCT (2022), Performance Analysis of Evolutionary Hydrogen-powered Aircraft.

[22] EC (2020), Circular economy action plan.

[23] EU (2022), SUSTANAIR - Circular economy for the aviation and aerospace sectors.

[24] AFRA (2022), Best Management Practice for Management of Used Aircraft Parts and Assemblies and for Recycling of Aircraft Materials.

[25] IATA (2022), Best Industry Practices for Aircraft Decommissioning.

[26] Clean Sky 2 (2021), Technology Evaluator First Global Assessment 2020 Technical Report.

SUSTAINABLE AVIATION FUELS

[1] EU (2018),Directive (EU) 2018/2001 of the European Parliament and of the Council of 11 December 2018 on the promotion of the use of energy from renewable sources (Text with EEA relevance.).

[2] ASTM (2021), ASTM D4054, 2021, Standard Practice for Evaluation of New Aviation Turbine Fuels and Fuel Additives. DOI: 10.1520/D4054-21A.

[3] ASTM (2021), D7566, 2021, Standard Specification for Aviation Turbine Fuel Containing Synthesized Hydrocarbons. DOI: 10.1520/D7566-21.

[4] ASTM (2021) D1655, 2021, Standard Specification for Aviation Turbine Fuels. DOI: 10.1520/D1655-21C.

[5] European Commission (2014), Technology Readiness Levels (TRL), Horizon 2020, Work Programme 2014-2015, General Annexes.

[6] Airbus (2021), First A319neo flight with 100% sustainable aviation fuel.

[7] Airbus, (2021), First Airbus helicopter flight with 100% sustainable aviation fuel. First Airbus helicopter flight with 100% sustainable aviation fuel.

[8] Rolls-Royce (2020), Rolls-Royce to test 100% Sustainable Aviation Fuel in next generation engine demonstrator.

[9] ICAO (2021), CORSIA Sustainability Criteria for CORSIA Eligible Fuels.

[10] Lukas Durdina, Benjamin T. Brem, Miriam Elser, David Schönenberger, Frithjof Siegerist, and Julien G. Anet (2021), Reduction of Nonvolatile Particulate Matter Emissions of a Commercial Turbofan Engine at the Ground Level from the Use of a Sustainable Aviation Fuel Blend.

[11] ICAO (2021), CORSIA Supporting Document "CORSIA Eligible Fuels - Lifecycle Assessment Methodology" (Version 3 – March 2021).

[12] Chuck, Christopher (2016), Biofuels for Aviation – Feedstocks. Technology and Implementation, ISBN: 978-0-12-804568-8.

[13] European Commission (2021), Proposal for a REGULATION OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL on ensuring a level playing field for sustainable air transport, 2021/0205.

[14] Businessgreen.com (2021), British Airways owner sets goal to run 10% of flights on sustainable biofuels by 2030.

[15] Greenairnews.com (2021), Ryanair donates $1.8m to sustainable aviation research as it commits to 12 % SAF uptake by 2030.

[16] Airlines.org (2021), Major U.S. Airlines Commit to Net-Zero carbon Emissions by 2050.

[17] European Commission (2021), Directorate-General for Mobility and Transport, Tsiropoulos, I., Humphris-Bach, A., Statharas, S., et al., Study supporting the impact assessment of the ReFuelEU Aviation initiative : final report.

[18] World Economic Forum (2021), Clean Skies for Tomorrow, Guidelines for a Sustainable Aviation Fuel Blending Mandate in Europe.

[19] EU (2018), Regulation (EU) 2018/1999 of the European Parliament and of the Council of 11 December 2018 on the Governance of the Energy Union and Climate Action.

[20] EUROCONTROL (2022), Selection of pioneering use of Sustainable Aviation Fuels in Europe.

[21] ICAO (2022), GFAAF - Aviation Fuel Maps.

[22] BMDV - Federal Ministry for Digital and Transport (2021), BMDV - Federal government, states and industry agree on roadmap for market ramp-up of climate friendly electricity-based aviation fuel.

[23] République Française (2019), Feuille de route française pour le déploiement des biocarburants aéronautiques durables.

[24] Transport & Environment (2022), Roadmap to climate neutral aviation in Europe, Roadmap to climate neutral aviation in Europe.

[25] USA (2021), FACT SHEET: Biden Administration Advances the Future of Sustainable Fuels in American Aviation.

