STUDY
Requested by the TRAN Committee

Investment scenario and roadmap for achieving aviation Green Deal objectives by 2050

Final Study

Policy Department for Structural and Cohesion Policies
Directorate-General for Internal Policies
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RESEARCH FOR TRAN COMMITTEE

Investment scenario and roadmap for achieving aviation Green Deal objectives by 2050

Final Study

Abstract

This study discusses the technological innovations, operational measures and alternative fuels that are needed for the aviation industry to achieve the objectives of the European Green Deal by 2050. It also presents estimates of the investment needed for the industry to achieve those goals and analyses the EU regulatory framework and funding sources that can support the industry in its decarbonisation pathway.

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AUTHORS

Ricardo: Rui NEIVA, Gareth HORTON, Aleix PONS, Kadambari LOKESH, Lorenzo CASULLO, Alexander KAUFFMANN, Giannis GIANNELOS; Milieu: Marta BALLESTEROS, Max KEMP, Nina KUSNIERKIEWICZ

Research administrator: Ariane DEBYSER, Davide PERNICE
Project, publication and communication assistance: Mariana VÁCLAVOVÁ, Kinga OSTAŃSKA, Stephanie DUPONT
Policy Department for Structural and Cohesion Policies, European Parliament

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ABOUT THE PUBLISHER

To contact the Policy Department or to subscribe to updates on our work for the TRAN Committee please write to: Poldep-cohesion@ep.europa.eu

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LIST OF ABBREVIATIONS

A-CDM	Airports collaborative decision-making
ADS-B	Automatic Dependent Surveillance – Broadcast
APU	Auxiliary power unit
ASBUs	Aviation System Block Upgrades
AtJ	Alcohol to jet (alternative fuel)
ATM	Air traffic management
BLI	Boundary layer ingestion
BPR	Bypass ratio
BWB	Blended wing body
CAAC	Civil Aviation Administration of China
CEF	Connecting Europe Facility
CF	Cohesion Fund
CINEA	Climate Infrastructure and Environment Executive Agency
CO_2	Carbon dioxide
CORSIA	Carbon Offsetting and Reduction Scheme for International Aviation
CROR	Counter-rotating open rotor (engine)
DARPA	Defence Advanced Research Projects Agency
DNSH	Do-no-significant-harm
EASA	European Union Aviation Safety Agency
EEA	European Environment Agency
EGDIP	European Green Deal Investment Plan
EIB	European Investment Bank
ERDF	European Regional Development Fund

ETD	Energy Taxation Directive
ETS	Emissions Trading System
EUA	European Union allowances
EUAA	European Union aviation allowances
FAA	United States Federal Aviation Administration
FEED	Front-end engineering design
FEGP	Fixed electrical ground power
FOAK	First-of-a-kind
GARDN	Green Aviation Research and Development Network
GFGS	Green Fuels, Green Skies
GHG	Greenhouse gases
GJ	Giga Joule
HEFA	Hydroprocessed esters and fatty acids (alternative fuel)
IATA	International Air Transport Association
ICAO	International Civil Aviation Organisation
ICCAIA	International Coordinating Council of Aerospace Industries Associations
ICCT	International Council on Clean Transportation
ILUC	Indirect land-use change
IPCEI	Important Projects of Common European Interest
LCA	Lifecycle assessment
LCFS	Low-carbon fuel standards
LH2	Liquified hydrogen
LP	Low pressure (turbine)
MOU	Memorandum of Understanding

MT	Megatonne
NASA	National Aeronautics and Space Administration
NOx	Oxides of nitrogen
NPBI	National Promotional Banks and Institutions
NPV	Net present value
NRC	Canada’s National Research Council
NRRP	National Recovery and Resilience Plan
OPR	Overall pressure ratio
PBN	Performance-based navigation
PCA	Pre-conditioned air
PJ	PetaJoule (10^{15} Joules)
PSO	Public service obligation
PV	Present value
R&D	Research and development
RCF	Recycled carbon fuels
RED	Renewable Energy Directive
RFNBO	Renewable fuels of non-biological origin
RRF	Recovery and Resilience Facility
SAF	Sustainable aviation fuel
SES	Single European Sky
SESAR	Single European Sky Air traffic management Research
SPK	Synthetic paraffinic kerosene
TFEU	Treaty on the Functioning of the European Union
TRL	Technology readiness level

TSC	Technical screening criteria
TTW	Tank-to-wake
UCO	Used cooking oil
WTW	Well-to-wake

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EXECUTIVE SUMMARY

KEY FINDINGS

- As part of the European Green Deal decarbonisation targets, emissions from EU aviation will need to decrease significantly.
- Decarbonising aviation is challenging because of long aircraft replacement cycles and the lack of viable zero-carbon alternatives to kerosene fuel in the short-term. Most of the reduction will occur after 2030; emissions are expected to decrease by 61 % from 2030 to 2050.
- Achieving reductions requires a multitude of technical measures, such as improvements in aircraft technology and operations, together with a significant uptake in the use of sustainable aviation fuels (SAF).
- New zero-carbon aircraft using hydrogen may be available for all market segments between 2030 and 2040, but this is too late to be the main means for decarbonising aviation.
- Significant investments of EUR 378 billion between 2020 and 2050 will be needed to replace aircraft and introduce new technologies. This investment may deliver improvements in efficiency leading to lower operating costs for the industry, potentially balancing out the increase in fuel costs as a result of wider uptake of SAF.
- The EU supports this transition by funding research and development activities on aircraft and air traffic management (ATM) technologies, together with the deployment of digital and physical ATM infrastructure.
- The EU should continue to use funding and regulatory action to support increased production of SAF to achieve large scale cost reductions and technology maturity.
- Expanding the scope of the Taxonomy Regulation to include activities such as the sale or lease of more efficient/low-carbon emission aircraft, aircraft manufacturing and technology development aiming at/supporting decarbonisation, and production, storage and distribution of SAF, would attract green finance to the sector.

The European Green Deal and the challenge of decarbonising aviation

This study assesses the cost to decarbonise aviation by 2050, the technologies to do so, and the European Union (EU) role in this process. Meeting the targets for a decarbonised European aviation system will require significant reductions from aircraft, through more efficient technology or low-carbon fuels, which form the focus of this work.

The European Green Deal targets carbon neutrality by 2050. Overall, the transport sector is expected to contribute a 90 % reduction in emissions relative to 1990 levels; decarbonisation scenarios from the European Commission indicate that emissions from European aviation are expected to be 89 % lower under the Green Deal. While emissions are expected to peak by 2025, the majority of the reduction will come after 2030, declining by 61 % from 2030 to 2050, and significant residual emissions will remain by then. Aviation is considered a difficult sector to decarbonise (due to substantial obstacles in electrifying aircraft) and will require measures on several fronts – technological, regulatory, financial.

Technological landscape

The study considered a wide range of developing technologies to support the decarbonisation of the aviation sector:

- Aircraft technologies;
- Operational measures;
- Sustainable aviation fuels (SAF).

Technologies were identified that could reduce energy consumption of aircraft by up to 50%[1]. While efficiency improvements are expected, several issues will limit the impact of new technologies on emissions:

i. Manufacturers will wish to avoid high business risks of launching new aircraft with multiple new technologies;
ii. Most aircraft in the market have been released recently and will not be upgraded for several years;
iii. Aircraft have long replacement cycles: many aircraft delivered in the coming decade, with current technologies will still be flying in 2050.

For the past two decades, the EU has been developing its Single European Sky to improve air traffic management (ATM), which may offer fuel savings of 9-11 % by enabling aircraft to fly at optimum speed and altitude.

One area offering great potential is SAF (drop-in fuels, hydrogen, electricity), which can offer emissions reductions of 20-100%. While hydrogen and electricity will require novel aircraft types and may not be available for all market segments before 2040, drop-in SAF has the potential to reduce aviation emissions today. The main constraints on drop-in fuel use are the price and availability at commercial scale.

Table 1-1: Effects of technologies and alternative fuels on emissions in 2050

	Tank-to-wake (TTW) emissions (MT)	**Well-to-wake (WTW) emissions (MT)**	**Change in WTW emissions relative to baseline**
Baseline	150.2	184.8	
With technologies	67.0	82.4	-55.4 %
With technologies and alternative fuels	31.6	18.4	-90.1 %

Source: Authors' calculations using demand data from the 2020 Reference Scenario, energy consumption data from the MIX scenario, energy efficiency assumptions for technologies and emissions factors from ICAO Annex 16 Volume IV.

To meet the objectives of the Green Deal, WTW emissions in 2050 need to be less than 49.1 MT (a reduction of 73 % relative to the baseline value of 184.8 MT in Table 1-1). Table 1-1 shows that aircraft technologies and operational measures alone will not deliver these objectives. Including alternative fuels, however, allows the targets to be met with a comfortable margin.

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[1] The greatest reduction in energy consumption identified for an individual technology is 50% for the full-electric propeller-driven aircraft.

The development of new technologies, the purchase of new aircraft with those technologies, and the uptake of SAF will impose costs on the aviation industry. While the purchase of aircraft with new technologies is expected to lead to *additional* costs (compared to aircraft with current technology) of EUR 378 billion between 2020 and 2050[2], with the research and development (R&D) of those technologies incurring costs of EUR 50 billion[3], the increased efficiency of new aircraft is expected to give fuel cost savings of EUR 395 billion (2020-2050). The overall costs of decarbonisation measures are expected to be about EUR 33 billion between 2020 and 2050[4].

EU role – legislation

The EU has and will continue to have an important legislative role in strengthening the decarbonisation of aviation. The main areas of action have been:

- Market-based measures to support emissions reduction;
- Aviation fuel;
- Financial incentives to promote measures on infrastructure.

Perhaps the most consequential EU action to date has been including aviation in the EU Emissions Trading System (ETS), which requires all airlines operating in the EU to verify and report their emissions. However, its scope was limited by excluding flights to outside the EU and granting airlines a certain number of free allowances. The EU ETS is expected to be amended, removing free allowances and integrating it with the ICAO CORSIA scheme, which may improve its effectiveness.

Two proposals on aviation fuel are included in the 'Fit for 55'[5] package. First, an amendment to the Energy Taxation Directive will impose a tax on fossil kerosene used as jet fuel. Second, the ReFuelEU Aviation Regulation will impose a blending mandate requiring the minimum proportion of SAF in aviation fuel to increase from 2025 to 2050. Together, these two initiatives offer substantial potential to shift demand from fossil fuel towards SAF.

The main EU tool on financial incentives is Regulation (EU) 2020/852, the Taxonomy Regulation, which defines environmentally sustainable economic activities and sets a framework to facilitate sustainable investment in economic activities associated with major GHG emissions. The Regulation already covers a number of activities that can support the decarbonisation of the aviation sector, such as the production of hydrogen and biofuels, and the construction of low-carbon airport infrastructure.

EU role – funding

Existing EU programmes have typically funded R&D for aircraft and ATM-related technologies, as well as deployment of the technologies. While these are key areas in the pathway to decarbonisation, an important share of future investments will need to cover the commercial availability of new fuels and purchase of more efficient aircraft. The EU can play a role in creating the necessary regulatory conditions for commercial products to be more widely available and providing financial support (loans or grants) to spur investment in the low-carbon fuels market. For example, the EU could promote the

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[2] For context, some estimates put the costs of achieving the European Green Deal objective of carbon neutrality across the EU economy at up to EUR 800 billion *per year* for the next 30 years (Consultancy.eu, 2021).

[3] Estimated development costs here should be considered those supported through major European research programmes. The additional costs to take a new technology through to a new aircraft type are borne by the manufacturer and are uncertain and significantly higher. These latter costs are not considered in this study.

[4] All values in the text are undiscounted. The application of discount rates changes the magnitude of these total net costs.

[5] The EU is working on a revision of its climate, energy and transport-related legislation under the Fit for 55 package to align current law with the 2030 and 2050 ambitions.

uptake of lower emission aircraft and the shortening of the aircraft replacement cycle via the inclusion of the sale or lease of more efficient aircraft in the Taxonomy Regulation.

Policy recommendations

The EU can accelerate progress in aviation decarbonisation by taking action in a number of fields:

- The EU should continue to pursue a multifaceted approach and act in all areas of aviation, including deployment of new aircraft technologies, market-based measures and wider use of SAF.
- The EU can continue to play a key role in innovation through ongoing support for R&D of new technologies for aircraft, ATM and SAF. Funding from the EU ETS for aviation and the proposed tax on kerosene could be earmarked for research in these areas.
- Increasing the production of SAF and hydrogen is crucial. Without large-scale production of sustainable fuels, it will be impossible to achieve the targeted emissions reductions. In its funding and regulatory capacity, the EU can play a role in this market to ensure that all types of SAF are produced in the necessary volume.
- EU action will be needed to certify SAF (in collaboration with other economic blocks), ensure that feedstocks are prioritised for aviation (and other sectors where decarbonisation depends on drop-in fuels), and create the conditions for investment in production capacity (and potentially support that production capacity directly).
- To incentivise investment in aviation decarbonisation, the Taxonomy Regulation should be expanded to include activities such as the sale or lease of more efficient/low-carbon emission aircraft, aircraft manufacturing and technology development, and production, storage and distribution of SAF.

1. INTRODUCTION

This report presents the results of the research study commissioned by the European Parliament Committee on Transport and Tourism (TRAN) on the 'Investment scenario and roadmap for achieving aviation Green Deal objectives by 2050'.

The overall objective of the study was to analyse the technical, operational and innovative (new aircraft, new fuel, regulatory requirements) elements needed for the aviation sector to achieve the objective of the European Green Deal by 2050, notably in the context of new and forthcoming European Union (EU) legislation and policy initiatives. It also aimed to present investment scenarios, either from the sector itself or with the help of public and private funding, to support decarbonisation of aviation.

The report is structured as follows:

- Section 2 discusses the decarbonisation needs of the aviation sector by 2050, including compared to the transport sector in general.
- Section 3 presents an overview of developing technologies to reduce fuel consumption and aircraft emissions. It covers aircraft technologies, operational measures and sustainable aviation fuels (SAF)[6].
- Section 4 discusses the investments needed in the aviation sector to achieve the decarbonisation goals[7].
- Section 5 covers the EU role in supporting decarbonisation of the aviation sector, i.e. the EU legal framework and potential EU funding support for aviation and related needs[8].
- Section 6 discusses the main challenges the EU may face in decarbonising aviation, such as competitiveness of EU carriers and airports, and connectivity.
- Section 7 presents three case studies highlighting global best practice in SAF, technologies and associated infrastructure, and air traffic management (ATM).
- Section 8 compares the major aviation markets worldwide (Brazil, Canada, China, Japan, and the United States (US)) in the fields of policy and research.
- Section 9 presents conclusions and a set of policy recommendations.

The study was primarily based on desk research, with an in-depth review of research reports, academic literature, EU legislation, proposal for legislation and accompanying support studies. This was complemented by a set of stakeholder interviews covering research institutes, aircraft design consultancies, airports, and green finance specialists. These interviews were used to collect data, get a better understanding of some issues (e.g. on green finance) and to discuss assumptions around the forecast emissions reduction and timeline for introducing novel technologies. Inputs from stakeholders informed the analysis where relevant.

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[6] Supporting information in Annexes A1 and A2.
[7] Supporting information in Annex A3.
[8] Supporting information in Annex A4.

2. THE CHALLENGE OF DECARBONISING AVIATION

KEY FINDINGS

- Based on the scenarios published by the European Commission, the study developed estimates of the scale of emissions reductions required to meet the goals of the European Green Deal.
- To meet those objectives, emissions from European aviation will need to be 89 % lower than what they are projected to be in 2050 in the absence of any European Green Deal related actions. This implies a need to reduce emissions by 646 million tonnes of carbon dioxide (CO_2) by 2050.
- Such a reduction would mean that, in 2050, emissions from extra-EU flights will need to be similar to those from 1990; however emissions from intra-EU flights will need to be about 56% below 1990 levels.
- Despite these reductions in aviation emissions, similar efforts to reduce emissions in other transport modes will see aviation's share of total transport emissions rising from 12% in 2015 to about 60% by 2050.

This study aims to identify the cost to decarbonise aviation by 2050, the technologies to do so, and the EU's role in the process. Meeting the targets of a decarbonised European aviation system will require significant reductions in emissions from aircraft, which must be understood in the context of both expectations of the aviation sector as part of the delivery of the European Green Deal and how the reductions compare to those expected for other transport modes.

The European Green Deal targets carbon neutrality (a reduction in net CO_2 emissions from the EU to zero) by 2050. The expected contribution from the transport sector is a 90 % reduction in emissions compared to 1990 levels. The specific contribution from aviation is not defined, but some expectations were included in scenarios published recently by the European Commission in support of the European Green Deal and the 'Fit for 55' proposals. Data were analysed for two such scenarios:

1) 2020 Reference scenario provides a view of the future developments of the transport sector emissions prior to the adoption of the European Green Deal and the 'Fit for 55' proposals to accelerate decarbonisation of the EU economy;
2) MIX scenario (produced as part of the development of the Fit for 55 initiative) provides a view on the development on emissions, assuming that the relevant policies described in the European Green Deal will be adopted towards achieving the carbon neutral initiative's objectives by 2050[9] and, hence, indirectly setting targets for emission reductions from aviation. The total transport emission projections published for the MIX scenario only extended to 2030 and were therefore extrapolated to 2050 for the purposes of this study. The 2020 Reference scenario data already extend to 2050.

Figure 2-1 compares the forecast emissions for the total transport sector (including all modes) under the MIX and Reference 2020 scenarios. The forecast emissions from the aviation sector under the MIX scenario are shown as the amber area within the blue area.