[26] Greenair Communication (2022), New SAF and hydrogen aerospace ventures launched in South Korea and Singapore.

[27] Greenair Communication (2021), New sustainable fuel initiatives in Singapore and New Zealand seek to progress Asia-Pacific capabilities.

[28] Greenair Communication (2021), Major government-backed ventures launched to progress commercial-scale SAF production in Japan.

AIR TRAFFIC MANAGEMENT AND OPERATIONS

[1] EC (2004), Regulation (EC) No 549/2004 laying down the framework for the creation of the Single European Sky.

[2] SESAR (2019), European ATM Master Plan.

[3] EU (2019), Regulation (EU) 2019/123 of 24 January 2019 laying down detailed rules for the implementation of air traffic management (ATM) network functions.

[4] EU (2019), Decision (EU) 2019/709 of 6 May 2019 on the appointment of the network manager for air traffic management (ATM) network functions of the Single European Sky.

[5] EU (2021), Regulation (EU) 2021/2085 of 19 November 2021 establishing the Joint Undertakings under Horizon Europe.

[6] EU (2019), Regulation (EU) 2019/317 of 11 February 2019 laying down a performance and charging scheme in the single European sky.

[7] PRB (2019), PRB Monitoring Report 2020.

[8] EU (2005), Regulation (EC) No 2150/2005 of 23 December 2005 laying down common rules for the flexible use of airspace.

[9] EU (2020), Regulation (EU) 2020/1627 of 3 November 2020 on exceptional measures for the third reference period (2020-2024).

[10] EUROCONTROL (2022), Route Availability Document (RAD).

[11] EUROCONTROL (2021), Environmental Assessment: European ATM Network Fuel Inefficiency Study.

[12] EUROCONTROL (2019), Fuel Tankering: Economic Benefits and Environmental Impact.

[13] European Commission (2021), Proposal for a REGULATION OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL on ensuring a level playing field for sustainable air transport, 2021/0205.

[14] EASA (2022), Decision 2022/005/R on Fuel/energy planning and management — fuel schemes.

[15] EU (2021), Regulation 2021/1296 as regards the requirements for fuel/energy planning and management.

[16] EUROCONTROL Network Manager (2022), Optimised operational performance.

[17] EUROCONTROL (2022), Free route airspace.

[18] EUROCONTROL (2021), European Route Network Improvement Plan (ERNIP) - Part 2.

[19] EUROCONTROL (2020), European Continuous Climb and Descent Operations Action Plan.

[20] EUROCONTROL (2022), Vertical flight efficiency at airports.

[21] SESAR (2022), DIGITS - SESAR 3 JU very large demonstration project.

[22] EUROCONTROL (2022), EUROCONTROL learning zone.

[23] SESAR (2021), SESAR Solutions Catalogue charting progress towards the Digital European Sky.

[24] SESAR (2022), ALBATROSS - SESAR 3 JU very large-scale demonstration project.

[25] SESAR (2022), SESAR 3 Joint Undertaking Multiannual Work Programme 2022-2031.

[26] SESAR Deployment Manager (2022), SESAR Deployment Manager.

[27] EU (2021), Regulation (EU) 2021/116 - Common Project 1 Regulation.

[28] SESAR (2022), SORT - SESAR 3 JU very large-scale demonstration project.

[29] SESAR (2022), ADSCENSIO - SESAR 3 JU very large-scale demonstration project.

[30] Airbus (2022), Fello'fly.

AIRPORTS

[1] EC (2002), Directive 2002/49/EC of the European Parliament and of the Council of 25 June 2002 relating to the assessment and management of environmental noise.

[2] EU (2014), Regulation (EU) 598/2014 of the European Parliament and the Council of 16 April 2014 on the establishment of rules and procedures with regard to the introduction of noise related operating restrictions at Union airports within a Balanced Approach and repealing Directive 2002/30/EC.

[3] ICAO (2008), ICAO 9829. Guidance on the Balanced Approach to aircraft noise management.

[4] EASA (2022), EASA Environmental Portal's ANC Database.

[5] ICAO (2018), ICAO Doc 8168. Procedures for air navigation services. Aircraft operations. Volume I - Flight Procedures. Six Edition.

[6] Alonso et al. (2017), The efficiency of noise mitigation measures at European airports.

[7] CAA (2020), Quota Count validation study at Heathrow Airport.

[8] EUROCONTROL (2021), EUROCONTROL Specification for Collaborative Environmental Management (CEM).