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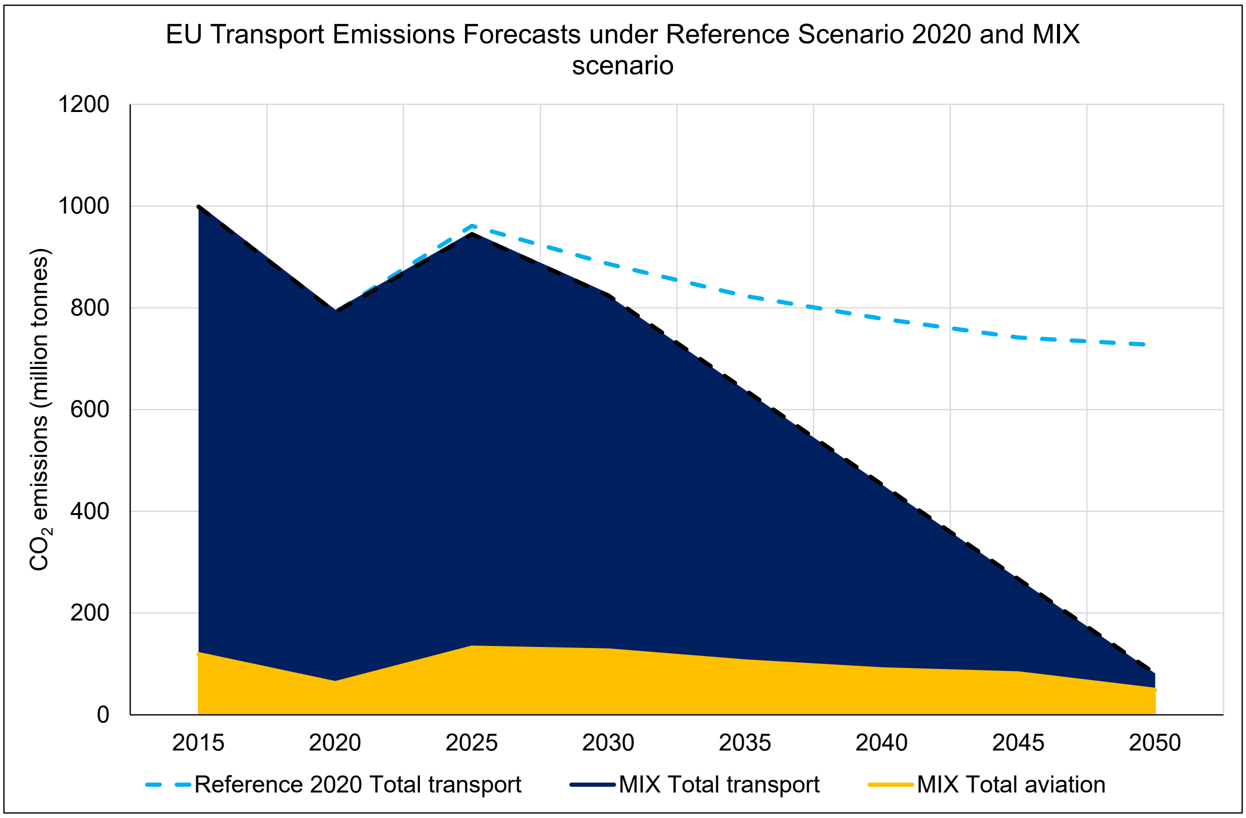
[9] The MIX scenario includes the extension of carbon price signals to road transport and buildings and a strong intensification of energy and transport policies. It uses a uniform carbon price and either an extended and fully integrated EU ETS, or the current EU ETS scope (including extension to the maritime sector) with a new ETS for road transport and buildings, or an existing EU ETS and a new ETS for road transport and buildings with emission caps set in line with cost-effective contributions of the respective sectors. It does not explicitly include the proposed introduction of mandated minimum blends of alternative fuels, nor changes in the Energy Taxation Directive.

Figure 2-1: Comparisons of transport CO_2 emissions under the MIX and Reference 2020 scenarios

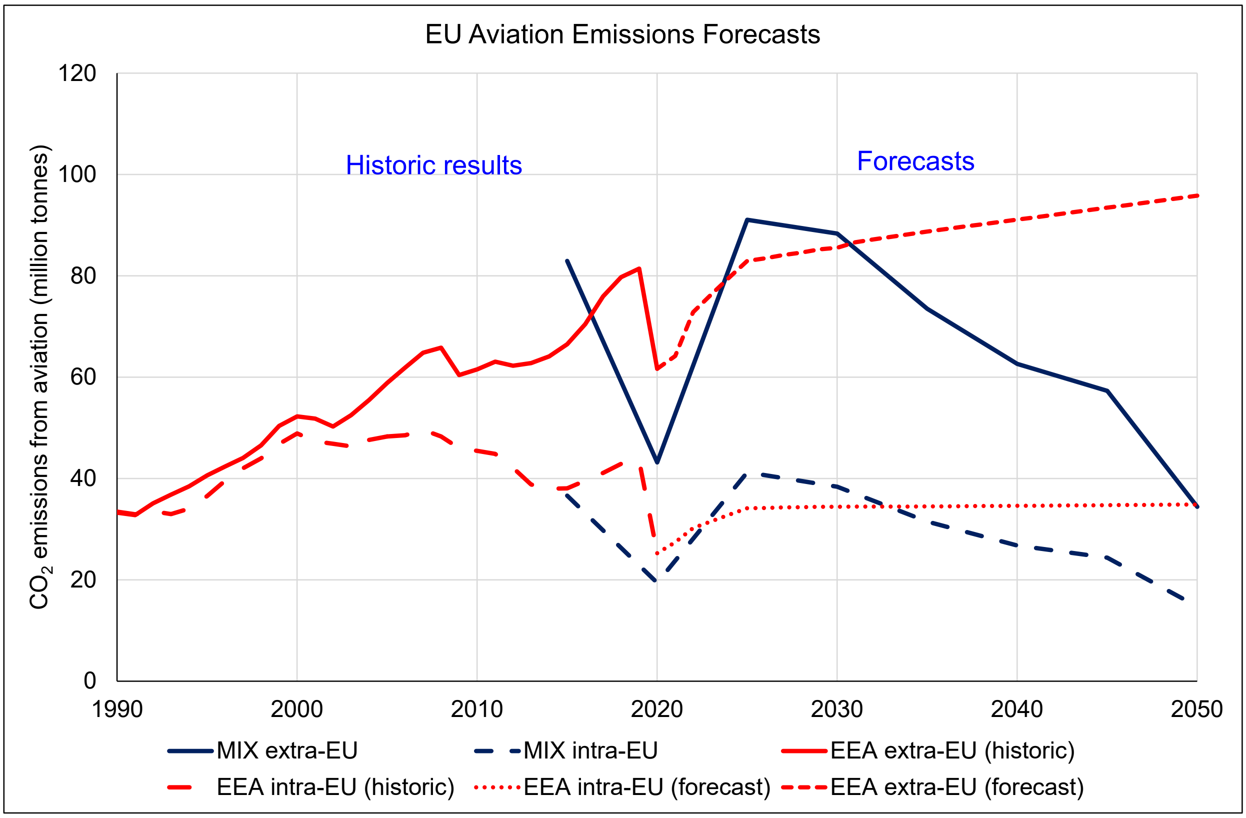


Source: PRIMES/TREMOVE data (2020 Reference Scenario, MIX scenario, plus additional data for the MIX scenario provided by the European Commission for this study).

From Figure 2-1, it is clear that the MIX scenario (extrapolated to achieve the European Green Deal objectives) requires a far greater reduction in total transport emissions to 2050 than the 2020 Reference scenario. Both scenarios show peak emissions in 2025; the 2020 Reference scenario then declines by 8 % by 2030, then a further 17 % by 2050. The MIX scenario shows a greater reduction (13 %) to 2030, then a further 79 % by 2050. As a result, the total transport emissions from the MIX scenario are 89 % lower in 2050 than those from the 2020 Reference scenario (a difference of 646 million tonnes of CO_2). Although some reductions are expected from the aviation sector, they are considerably smaller than what is expected for other transport modes. Between 2030 and 2050, the emissions for the aviation sector (the top of the amber area in Figure 2-1) reduce from 126.7 million tonnes to 49.1 million tonnes (61 %). This results in aviation's contribution to total transport sector emissions growing from approximately 12 % in 2015 to approximately 60 % by 2050. This significant reduction in emissions from aviation in the post-2030 period illustrates that aviation is expected to be one of the last transport modes to decarbonise. This is due to the requirements for a high specific energy (energy per unit mass) of fuels which, if aircraft where to be electric, would lead to the need for a substantial weight in equivalent batteries, leading to substantial difficulties in electrifying aircraft for anything other than very short flights.

The emissions projections from the MIX scenario were also compared with those published by the European Environment Agency (EEA), distinguishing between emissions from intra-EU flights and extra-EU flights.

Figure 2-2: Comparisons of aviation emissions under the EU MIX scenario and the EEA forecasts



Source: PRIMES/TREMOVE data (MIX scenario); EEA forecast: (EEA, 2021).
Note: The EEA forecasts only extend to 2040; the chart includes extrapolations to 2050 by the authors.

The analysis shows that the EEA forecasts (to 2040), developed without the inclusion of the European Green Deal measures, include continuing increases in emissions for extra-EU flights, while those for intra-EU flights level off after 2025. By contrast, the MIX scenario includes the effects of the updated policy measures[10] targeting the achievement of the European Green Deal objectives and shows significant reductions in emissions following the recovery from COVID-19. These lead to emission levels similar to those of 1990 for extra-EU flights (34.4 million tonnes in 2050, compared to 33.3 million tonnes in 1990) and about 56 % below 1990 levels for intra-EU flights (14.7 million tonnes in 2050 compared to 33.5 million tonnes in 1990). In 2050, the aviation emissions under the MIX scenario are 58 % (intra-EU flights) and 64 % (extra-EU flights) lower than under the respective EEA forecasts (extrapolated to 2050). These values show the scale of reductions necessary from the aviation sector to meet the objectives of the European Green Deal (20 million tonnes CO_2 reduction for intra-EU flights and 60 million tonnes for extra-EU flights) and are the emissions trajectories against which the potential reductions from the identified technologies and operational measures will be compared.

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[10] An extension of the carbon price signals under the EU ETS to additional sectors (road and maritime transport, and buildings) and a strong intensification of energy and transport policies.

3. TECHNOLOGIES TO DRIVE DECARBONISATION

KEY FINDINGS

- Unconventional aircraft configurations such as blended wing bodies (BWB) may offer significant improvements in efficiency through reductions in fuel consumption (up to 30%). However, these technologies may not be available for several years. Similarly, unconventional propulsion systems such as the open rotor engine would deliver efficiency improvements (up to 20%), but also face development and adoption challenges, and are likely to be restricted to medium-haul operations (on single-aisle aircraft).
- Other aircraft and engine technologies, including composite structures, hybrid laminar flow, increased engine bypass ratio (BPR) and pressure ratio, are in continuous development and although they may not offer large reductions in emissions (up to 15%), they are more likely to be adopted in the short term.
- Replacing kerosene yields greater emission reductions. In the short to medium term, sustainable aviation fuels produced on a small scale can provide significant reductions in emissions on a well-to-wake (WTW) basis (up to 90%). The greatest challenges for such fuels are scaling-up their production facilities and their higher cost relative to conventional fuels. Long-term options for electric and hydrogen-fuelled aircraft may lead to zero-carbon flights, but both energy carriers give poorer energy density than conventional kerosene in an aircraft application, which will restrict their use to smaller aircraft, at least initially.

3.1. Introduction

Since the beginning of the jet age, the aviation industry has focused on reducing the fuel consumption of aircraft, as fuel costs represent a major portion of airline operating costs: at a global level, these were about 19 % of airline operating costs in 2021 (IATA, 2021c), compared to over 30 % in 2008 (IATA, 2010). Technological developments in aircraft and engines meant that aircraft types were over 70 % more efficient in 2000 than the first jet aircraft (Peeters, Middel, & Hoolhorst, 2005). Subsequent updates to the analyses ((Kharina & Rutherford, 2015), (Zheng & Rutherford, 2020)) show that developments have continued, although at a less rapid pace (0.5% average reduction per annum 2000 to 2010, 1.5% average reduction per annum 2010 to 2019), so that new aircraft in 2019 were 17% more fuel efficient than those in 2000 and over 75% more fuel efficient than the first jet aircraft[11]. As CO$_2$ emissions are directly proportional to fuel consumed[12], this also implies a 75% reduction in emissions (per passenger-km). However, increased demand for flights has outpaced efficiency improvements, resulting in continuous increases in total emissions[13].

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[11] Calculated from 70% (first jet aircraft to 2000) plus ten years at 0.5% per annum and nine years at 1.5% per annum ((1-0.7)x(1-0.005)^{10}x(1-0.015)^{9} gives 0.249, or 75.1% reduction)

[12] For tank-to-wake (TTW) emissions. For well-to-wake (WTW) emissions, the total emissions depend on the emissions produced during the extraction (if appropriate), processing and delivery phases and are not necessarily directly proportional to the fuel burn (particularly if alternative fuels are considered) (see Annex A2).

[13] Some organisations argue that 'demand management' (restricting the allowable growth of demand) will need to be considered as a tool to support the aviation sector in reaching net zero emissions (Transport & Environment, 2022).

In recent years, there has been an increased focus on reducing CO_2 emissions (and those of other greenhouse gases (GHG)), beyond incremental efficiency developments, driven by the policy goals described in Section 2. As a result, the technologies being investigated have widened to include alternative fuels, which can give reduced emissions for the same fuel consumption. These alternative fuels include drop-in liquid fuels (commonly referred to as SAF), as well as hydrogen and battery electric[14]. For drop-in fuels, no additional technology developments are required in aircraft, engines or fuel handling and storage. By contrast, hydrogen or battery electric (or a hybrid of conventional gas turbine and battery electric) requires significant new aircraft and engine technology developments.

Reductions in energy consumption can be achieved through advances in engine efficiency, aerodynamics or aircraft weight (or combinations of all three). Annex A1 describes how these three technological areas contribute to improvements in energy consumption.

The study undertook a review of the technologies in development for aircraft, engines, alternative fuels and operational measures, including their expected reductions in GHG emissions. The analysis of the financial investments required to deliver the technologies necessitated data on the expected costs to develop the technology for use in operational aircraft and the expected additional purchase costs for aircraft employing the specific technologies. Accordingly, these were identified from literature review, where available.

3.2. Aircraft technologies

At the aircraft level, the technologies identified can be further sub-divided into those related to:

- Overall aircraft concept and design (unconventional configurations);
- Aircraft structure and aerodynamics (conventional configurations);
- Propulsion system.

3.2.1. Unconventional configurations

Table 3-1 summarises the technologies identified under unconventional configurations (see full set of technologies in Annex A2). It includes the market segment(s) to which the technology is applicable, an indication of the current availability of the technology for use - or an earliest expected availability - and the expected reduction in energy consumption from its use. For some technologies, different sources provide different estimates of the expected energy consumption, or a reference may give a range of values depending on the application. In such cases, an overall average value was selected to provide a single input value to the calculation (for example, for the blended wing body technology in Table 3-1, the IATA reference (IATA, 2019) gave values of 27 % to 50 % for large aircraft and 30 % for a small aircraft; a value of 30 % was selected to represent a conservative assumption covering all potential applications of the technology).

Table 3-1: Summary of unconventional aircraft configurations

Technology	Market segment	Availability/readiness	Energy reduction
Blended wing body (BWB)	Long-range, wide-body	2040	30 %
Boundary layer ingestion (BLI)	Long-range, wide-body	2030	8.5 %

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[14] Batteries are not fuel in the same sense as liquid fuels; they, together with their electric charge, are better considered 'energy carriers'.

Technology	Market segment	Availability/readiness	Energy reduction
Windowless fuselage	All market segments	2035	0.7 %
Truss-braced/strut-braced wing	Short/medium-range, narrow-body	2035	8-15 %

Source: Compiled by authors based on information from Clean Sky (Clean Sky, 2021), International Air Transport Association (IATA, 2019), Bagassi, Lucchi and Moruzzi (Bagassi, Lucchi, & Moruzzi, 2018) and NASA (NASA, 2022a).

The **BWB** aircraft design is based on a concept in which the aircraft wing and fuselage are 'blended' together, with a large area wing and no tail surfaces. This is expected to reduce overall drag (air resistance) and mass for the same passenger/freight-carrying capacity. In general, it is considered more appropriate to long-range aircraft, as the benefits are obtained mainly during the cruising portion of the flight. The design presents certain challenges (e.g. engine placement), with additional challenges in the control system (due to the lack of a tail section on the aircraft). There are also questions about passengers' acceptance of an aircraft with such a wide fuselage, with most people sitting some distance from the nearest window. The concept has the potential to deliver reductions in fuel consumption and emissions of up to 30 %, but has been investigated for several years without any firm commercial projects underway. Table 3-1 suggests an entry-into-service date in 2040, reflecting the scale of challenges to be overcome and the risks in its development.

The concept behind **BLI** is to place one of the engines at the rear of the fuselage rather than on a pylon under the wing or to the side of the fuselage. The engine is positioned with its centreline aligned with that of the fuselage itself. The boundary layer that has been growing along the fuselage surface is then swallowed by the engine. As the air in the boundary layer is moving more slowly than the air entering an engine mounted under the wing, for example, it is easier for the engine to accelerate it to produce thrust, reducing engine fuel consumption. Having the boundary layer swallowed (and accelerated) by the engine reduces the aircraft drag on the rear fuselage, further improving the fuel efficiency. Overall, the BLI concept is expected to deliver up to 8.5 % reduction in fuel consumption. However, current aircraft engines are designed to operate with a 'clean' inlet airflow, and significant engine development will be required to enable them to operate with the highly distorted inlet flow that arises from ingesting the fuselage boundary layer. From a technological point of view, aircraft using BLI could be available in the 2030 timeframe.