[9] EC (2018), Air Traffic Management for environment study.

[10] EC (2020), Increased Runway and Airport Throughput study.

[11] ACI / CANSO (2020), Use of Performance Based Navigation (PBN) for Noise Management.

[12] EUROCONTROL (2020), European CCO / CDO Action Plan.

[13] EU (2018), Regulation 2018/1048 laying down airspace usage requirements and operating procedures concerning performance based navigation.

[14] EASA (2018), AMC and GM Regulation (EU) No 1332/2011 and Regulation (EU) 2018/1048 on common airspace usage requirements and operating procedures.

[15] EU (2020), Increased Runway and Airport Throughput study.

[16] SESAR (2022), VLD1-DREAMS Project.
[17] EC (2021), Assessment of potential health benefits of noise abatement measures in the EU. Phenomena project.
[18] EC (2021), Zero pollution action plan.
[19] EU (2022), Trans European Transport Network (TEN-T).
[20] ACI, ATI (2022), Integration of SAF into the air transportation system.
[21] ACI (2020), Integration of Hydrogen Aircraft into the Air Transport System.
[22] SESAR (2022), Large-Scale Demonstration Project - ALBATROSS.
[23] ACI-E (2020), Sustainability Strategy for Airports, and ACI-E (2021), Guidance Document - Developing an Airport Net Zero Carbon Roadmap.
[24] ACI-E (2022), Repository for airport net zero CO2 roadmaps.
[25] ACI-E (2022), Airport Carbon Accreditation programme.
[26] ACI (2020), Airport Carbon Accreditation Offsetting Manual. Issue 2.
[27] FrankfurtRheinMain Regional Verband (2021), Radschnellwege FrankfurtRheinMain.
[28] Possible (2022), Missed targets - a brief history of aviation climate targets.
[29] T&E, ICCT, ODI (2022), Airport Tracker.

MARKET-BASED MEASURES

[1] EC (2003), Directive 2003/87/EC of the European Parliament and of the Council of 13 October 2003 establishing a scheme for greenhouse gas emission allowance trading within the Community and amending Council Directive 96/61/EC.
[2] EC (2008), Directive 2008/101/EC of the European Parliament and of the Council of 19 November 2008 amending Directive 2003 87 EC so as to include aviation activities in the scheme for greenhouse gas emission allowance trading within the Community.
[3] EU (2014), Regulation (EU) No 421/2014 of the European Parliament and of the Council of 16 April 2014 amending Directive 2003/87/EC establishing a scheme for greenhouse gas emission allowance trading within the Community, in view of the implementation by 2020 of an international agreement applying a single global market-based measure to international aviation emissions.
[4] EU (2017), Regulation (EU) 2017/2392 of the European Parliament and of the Council of 13 December 2017 amending Directive 2003/87/EC to continue current limitations of scope for aviation activities and to prepare to implement a global market-based measure from 2021.
[5] EU (2017), Agreement between the European Union and the Swiss Confederation on the linking of their greenhouse gas emissions trading systems.
[6] EU (2020), Commission Delegated Decision (EU) 2020/1071 Amending Directive 2003/87/EC of the European Parliament and of the Council, as regards the exclusion of incoming flights from Switzerland from the EU emissions trading system.
[7] Eurocontrol (2022), EU ETS Support Facility.
[8] EC (2021), Proposal for a Directive of the European Parliament and of the Council amending Directive 2003/87/EC as regards aviation's contribution to the Union’s economy-wide emission reduction target and appropriately implementing a global market-based measure.
[9] EC (2021), Proposal for a Decision of the European Parliament and of the Council amending Directive 2003/87/EC as regards the notification of offsetting in respect of a global market-based measure for aircraft operators based in the Union.
[10] European Parliament (2021), 2021/0207(COD). Revision of the EU Emissions Trading System for aviation.
[11] EC (2020), Report from the Commission to the European Parliament and the Council. Report on the Functioning of the European Carbon Market.
[12] EEA (2021), EU Emissions Trading System (ETS) data viewer.
[13] EEX Group (2022), Market Data - Environmental markets.

[14] EU (2018), Directive (EU) 2018/410 of the European Parliament and of the Council of 14 March 2018 amending Directive 2003/87/EC to enhance cost-effective emission reductions and low-carbon investments, and Decision (EU) 2015/1814.
[15] ICAO (2016), Resolution A39-3: Consolidated statement of continuing ICAO policies and practices related to environmental protection – Global Market-based Measure (MBM) scheme.
[16] ICAO (2019), Resolution A40-19: Consolidated statement of continuing ICAO policies and practices related to environmental protection - Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA).
[17] EC (2018), Commission Implementing Regulation (EU) 2018/2066 of 19 December 2018 on the monitoring and reporting of greenhouse gas emissions pursuant to Directive 2003/87/EC of the European Parliament and of the Council and amending Commission Regulation (EU) No 601/2012.
[18] EC (2018), Commission Implementing Regulation (EU) 2018/2067 of 19 December 2018 on the verification of data and on the accreditation of verifiers pursuant to Directive 2003/87/EC of the European Parliament and of the Council.
[19] ICAO (2021), ICAO document – CORSIA States for Chapter 3 State Pairs.
[20] ICAO (2021), ICAO document — CORSIA Sustainability Criteria for CORSIA Eligible Fuels.
[21] ICAO (2019), ICAO document – CORSIA Emissions Unit Eligibility Criteria.
[22] ICAO (2021), ICAO document – CORSIA Eligible Emissions Units.
[23] UNFCCC (2021), Guidance on cooperative approaches referred to in Article 6, paragraph 2, of the Paris Agreement.
[24] ICAO (2021), CORSIA Newsletter November 2021.
[25] EASA (2022), International cooperation – EASA by country.
[26] Unearthed (2021), Top airlines' promises to offset flights rely on 'phantom credits'.
[27] EU (2020), Regulation (EU) 2020/852 of the European Parliament and of the Council of 18 June 2020 on the establishment of a framework to facilitate sustainable investment, and amending Regulation (EU) 2019/2088.
[28] EC (2019), Taxes in the field of aviation and their impact.
[29] EC (2021), Proposal for a Council Directive restructuring the Union framework for the taxation of energy products and electricity.
[30] Jet-A1-Fuel (2022), Average Jet A1 price 2021

APPENDIX B: ACRONYMS AND UNITS

ANSP	Air Navigation Service Provider
ATM	Air Traffic Management
CAEP	Committee on Aviation Environmental Protection
CEM	Collaborative Environmental Management
CO / CO_2	Carbon monoxide / Carbon dioxide
CORSIA	Carbon Offsetting and Reduction Scheme for International Aviation
dB	decibel
EASA	European Union Aviation Safety Agency
EC	European Commission
EEA	European Environment Agency
EFTA	European Free Trade Association
EPNdB	Effective Perceived Noise decibel
ETS	Emissions Trading System
EU	European Union
EU27	27 Member States of the European Union
ft	Feet
gCO_2e	gram of carbon dioxide equivalent
GHG	Greenhouse gas
GWP	Global Warming Potential
ICAO	International Civil Aviation Organization
IPCC	Intergovernmental Panel on Climate Change
kg	Kilogram
km	Kilometre
kN	Kilonewton
kW	Kilowatts
lbf	Pound (force)
L_{den} / L_{night}	Day-evening-night / Night-time sound pressure level
LTO	Landing and Take-Off
MJ	Megajoule
MRV	Monitoring, Reporting and Verification
Mt	Megatonne, million metric tonnes
MTOM	Maximum Take-Off Mass
MW	Megawatts
mW	Milliwatts
NM	Network Manager
NO_X	Nitrogen Oxides
NGO	Non-Governmental Organization
O_3	Ozone
PM	Particulate Matter
RED	Renewable Energy Directive
RTK	Revenue Tonne Kilometre
SES	Single European Sky
SESAR	Single European Sky ATM Research
SO_2	Sulphur Dioxide
UAV	Unmanned Aerial Vehicle
UNFCCC	United Nations Framework Convention on Climate Change
WHO	World Health Organization

APPENDIX C: DATA SOURCES, MODELS AND ASSUMPTIONS

This appendix provides an overview of the data sources, models and assumptions used to develop the information presented in Chapter 1 (Overview of Aviation Sector), Chapter 2 (Technology and Design) and Chapter 6 (Airports). These modelling capabilities have been developed and used to support various European initiatives, including SESAR and Clean Sky, as well as international policy assessments in ICAO CAEP.