A further technology associated with the aircraft fuselage is that of the '**windowless fuselage**'. The inclusion of windows in the fuselage structure requires additional strengthening around them, adding weight. The aircraft structure could be made lighter if it was built without windows and lightweight panels were used to project images of the outside world to passengers. Some airlines are already using the lightweight panels for their first-class customers (those seated away from the windows); further developments could enable the same technology to be used throughout the cabin. This technology could deliver savings of 0.7 % in fuel consumption and emissions and could be available on new aircraft types from around 2035.

On aircraft wings, a high aspect ratio (the length or span of the wing, divided by its width or chord) gives a higher efficiency than a low aspect ratio. However, a long, thin wing brings structural problems (to ensure that it remains sufficiently rigid and does not twist in flight) and possible challenges in incorporating the aircraft systems in the smaller wing box. Solutions under consideration include the use of **trusses or struts** to support the wing. The aerodynamic improvements when using such wings could reduce fuel consumption by up to 8-15%. Such technologies could be used on new aircraft types, particularly a future generation of narrow-body aircraft, from about 2035.

It is unlikely that the BWB and strut/truss-braced wing could be combined on the same aircraft. The BLI and windowless fuselage could be combined with either of the other technologies for added improvements. When adding multiple technologies, the overall improvement should combine the improvements of the individual technologies[15].

3.2.2. Aerodynamics and structures (conventional configurations)

Table 3-2 presents the technologies identified with aircraft aerodynamics and structures on conventional configurations.

Table 3-2: Summary of aerodynamics and structures technologies

Technology	Market segment	Availability/readiness	Energy reduction
Natural laminar flow	All market segments	Technology available now – further development progressing	5-10 %
Hybrid laminar flow	All market segments	Technology available now – further development progressing	10-15 %
Riblets	All market segments	Technology available now	1-2 %
Composite materials for aircraft structures	All market segments	Technology available now	7-11 %
Morphing airframes	Most effective on long-range aircraft	2040	2-8 %
Reduced design cruise Mach number	Long-range aircraft	Technology available now	5 %

Source: Compiled by authors based on information from Air Transport Analytics (Air Transport Analytics, 2018), Clean Sky (Clean Sky, 2021), International Air Transport Association (IATA, 2019), International Coordinating Council of Aerospace Industries Associations (ICCAIA, 2019) and Tecolote Research (Tecolote Research, 2015).

A key element of aircraft drag is the boundary layers that form on its surfaces. The air flow within these boundary layers can either be laminar (layers of air flowing smoothly parallel to the surface) or turbulent (air flowing unsteadily in multiple directions). A boundary layer with laminar air flow causes lower drag, increasing the interest in designing aircraft to achieve greater regions of laminar air flow. The achievement of **natural laminar flow** ((IATA, 2019), (ICCAIA, 2019)) involves changes to the aircraft shape (particularly wing aerofoil profiles) to manage the velocity profiles, together with changes in the construction and surface treatments to reduce the disturbances to the shape. However, while progress is being made in improving the design technology for natural laminar flow, achieving large areas of laminar boundary layers will require additional technology. **Hybrid laminar flow technology** ((IATA, 2019), (Air Transport Analytics, 2018), (Clean Sky, 2021)) increases the area over which laminar flow boundary layers can be maintained by using suction to 'suck' the air from within

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[15] When combining the energy reduction percentages of multiple technologies, rather than simply summing the percentage reductions, each reduction should be converted to a factor by subtracting the percentage reduction from 100 %. An overall factor is obtained by multiplying the individual factors together. The overall percentage reduction is then obtained by subtracting the overall factor from 100 %. For example, if three technologies are combined with energy reductions of 5 %, 8 % and 12 %, the factors would be 0.95, 0.92 and 0.88. The overall factor is then approximately 0.769 and the overall energy reduction is 23.1 %, rather than the 25 % that would be obtained from a simple summation.

the boundary layer through small holes in the aircraft surface in areas that natural laminar flow cannot be achieved. This technology was included in the vertical tail ('fin') of the Boeing 787 aircraft, which first entered service in 2011. Research is seeking to extend the use of hybrid laminar flow technology to other aircraft surfaces, particularly the wing and fuselage. Ultimately, the achievement of large areas of laminar flow over the aircraft wing and fuselage surfaces (using hybrid technology) could reduce energy consumption by 10-15 %, compared to the 5-10% improvements that may be possible through improved natural laminar flow.

Riblets also reduce the drag from aircraft surfaces (Air Transport Analytics, 2018). These are very small vertical ribs or fences on the aircraft surfaces, applied by a film coating, with the 'riblets' aligned with the main flow direction. The aim is to clean up the air flow in the lower part of the boundary layer, reducing cross-flows and increasing the regions of laminar flow over the surface. Riblets have been considered for application to aircraft for many years (e.g. (Walsh, 1986)), but have yet to be applied widely, chiefly due to the additional cleaning and maintenance they require. Expected reductions in energy consumption from riblets are approximately 1-2 %.

Composite materials, particularly carbon fibre reinforced plastic can be used in aircraft structures to replace traditional metals such as aluminium (Tecolote Research, 2015). The high strength of the material reduces aircraft weight, while the alignment of the fibres can be varied to tailor the structural properties as needed (e.g. giving greater or lesser stiffness in particular directions). Several current aircraft types now have some, or all, major components made from composite materials, including the Boeing 787 and Airbus A350. Extending the widespread use of the material to new aircraft types in other categories will deliver further reductions of 7-11 % in overall energy consumption.

Traditionally, aircraft use control surfaces attached to the main wing and tail surfaces to control the flight paths, with the wing and tail otherwise having a constant shape throughout the flight. However, the ideal wing section may change during the flight as the aircraft weight and altitude changes. The morphing airframe concept (IATA, 2019) uses a more flexible wing structure combined with internal actuators to adjust the wing shape during the flight to optimise its performance throughout. The use of **morphing airframes** is expected to deliver 2% to 8% reduction in energy consumption. As this represents a significant development in aircraft technology, it is unlikely to be available for new aircraft before 2040.

A key reason for flying to a destination (rather than using another mode of transport) is the speed at which aircraft fly: current aircraft cruise at around 0.80 to 0.85 times the speed of sound (Mach 0.80 to Mach 0.85) (Air Transport Analytics, 2018). However, higher flight speeds increase drag, resulting in greater energy consumption for a given flight distance. A **reduced design cruise Mach number** (by Mach 0.06) was investigated by Air Transport Analytics (Air Transport Analytics, 2018), which found that it could reduce energy consumption by up to 5 %. The downside is a longer flight time (by about 7 %, an increase of about 30 minutes on an eight-hour transatlantic flight) and reduced overall capacity of the air transport system. Limited technology development would be required, as existing design tools could adapt aircraft to a lower cruising speed.

These aerodynamics and structural technologies can all be combined on a single airframe, except that 'hybrid' laminar flow technology includes 'natural' laminar flow where feasible. There might be some additional challenges in incorporating hybrid laminar flow technology on an aircraft with a morphing airframe, due to the need to have a suction system and large numbers of small holes in a surface that changes shape, as well as integrating the suction system and the actuation system for the morphing aircraft in the same parts of the structure. Otherwise, the total reduction in energy requirement should be obtained by combining the individual improvements of the technologies (see method in Section 3.2.1).

3.2.3. Propulsion system technologies

Table 3-3 presents the technologies identified in relation to aircraft propulsion systems.

Table 3-3: Summary of propulsion system technologies

Technology	Market segment	Availability/readiness	Energy reduction
Very high bypass ratio (BPR) large turbofan	Long-range, wide-body	2035	Up to 20 %
Very high overall pressure (OPR) ratio	Long-range, wide-body	2035	15-20 %
Geared fan	All market segments	Technology available now (for narrow-body aircraft)	5 %
Composite fan	All market segments	Technology available now	N/A
Contra-rotating open rotor (CROR) engine	Short/medium-range, narrow-body	2035	14 %
Full electric propeller-driven aircraft	Short-range, narrow-body	2030	50 %
Hybrid electric powertrain	Short/medium-range, narrow-body	2035	Up to 40 %
Hydrogen-fuelled gas turbine engine	All market segments	2030	5-26 % *increase* in energy consumption
Hydrogen fuel cell plus electric power for turboprop	Short-range, narrow-body	2035	8-10 %
Hydrogen fuel cell plus electric powered fans for jet propulsion	Short/medium range	2035	4 %

Source: Compiled by authors based on information from Clean Sky (Clean Sky, 2021), International Coordinating Council of Aerospace Industries Associations (ICCAIA, 2019), Clean Sky (Clean Sky, 2020), Mukhopadhaya & Rutherford (Mukhopadhaya & Rutherford, 2022) and Schäfer, et al (Schäfer, et al., 2018).

The first four of the technologies identified above are evolutionary developments that can be incorporated in relatively conventional jet engine architectures. Key design parameters for a conventional aircraft jet engine are the **bypass ratio**[16] (BPR) and the **overall pressure ratio**[17] (OPR). Increasing both BPR and OPR tends to increase engine efficiency, although at the expense of higher

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[16] All of the air that enters the front of a turbofan engine (used on all modern civil jet aircraft) passes through the 'fan'. Following the fan, the air is split, with some passing into the core of the engine, where it is compressed further before entering the combustion chamber. The remainder of the air passes down the bypass duct and exits through a nozzle to produce thrust. The ratio of the mass of air that passes down the bypass duct to that which enters the engine core is the BPR. An engine with a high BPR has most of the thrust generated by the air that passes down the bypass duct after passing through the fan and has a higher overall efficiency compared to a low BPR.