SCOPE

The information in this report covers all flights from or to airports in the European Union (EU) and European Free Trade Association (EFTA). For consistency, regardless of the year, the EU here consists of the current 27 member States: Austria, Belgium, Bulgaria, Croatia, Republic of Cyprus, Czech Republic, Denmark, Estonia, Finland, France, Germany, Greece, Hungary, Ireland, Italy, Latvia, Lithuania, Luxembourg, Malta, Netherlands, Poland, Portugal, Romania, Slovakia, Slovenia, Spain and Sweden. EFTA members are Iceland, Liechtenstein, Norway and Switzerland. Compared to previous reports, statistics for UK are therefore not included, also for the years preceding the Brexit.

The calculation of the L_{den}, L_{night} and $N_{50}A_{70}$ noise indicators was performed over 98 major EU27+EFTA airports (see map on next page) representing about 90% of the total landing and take-off noise energy emitted in the region during 2019.

DATA SOURCES

EUROCONTROL Flight Data

Historical 2005-2021 flight operations were extracted from the EUROCONTROL database of filed flight plans. This covers all instrument flight rules (IFR) flights in Europe. Flight data are enriched with and validated against, for example, radar updates, billing data from the Central Route Charges Office and an internal database of global aircraft. Each flight is categorised into one of the market segments: scheduled flights are divided into “low-cost” and “traditional scheduled”; “business aviation” captures flights by jets, turboprops and piston aircraft typically used for business aviation (mostly under 20 seats nominal size); “all-cargo” captures dedicated freighter flights; etc. These market segments are defined in terms of aircraft operator, aircraft type, ICAO flight type or callsign, as appropriate. The detailed definitions are available on the EUROCONTROL website.

Eurostat

European States collect statistics on air transport from their airports and airlines and provide these to Eurostat, which makes them public, although airline details are treated as confidential. Statistics on total activity (total passengers, total tonnes shipped, etc.) are as complete as possible. More detailed statistics, such as passengers and available seats for individual airport pairs, are focused on major flows. For example, we use these data to indicate trends in load factors, but we cannot calculate total available seat-kilometres solely from them. The estimates of total passenger kilometres flown in Chapter 1 are based on Eurostat directly, on analysis of other Eurostat flows and on data from PRISME. The great circle (i.e. shortest) distance between airport pairs is used when reporting passenger kilometres and calculating the average fuel consumption per passenger

kilometre. The fuel consumption reported is however based on the actual distance flown. Consequently, the effect of ATM horizontal inefficiency is captured in the fuel efficiency indicator.

STATFOR

The EUROCONTROL Aviation Outlook 2050] that was published in April 2022 provided the traffic forecast to 2050 used in this report. It has three scenarios: the ‘high’ has strong economic growth with intense investment in technology to support sustainability, leading to relatively high growth in demand; the most-likely, ‘base’ scenario has moderate economic growth following current trends; the ‘low’ has slower economic growth and higher fuel prices, leading to fewer flights and lower investment. As is usual for STATFOR forecasts, airports provided their future capacity plans, and the forecast traffic respects the capacity constraints implied by these plans, although the EAO notes that increasingly the primary constraint is sustainability rather than capacity.

BADA

BADA (Base of Aircraft Data) is an Aircraft Performance Model developed and maintained by EUROCONTROL, in cooperation with aircraft manufacturers and operating airlines. BADA is based on a kinetic approach to aircraft performance modelling, which enables to accurately predict aircraft trajectories and the associated fuel consumption. BADA includes both model specifications which provide the theoretical fundamentals to calculate aircraft performance parameters, and the datasets containing aircraft-specific coefficients required to calculate their trajectories. The BADA 3 family is today's industry standard for aircraft performance modelling in the nominal part of the flight envelope, and provides close to 100% coverage of aircraft types operating in the European region. The latest BADA 4 family provides increased levels of precision in aircraft performance parameters over the nearly entire flight envelope, and covers 80% of aircraft types operating in the European region. This report uses BADA 4, complemented by BADA 3 for aircraft types not yet covered in BADA 4.

Aircraft Noise and Performance (ANP) Database

The Aircraft Noise and Performance (ANP) database is maintained by EASA, EUROCONTROL and the US Department of Transportation. It provides the noise and performance characteristics for over 150 civil aircraft types, which are required to compute noise contours around civil airports using the calculation method described in Annex II of European Directive 2002/49/EC relating to assessment and management of environmental noise, ECAC Doc 29 and ICAO Doc 9911 guidance documents. ANP datasets are supplied by aircraft manufacturers for specific airframe-engine types, in accordance with specifications developed by the ICAO and European bodies. EASA is responsible for collecting, verifying and publishing ANP data for aircraft which fall under the scope of Regulation (EU) 598/2014.

EASA Certification Noise Levels

EASA maintains a database of all aircraft noise certification levels which the Agency has approved. The database provides certified noise levels for over 34,000 aircraft variants, including jet, heavy and light propeller aircraft as well as helicopters. In this report, the certified noise levels are used to assess the Noise Energy Index, to attribute an ANP airframe-engine type to each aircraft type in the fleet using the ECAC Doc 29 4th Edition recommended substitution method, as well as to create the noise charts in the Technology and Design and Airport chapters.

ICAO Aircraft Engine Emissions Databank

The ICAO Aircraft Engine Emissions Databank (EEDB) hosted by EASA contains Landing and Take-Off (LTO) emissions data for NO_X, HC, CO, smoke number and non-volatile PM for over 400 jet engine types. The EEDB emission indices are used by the IMPACT model to compute NO_X, HC, CO and PM, and to create the NO_X charts in the Technology and Design chapter.

FOI Turboprop Emissions Database

The Swedish Defence Research Agency (FOI) hosts a database of NO_X, HC and CO emission indices for turboprop engine types. The data was supplied by the turboprop engine manufacturers, originally for the purposes of calculating emissions-related landing charges. It is used to complement the ICAO EEDB for the NO_X, HC and CO estimates in this report.

FOCA Piston Emissions Database

The Swiss Federal Office of Civil Aviation (FOCA) hosts a database of NO_X, HC, CO and aggregated non-volatile and volatile Particles Matters emission indices for piston engine types. The data was measured and calculated by the FOCA. It is used to complement the ICAO EEDB for the NO_X, HC, CO and PM estimates in this report.

CODA Taxi Times Database

EUROCONTROL's Central Office for Delay Analysis (CODA) collects flight-by-flight data from around 100 airlines and 130 airports, such as actual off-block and take-off times, and delay causes. Largely this is on a voluntary basis in return for performance and benchmarking reports, but increasingly the data collection is influenced by the EU performance regulations. CODA publishes aggregated performance statistics, such as on punctuality and all-causes delays from these data. The detailed actual taxi times from this source were used to assess taxi fuel burn and emissions.

Population Data

The JRC Global Human Settlement population grid was used to calculate the number of people exposed to aircraft noise. This spatial dataset, developed in the European Copernicus Program, depicts the distribution and density of residential population. The dataset is generated using the 2011 censuses provided by Eurostat/GEOSTAT and the best available sources by country. The initial 1 km resolution has been further disaggregated to 100 m based on information from Corine Land Cover Refined 2006 and the European Settlement Map 2016.

MODELS AND METHODS

IMPACT

IMPACT is a web-based modelling platform developed and hosted by EUROCONTROL to assess the environmental impacts of aviation (noise and emissions). It allows to compute full-flight trajectories with associated fuel burn and CO_2 emissions thanks to an advanced aircraft performance-based trajectory model using a combination of ANP and BADA reference data. Other gaseous emissions such as NO_X, HC, CO and PM emissions are computed using the LTO emission indices from the ICAO EEDB, FOI Turboprop and FOCA Piston Emissions reference databases, combined with the Boeing Fuel Flow Method 2 (BFFM2). PM emission indices of jet engines are estimated using the First Order Approximation (FOA4) method[53], which is detailed in the ICAO Airport Air Quality Manual (Doc 9889 2nd edition 2020). En-route non-volatile PM emissions[54] are calculated using the up-to-date implementation of the black carbon emissions methodology[55]. The IMPACT calculation methods and reference data to assess fuel burn and emissions may differ from those used by Member States to report their emissions to UNFCCC or CLRTAP, hence the delta in estimates between these data sources.

SysTem for AirPort noise Exposure Studies (STAPES)

STAPES is a multi-airport noise model jointly developed by the European Commission, EASA and EUROCONTROL. It consists of a software compliant with Annex II of Directive 2002/49/EC and the 4th Edition of the ECAC Doc 29 modelling methodology, combined with a database of over 100 airports with information on runway and route layout, as well as the distribution of aircraft movements over these runways and routes. The STAPES airport database also includes airport-specific aircraft flight profiles and noise-power-distance (NPD) data, which reflect the local atmospheric conditions at each airport in terms of temperature, pressure and relative humidity.