[17] The OPR of a gas turbine engine is the ratio of the pressure at the exit of the compression system (before entering the combustion chamber) to that at the entry to the engine. A high OPR leads to a higher cycle efficiency.

weight and increased emissions of nitrogen oxide (NOx), a key pollutant of local air quality. Over time, aircraft engine developments have tended to focus on delivering higher BPRs and OPRs (see Table 3-4).

Table 3-4: Aircraft engine BPR and OPR values

Engine	Year	BPR	OPR
Pratt & Whitney JT8D-15	1971	1.0	16.8
International Aero Engines V2500-A1	1988	5.3	29.8
General Electric GE90-76B	1995	8.5	35.3
Rolls-Royce Trent 1000-A	2009	9.5	41.0
Pratt & Whitney PW1133G-JM	2017	11.6	38.1
Rolls-Royce Trent XWB-97	2020	8.1	48.4

Source: Engine BPR and OPR values taken from International Civil Aviation Organisation (ICAO) engine emissions databank (European Union Aviation Safety Agency) (EASA, 2021). Engine dates taken as initial test date from same source, except for Pratt & Whitney JT8D-15.

Engine developments continue to aim for further increases in BPR and OPR (Clean Sky, 2021), (ICCAIA, 2019) and to produce **very high BPR** and **OPR** engine designs. These technologies have delivered significant improvements in engine efficiencies in the past and it is estimated that further improvements of up to 20% may be feasible through continued developments. An important challenge with increased BPR is that as the fan becomes larger, its rotational speed must be reduced to avoid excessive speeds at the fan blade tips. However, the fan is driven by the low pressure (LP) turbine situated at the rear of the engine, to which it is connected by a rigid shaft. From an aerodynamic perspective, improving efficiency would suggest reducing the fan speed and increasing the LP turbine speed; the inability to meet both drivers has resulted in significant increases in size and weight of the LP turbine, partially offsetting the performance gains from the increased BPR.

An option that has been developed to overcome the problems of the increased load on the turbine in high BPR engines is to put a gearbox between the LP turbine and the fan, giving a '**geared fan**', allowing it to operate at optimum speeds and to be made significantly smaller and lighter. This is the approach adopted by Pratt & Whitney for their GTF family of engines (marketed as the PW1000G family), as fitted to the Airbus A220 and A320neo families, the Embraer E2 family and the Irkut MC-21. A geared fan architecture will also be included in the Rolls-Royce UltraFan technology demonstrator, which will apply the technology to an engine for long-range twin-aisle aircraft for the first time. As noted, a key benefit from the use of a geared fan is to enable the use of higher BPR; however, the technology itself can also deliver additional benefits, perhaps up to 5%, through the reductions in fan speed and the increases in turbine speed that it allows.

Composite materials can also be used in engine components. In particular, **composite fans** have been used in the General Electric GE90 engine and are expected to feature more widely in future engines. For example, they are included in the Rolls-Royce Advance 3 and UltraFan demonstrators. As well as reducing the weight of the fan blades (allowing a lighter hub to be used), the use of composites allows the development of different fan blade shapes, with benefits for aerodynamic efficiency.

The four technologies for conventional architecture engines described above can also be combined in a single engine design; the overall reduction in energy consumption would be obtained as described in Section 3.2.1.

Further improvements in propulsion system efficiency will likely require further increases in BPR, but doing so in a conventional engine configuration would lead to excessive increases in weight. One concept to deal with this challenge is the **CROR engine**, which features two rows of blades, rotating in opposite directions, without any shroud. Such a design allows a significant further increase in fan diameter, with the second row of rotating blades adding additional thrust while removing the swirling flow that the first blade row produces. However, the air speed achievable with a CROR is lower than a jet engine, so they are unlikely to be suitable for large, long-range aircraft. The most significant problem with the early prototypes of CROR engines (in the late 1980s) was the noise they produced (the aerodynamic interactions between the two blade rows generated high noise, while the lack of a shroud removed a key means of absorbing the noise). Substantial research into reducing the noise from the concept has yielded promising results that may meet current aircraft certification noise limits (ICAO Chapter 14). However, these certification limits are likely to change in the future (in the 12th CAEP meeting, the CAEP members requested an analysis of potential changes to both the noise and CO_2 certification limits for consideration at their 13th meeting in 2025 (IBAC, 2022)) and further development of the CROR may be required to ensure that it can meet the regulations in force when it enters service. If these challenges can be overcome, the CROR may reduce energy consumption by up to 14 % relative to today's short to medium-range jet aircraft. The technology may be available in the 2035 timeframe (likely to be associated with, and driven by the timing of, the introduction of a new generation single-aisle aircraft family).

For other modes of transport, particularly road transport, the focus for decarbonisation has largely been on electric and hybrid-electric vehicles. For aviation, the energy density of batteries (in kWh per kg) is expected to remain too low for practical use in a large airliner. Nevertheless, R&D has continued investigating electric aircraft and it now appears feasible to develop a small, **full electric propeller-driven** ('turboprop') aircraft (Schäfer, et al., 2018). Such an aircraft is likely to be limited to short-range operations, but will be able to perform these operations with zero emissions (depending on the source of the electricity used for charging). The improved efficiency of the electric powertrain may deliver energy consumption up to 50 % less than a conventionally-engined equivalent aircraft.

In the shorter-term, and perhaps for larger aircraft, a potential option is the **hybrid electric powertrain** (IATA, 2019), (Clean Aviation, n.d.). This combines a battery electric system and gas turbine engines in the same airframe. A number of possible systems are under investigation, including parallel hybrid[18] and serial hybrid[19] systems. In 2017, Airbus Industrie, in partnership with Rolls-Royce, launched the E- Fan X demonstrator programme, based on a serial-hybrid system installed in an existing regional aircraft. In 2020, they brought the programme to an end, stating that it had already achieved its main goals:

- Testing the possibilities and limitations of a serial hybrid-electric propulsion system in a demonstration aircraft;
- Gaining insights to develop a more focused roadmap on how to progress their decarbonisation commitments;

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[18] In a parallel hybrid system, the electric motor is attached to the gas turbine engine shaft, and used to provide additional power when required (allowing the main gas turbine engines to be made smaller) or used on its own with no fuel consumed by the gas turbine, depending on the phase of flight. A possible mode of operation would be to use electric power on the ground, then both electric and gas turbine power during take-off and climb, reducing to just the gas turbine during the cruise portion (with the gas turbine engine optimised for the cruise condition) and, if the battery capacity is sufficient, reverting to electric-only power for the approach and landing.

[19] The serial hybrid system uses a set of multiple fans powered by electric motors to produce all of the thrust. These electric motors can then be driven by electricity from the on-board battery or the gas turbine engine (which is used in 'turboshaft' mode, solely producing shaft power, not thrust) via a generator. The gas turbine generator can also be used to recharge the batteries.

- Laying a foundation for the future industry-wide adoption and regulatory acceptance of alternative-propulsion commercial aircraft.

Depending on its configuration, a hybrid-electric system has the potential to provide significant reductions in aircraft CO_2 emissions during operations. However, for regional or longer flights, much of the power would still be obtained from liquid fuels such as kerosene. The potential to reduce in-service CO_2 emissions to zero on such flights will require a change in fuel to one that does not contain carbon. Hydrogen represents the most likely option for such a step-change to a zero-carbon fuel. Different options are being developed for hydrogen-fuelled aircraft for the future.

In principle, it is feasible to produce a **hydrogen-fuelled gas turbine engine**, with engine changes primarily to the combustion system (Mukhopadhaya & Rutherford, 2022). Compared to kerosene, hydrogen has a very good specific energy[20], although it has a poor energy density (energy per unit volume) in both gas and liquid form[21]. As a result of the very low energy density (thus large fuel tanks), the use of gaseous hydrogen as a fuel is likely to be restricted to very small aircraft flying short distances. The energy density of liquid hydrogen is still significantly lower than that of kerosene, with the fuel tank volume imposing restrictions on the size and range of the aircraft. Hydrogen in its liquid state is stored at very low temperatures (below -252.8°C at atmospheric pressure), which requires significant insulation in the fuel tank, adding to the volume and partially offsetting the weight advantage. That additional weight of the fuel tanks means that the energy consumption for a medium or long-range aircraft would be 22-42 % higher than that of a conventionally fuelled aircraft, although the resulting CO_2 emissions would be zero. However, the combustion of hydrogen produces water vapour which, depending on the altitude and weather conditions, can produce contrails that can contribute to global warming (through the creation of cirrus clouds). Contrails are already a concern from aircraft using conventional fuels, and a hydrogen fuelled aircraft would produce between 3.0 and 3.5[22] times the mass of water vapour. It is estimated that a hydrogen-fuelled aircraft could be available around 2035.