Aircraft Assignment Tool (AAT)

AAT is a fleet and operations forecasting model jointly developed by the European Commission, EASA and EUROCONTROL. AAT converts a passenger and flight demand forecast into detailed operations by aircraft type and airport pair for a given future year and scenario, taking into account aircraft retirement and the introduction of new aircraft into the fleet. It is an integral part of the STATFOR 20-year forecast methodology that was followed for the EAO. The forecast operations are processed through the IMPACT and STAPES models to assess the fuel burn, emissions and noise data for years 2030 to 2050 presented in the Sector Overview chapter.

ASSUMPTIONS

Fuel burn, emissions and noise assessment

For consistency with other international emission inventories, full-flight emissions presented in this report are for all flights departing from EU27 or EFTA, i.e. flights coming from outside EU27 or EFTA are not included. In contrast, noise indicators include all departures and all arrivals. Historical fuel burn and emission calculations are based on the actual flight plans from the EUROCONTROL Flight Data, including the actual flight distance and cruise altitude by airport pair. Default aircraft take-off weights from the ANP database (defined as a function of trip length) are used when assessing noise, fuel burn and emissions for this report; these may not always reflect the load factors and take-off weights observed in real operations. Future year fuel burn and emissions are based on actual flight distances and cruise altitudes by airport pair in 2019. Future taxi times are assumed to be identical to the 2019 taxi times; where non available, ICAO default taxi times are applied. Helicopter operations are excluded from the assessment. For years 2022 to 2030 all indicators were estimated by scaling their respective 2030 values in line with the STAFOR mid-term traffic forecast. This method may overestimate the rate of fleet renewal and lead to an underestimation of the noise and emissions during this period.

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[53] Due to the lack of smoke number data for turboprop engines, PM estimates currently exclude this category. As an indication, turboprop aircraft represented approximately 1% of the total fleet fuel burn in 2019.

[54] Non-volatile particulate matter (nvPM) refers to particles measured at the engine exit and is the basis for the regulation of engine emissions certification as defined in ICAO Annex 16 Volume II, “emitted particles that exist at a gas turbine engine exhaust nozzle plane, that do not volatilize when heated to a temperature of 350°C.

[55] Stettler, Marc E. J.; Boies, Adam M.; Petzold, Andreas; R. H. Barrett, Steven (2016): Global Civil Aviation Black Carbon Emissions. ACS Publications. Collection. https://doi.org/10.1021/es401356v

For the STAPES noise assessments, the number of airports, together with their respective runway and route layout, were assumed to be constant over the full analysis period – i.e. only the fleet, the number and time of operations vary[56]. The standard take-off and landing profiles in the ANP database were applied. For historical noise, the day/evening/night flight distribution was based on actual local departure and landing times assuming the Environmental Noise Directive default times for the three periods: day = 7:00 to 19:00, evening = 19:00 to 23:00, night = 23:00 to 7:00. For future years, the day/evening/night flight distribution at each airport was assumed to remain unchanged compared to 2019. Population density around airports was also assumed to remain unchanged throughout the analysis period. The mapping of the fleet to the ANP aircraft follows the ECAC Doc 29 4th Edition recommended substitution method.

In addition to the noise contours at the 98 airports modelled in STAPES, the noise generated by aircraft take-offs and landings at all airports in the EU27 and EFTA area was estimated via the Noise Energy Index, by applying the following formula:

$$\text{Noise Energy Index} = \sum_{\text{aircraft}} \left(N_{dep} 10^{\frac{LAT+FO}{20}} + N_{arr} 10^{\frac{APP-9}{10}} \right)$$

where

N_{dep} and N_{arr} are the numbers of departures and arrivals by aircraft type weighted for aircraft substitution;

LAT, FO and APP are the certified noise levels in EPNdB at the three certification points (lateral, flyover, approach) for each aircraft type[57].

Noise dose-response curves

To estimate the total population highly annoyed (HA) and highly sleep disturbed (HSD) by aircraft noise, the following dose-response regression curves recommended by WHO for the European region were used:

Share of population highly annoyed (%HA) = $-50.9693 + 1.0168 * L_{den} + 0.0072 * L_{den}^2$

Share of population highly sleep disturbed (%HSD) = $16.79 - 0.9293 * L_{night} + 0.0198 * L_{night}^2$

The total population at the 98 major airports in STAPES was assessed for L_{den} values between 45 and 75 dB and for L_{night} values between 40 and 70 dB with one decibel increment, and then multiplied by the corresponding %HA and %HSD values. As the L_{den} and L_{night} values represent outdoor noise levels the annoyance and sleep disturbance estimates may not take into account the effect of local sound insulation campaigns for houses and buildings around airports.