An alternative to combusting hydrogen in a gas turbine engine is to use it in a fuel cell to generate electricity that can then be used to power electric motors. Although the power that can be generated is limited by heat issues in the fuel cells (and the overall power available is limited by the fuel cell mass), the increased efficiency of the fuel cell/electric motor combination (compared to a gas turbine) can bring benefits. The two options under investigation are a **hydrogen fuel cell plus electric power turboprop** (with the electric motors driving propellers, similar to the electric turboprop referred to above) or a **hydrogen fuel cell plus electric powered fans for jet propulsion** (Clean Sky, 2020). The propeller-driven aircraft would be more suitable for short-haul operations, while the jet propulsion aircraft would have a higher cruise speed and would be more suitable for medium-range operations. Although the on-board storage of the hydrogen fuel would still incur similar weight penalties as for the hydrogen-fuelled gas turbine engine, the higher overall efficiency of the fuel cell/electric motor combination (relative to the gas turbine) would allow such an aircraft to deliver a reduced energy consumption (relative to a conventionally fuelled aircraft). These hydrogen fuel cell options,

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[20] The specific energy of hydrogen is 122.8 MJ kg compared to 42.8 MJ/kg for kerosene (Seeckt & Scholz, 2009).

[21] The energy densities for gaseous and liquid hydrogen are 10.3 MJ/m^3 and 8,694 MJ/m^3, respectively, compared to 34,561 MJ/m^3 for kerosene. The density for gaseous hydrogen is quoted at normal temperature and pressure (NTP) of 20°C and 101.325 kPa. The density (and hence energy density) varies strongly with pressure and temperature.

[22] The water vapour produced by combusting 1 MJ of hydrogen is about 2.5 times that produced from 1 MJ of kerosene. Adding the additional energy consumed during the flight raises the ratio to 3.0-3.5, as per the text.

particularly the propeller driven aircraft, may provide an initial application of a hydrogen fuel in a regional aircraft[23].

A number of companies are already working on electric and/or hydrogen-fuel aircraft (e.g. Eviation, Wright Electric, Zunum, GKN Aerospace, Cranfield Aerospace Solutions, ZeroAvia. Some have quite ambitious targets for entry into service (e.g. 2026 for the GKN Aerospace H2GEAR project). However, all aircraft currently being developed are small (the current ZeroAvia development aircraft has 19 seats, although they are projecting 100-seat aircraft for the future) and will have short ranges. The timing for the extension of the technology to larger aircraft (e.g. 150-seat single-aisle aircraft or 300-seat twin-aisle aircraft) with longer ranges remains uncertain. The dates in Table 3-3 are based on the literature references, but should be considered the earliest that such aircraft may enter service. It is prudent to allow for this uncertainty in the availability dates in analyses of the impacts of such technologies.

The unconventional powerplant architectures described are essentially distinct and they would not be combined in a single system.

3.3. Operational measures

Table 3-5 presents the operational measures identified with the potential for reducing CO_2 emissions from aviation.

Table 3-5: Summary of operational measures

Technology	Market segment	Availability/readiness	Energy reduction
Cruise at optimum speed and altitude	All market segments	Technologically feasible now	9-11 % of full-flight energy consumption
Reduced take-off thrust	All market segments	Technologically feasible now	Up to 23 % during take-off
Single-engine taxiing	All market segments	Technologically feasible now	20-40 % during taxiing
E-tug for narrow-body aircraft	Narrow-body	Technologically feasible now	100 % during taxiing
E-taxi for wide-body aircraft	Wide-body	2030	Up to 100 % during taxiing
Substituting auxiliary power unit (APU) use by fixed electric ground power (FEGP) and preconditioned air (PCA)	All market segments	Technologically feasible now; requires investment by airport	100 % while parked at gate or stand

Source: Compiled by authors based on information from Air Transport Analytics (Air Transport Analytics, 2018), EUROCONTROL (EUROCONTROL, 2021), Koudis, et al. (Koudis, Hu, Majumdar, Jones, & Stettler, 2017), Mototok (Mototok, n.d.) and Sustainable Aviation (Sustainable Aviation, 2018).

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[23] The term 'regional aircraft' is mostly applied to an aircraft with 50-120 seats, which is designed to be flown on short to medium-haul routes. Compared to larger single-aisle aircraft, they have fewer seats and less capacity in the hold, allowing them to be both smaller and lighter.

Developments in flight trajectory optimisation as part of the Single European Sky (SES) programme should enable aircraft to **cruise at optimum speed and altitude**. This will allow flights to be optimised for minimum fuel consumption and emissions, rather than needing to fit into fixed ATM requirements (EUROCONTROL, 2021). This will also necessitate improved management of flight departure and arrival times (using systems such as Airports collaborative decision-making, A-CDM) so that the flight can depart at the correct time to arrive at the target time while flying at the optimised speed. In principle, this approach could be implemented in the near future and has the potential to deliver average fuel consumption reductions of 9-11 % (EUROCONTROL, 2021).

The other operational improvements identified relate to the operation of the aircraft on the ground. Although the emissions from the aircraft on the ground may be small compared to those during the rest of the flight (particularly for long-haul flights), they can have significant impacts on local air quality. **Reduced take-off thrust** (using less than maximum engine thrust available) is very widely used already, with the thrust selected based on the actual aircraft weight, the available runway length for the specific flight and the runway surface/weather conditions. **Single-engine taxiing** (or reduced-engine-taxiing, as more than one engine may be used in a four-engine aircraft) reduces fuel consumption and emissions, while retaining sufficient thrust to taxi. Single-engine taxiing is also already widely used; remaining limitations to single-engine taxiing are a need to use both engines during ice or snow conditions, and limitations on specific aircraft types due to the operation of on-board systems.

Currently, all aircraft taxi (e.g. from the gate to the runway) are using the same engines that are used for flight. Electric-powered alternatives are under investigation. An electric powered 'tug' (or '**E-tug**') which can tow the aircraft from the gate to close to the runway (the aircraft still needs three to five minutes to start its own engines) has been developed, but remains suitable only for single-aisle (narrow-body) aircraft. For larger (twin-aisle or wide-body) aircraft, an '**E-taxi**' system is being considered, with electric motors in the aircraft's wheels to drive it, with the required electric power being generated by the on-board APU, a small gas turbine engine that runs using the same fuel as the main aircraft engines.

When aircraft are parked at gates or stands, they require power to run the on-board systems and to provide air conditioning for the crew and passengers. This power is often provided by the on-board APU. To reduce noise and emissions, larger airports may now limit the use of APUs at the gates or stands. To provide the necessary power, airports have invested in FEGP systems and PCA to provide the aircraft systems power and air-conditioning functions. The **substitution of APU by FEGP and PCA** can reduce aircraft energy consumption at the gate or stand by almost 100 % (aircraft need to have the APU running, as they arrive at the gate before the FEGP and PCA systems are connected, and also during pushback, prior to starting the main engines for departure).

Except for the E-tug and E-taxi, which are distinct approaches to removing the need to run the aircraft main engines during taxiing, the other operational measures can be combined and the overall energy reduction obtained as described in Section 3.2.1. However, those reductions should first be converted to reductions for the full flight, rather than just for the particular phase of flight in which they are used.

3.4. Sustainable aviation fuels (SAF)

One way to reduce GHG emissions of aviation is with the use of alternative fuels. This leads to a reduction in the emissions associated with energy consumption. The alternative fuels that have already been tested and may be available more widely in the near future (e.g. biofuels, electrofuels) are generally known as 'drop-in' fuels, as they can, in principle, be used in current aircraft with little or no modification. These fuels are chemically very similar to conventional fuel and have the same GHG emissions from the engine exhausts. The reductions in emissions are achieved through the absorption of atmospheric CO_2 during their production process. Alternatively, the use of a fuel that does not contain carbon (electricity, hydrogen, ammonia) would produce no CO_2 in the engine exhaust and the overall GHG emissions would be only those that occur during the production process.

3.4.1. Drop-in fuels

Table 3-6 summarises the drop-in fuels most likely to make a significant contribution. Research to identify further potential pathways for producing sustainable fuels is ongoing and additional options are likely to be certified in the future. For example, a recent online article (AINonline, 2022) suggests that at least 15 new pathways are in the pipeline towards certification.

Table 3-6: Summary of drop-in fuels

Technology	Market segment	Availability/ readiness	Emissions reduction
Hydroprocessed Esters and Fatty Acids - Synthetic Paraffinic Kerosene (HEFA-SPK)	All market segments	Already available in small quantities; 2030 for wide availability	0 % at engine exhaust. 63-90 % on lifecycle (or WTW) basis
Alcohol-to-Jet (AtJ)	All market segments	2030	0 % at engine exhaust. 45-66 % on WTW basis
Biomass gasification + Fischer-Tropsch (may also be produced with aromatic content)	All market segments	2030	0 % at engine exhaust. Up to 90 % on WTW basis
Electrofuel (synthetic kerosene)	All market segments	2030	0 % at engine exhaust. Up to 97 % on WTW basis

Source: Compiled by authors based on information from European Commission (European Commission, 2021i) and Nordic Energy (Nordic Energy, 2016).