Future fleet technology scenarios

Future noise and emissions presented in the Sector Overview chapter were assessed for different technology scenarios.

The most conservative ‘frozen technology’ scenario assumes that the technology of new aircraft deliveries between 2019 and 2050 remains as it was in 2019. Under this scenario, the 2019 in-service fleet is progressively replaced with aircraft available for purchase in 2019. This includes the A320neo, B737 MAX, Airbus A220 (or Bombardier CSeries), Embraer E-Jet E2, etc.

On top of the fleet renewal, technology improvements for fuel burn (CO_2), NO_X and noise are applied on a year-by-year basis to all new aircraft deliveries from 2019 onwards following a single ‘advanced’ technology scenario. This technology scenario was derived from analyses performed by groups of Independent Experts for the ICAO CAEP, and is meant to represent the noise and emission reductions that can be expected from conventional aircraft and engine technology by 2040.

For noise, the advanced technology scenario modelled for this report assumes a reduction of 0.1 EPNdB per annum at each noise certification point for new aircraft deliveries. For fuel burn and CO_2, the advanced technology scenario assumes a 1.16% improvement per annum for new aircraft deliveries[58]. For NO_X, the

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[56] The closure of Berlin Tegel airport in 2020 was taken into account.

[57] For Chapter 6 and 10 aircraft (light propeller), the unique overflight or take-off level is used for the three values.

[58] ICAO Environmental Report 2010 (p. 33).

scenario assumes a 100% achievement of the CAEP/7 NO_X Goals by 2036[59]. No technology improvement was applied when estimating future HC, CO and PM emissions.

The above technology scenarios represent improvements in conventional aircraft designs, i.e. they do not take into account potential future designs like supersonic aircraft, electric/hydrogen aircraft or UAVs. For the forecast of net CO_2 emissions, electric/hydrogen aircraft were assumed to enter the fleet in 2035 and bring an additional emissions reduction gradually ramping up to 5% in 2050.

Future ATM improvements

The European ATM Master Plan, managed by SESAR 3, defines a common vision and roadmap for ATM stakeholders to modernise and harmonise European ATM systems, including an aspirational goal to reduce average CO_2 emission per flight by 5-10% (0.8-1.6 tonnes) by 2035 through enhanced cooperation. Improvements in ATM system efficiency beyond 2019 were assumed to bring reductions in full-flight CO_2 and NO_x emissions gradually ramping up to 5% in 2035 and 10% in 2050. These reductions are applied on top of those coming from aircraft/engine technology improvements.

Future SAF scenario

The sustainable aviation fuels (SAF) scenario used in the forecast of net CO_2 emissions assumes that the ReFuelEU mandate proposed by the European Commission in July 2021 is met, that is, that SAF usage gradually ramps up to 20% of total fuel burn in 2035 and 63% in 2050. The lifecycle CO_2 emissions of SAF were assumed to be on average 80% lower than those of fossil fuel.

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[59] ICAO Environmental Report 2010 (p. 29).

NOTES

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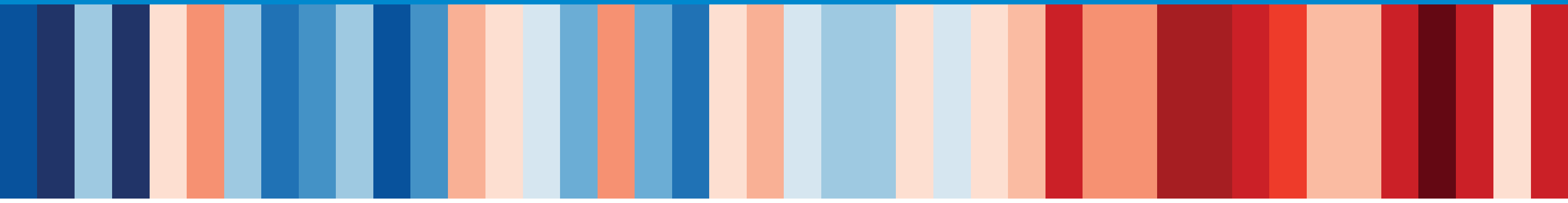

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