The first three of these fuel types are advanced biofuels[24], with the main inputs, or 'feedstocks' to their production derived from organic matter. **Electrofuel, or synthetic kerosene**, is produced using 'green' hydrogen (obtained through hydrolysis of water using renewable energy) and CO_2 extracted from the atmosphere or captured from emissions from other industrial processes. Synthetic fuels can potentially deliver the highest GHG reductions (up to 97 % if produced using renewable energy), but remain expensive, as the production technology is not mature. These will require additional regulatory support to create a sufficient investment signal for the technology to develop. The ReFuelEU Aviation proposal addresses this through a sub-mandate for synthetic fuels (see Section 5.1.2.c).

Advanced biofuels, as well as the specific feedstocks within them, have different characteristics in terms of GHG reduction (on a WTW basis) and sustainable availability. The technology for refining some

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[24] As noted in the recast of the Renewable Energy Directive (RED II (Joint Research Centre, n.d.)), advanced biofuels are defined as those produced from the feedstocks listed in Annex IX, Part A of the RED II.

feedstocks into transport fuel is already mature (for HEFA-SPK-based jet fuel, particularly with used cooking oils, UCOs), and they are therefore a relatively cheap source of biofuels with good carbon savings. However, these feedstocks are already used in other sectors, including road transport, which therefore would need to find substitutes if the supply was diverted by demand from aviation. This can have unintended negative consequences. For example, EU-sourced supplies of UCOs are limited and an increase in demand would have to be met through increased production or import. Most UCOs used as jet fuel feedstock are already imported, and there are quality control concerns about whether the waste oils might be blended with virgin palm oil, the production of which may be linked to deforestation. A further concern is that UCOs might be used to meet most of the blending mandate up to 2030, which would hamper development of SAF based on advanced feedstocks. Some of these more advanced feedstocks have higher domestic EU availability and some have existing or alternative uses in other sectors. Others (mainly cellulosic and ligno-cellulosic wastes and residues) could provide high volumes sustainably without forcing substitution. However, the current biofuel production capacity for feedstocks such as cellulosic and ligno-cellulosic wastes is lower, and significant investment is needed to develop the supply chain.

3.4.2. Non-drop-in fuels

Table 3-7 summarises the non-drop-in fuels/energy carriers.

Table 3-7: Summary of non-drop-in fuels/energy carriers

Technology	Market segment	Availability /readiness	Emissions reduction
Hydrogen fuel (sustainable, 'green' hydrogen)	All market segments	2030 to 2035 for small aircraft; 2035 to 2040 for larger types	100 % at engine exhaust On a WTW basis, about 64 % in 2030[25], reaching up to 100 % by 2050
Electricity	Short-range, narrow-body	2030 to 2040	100 % at engine exhaust On a WTW basis, about 64 % in 2030, reaching up to 100 % by 2050[26]

Source: Compiled by authors based on information from Clean Sky (Clean Sky, 2020), Mukhopadhaya & Rutherford (Mukhopadhaya & Rutherford, 2022) and Schäfer, et al. (Schäfer, et al., 2018).

Both of these energy carriers give zero emissions at the engine exhaust (if the aircraft still uses engines for power, rather than electric motors); the overall WTW emissions savings then depend on the pathway used to produce the hydrogen or electricity. The most recent data from the European Environment Agency puts the average GHG emissions from the EU electric grid in 2020 at 230.7 gCO_2e/kWh, with the expectation that it will reduce to between 110 and 118 gCO_2e/kWh by 2030. Unlike the drop-in fuels, hydrogen and electricity are not compatible with existing aircraft designs and significantly new aircraft technologies will be required to use them.

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[25] Estimate for 2030 derived from EEA projections (European Environment Agency, 2021). Assumed fully renewable electricity by 2050.

[26] With hydrogen produced by electrolysis of water, the WTW emissions are essentially those associated with the electricity consumption during its production, therefore it is assumed that the carbon intensities of the two energy carriers are the same for this analysis. A feasible option for the production of hydrogen for aviation use is to locate the electrolysers in or close to airports, thus eliminating emissions associated with the transport of the hydrogen fuel.

Although a number of companies are currently developing prototype electric and hydrogen-fuelled aircraft (see Section 3.2.3), there is considerable uncertainty about likely availability of aircraft using these fuels on a large-scale basis. Both fuels are listed in Table 3-7 as being available by 2030; however, the initial applications are expected to be for small, short-range aircraft that have only very small contributions to emissions. There is significantly greater uncertainty about the availability of zero-emission options for the larger, medium-range aircraft that have a much greater contribution to the overall emissions.

3.5. Conclusions

This chapter presented a range of developing technologies that have the potential to contribute to the decarbonisation of aviation by 2050.

The aviation industry continues to pursue improvements in aircraft (and engine) efficiency. These improvements can reduce emissions and, through reduced fuel consumption, offset the increase in fuel costs that would otherwise occur because of the higher prices of alternative fuels. The development of unconventional configurations, particularly BWB, appears to have the greatest potential in aircraft efficiency improvements (up to 30 % reduction in fuel consumption and CO_2 emissions), but also requires the greatest efforts in technology development and in integration in the aviation infrastructure, and ensuring that the public are willing to travel in such a wide cabin (namely because some passengers will be much further away from a window than in current aircraft).

Improvements in aircraft aerodynamics and structures are more evolutionary in nature and likely to appear more widely as new aircraft types are developed. Composite materials are already incorporated into several aircraft types and are likely to be used for more structural elements and on more aircraft types in the future. Hybrid laminar flow technology has been implemented on some existing aircraft and further development is likely to lead to its use on a greater portion of the aircraft surface and on more aircraft types. These evolutionary technologies may deliver reductions in CO_2 emissions of up to 15 %.

Propulsion system technologies have a role to play in improving efficiency. Evolutionary technologies, such as increases in BPRs and OPRs, will continue to be implemented as manufacturers develop improved designs and materials. Geared-fan engines, already available for the single-aisle market, are likely to be adapted for the larger, twin-aisle market. The open rotor engine offers more of a revolutionary change. Although in development for several years, a renewed interest in its potential for improved efficiency may lead to its adoption in the medium term. Its integration issues, however, mean it is likely to be restricted to use on medium haul, single-aisle aircraft. Individual improvements in propulsion system technologies may give reductions of up to 20 % in CO_2 emissions.

The other key propulsion system technologies in development are those associated with the use of non-drop-in, zero-carbon fuels (electricity and hydrogen). These may appear within the next 10 years, but will initially be restricted to small, short-range aircraft, because of energy density issues. Their use on larger, longer-range aircraft is likely to take significant extra development and is unlikely before 2040.

The potential for short-term widespread adoption of significant technology changes on aircraft is limited, as the main aircraft manufacturers (Airbus and Boeing) have introduced new or upgraded aircraft types in each market segment, pushing the incorporation of advanced technologies in completely new aircraft types several years into the future.

A further set of technologies considered are those associated with operational measures, including during flight and ground operations. Within Europe, improvements in flight efficiency through optimisation of aircraft speed and altitude are part of the SES programme (with research conducted under the SES Air traffic management research (SESAR) programme), and continued development of this programme will continue to bring benefits. The increased airspace congestion that will result from growing demand will require airspace improvements. The technologies identified for improving ground operations are typically already available and their wider adoption depends on the balance between their costs and perceived benefits. The exceptions are the electric taxiing systems. To date, the limited adoption of E-tug systems for narrow-body aircraft indicates that the costs, and potentially challenges of integrating with other airport operations, are perceived as outweighing the benefits, while further development and demonstration of on-board E-taxi systems is needed to encourage manufacturers to make them available on the aircraft they produce.

In the long-term, a transition to alternative fuels - particularly green electricity and hydrogen - offer the potential for flights without CO_2 emissions. However, these fuels will require significant changes to aircraft systems. In the shorter term, these options will only be applicable to small aircraft with short ranges. In the interim, the most promising solution is to increase the use of high energy density liquid fuels, known as SAF. SAF deliver overall emissions savings through the absorption of CO_2 from the atmosphere or from waste emissions during their production rather than through reductions in engine exhaust emissions.

Currently, the availability of feedstock and the production cost are limiting barriers to increasing the uptake of SAF. To maximise the production potential for SAF, different pathways will be required, with different feedstocks and production processes. Some pathways have already been certified for blending with conventional kerosene while others are in development. All SAF pathways have blend limits of 50 % or less, but engine manufacturers are testing to push those limits to 100 % (i.e. only SAF would be used, with no fossil kerosene in the mix). The greatest challenge to the widespread adoption of SAF is scaling-up production facilities to produce the fuel at reasonable cost.

4. INVESTMENTS NEEDED TO ACHIEVE DECARBONISATION

KEY FINDINGS

- To develop the technologies described in this report will require investment of EUR 50 billion by 2040.
- The additional costs of purchasing aircraft equipped with these technologies are significantly higher than the development costs, at EUR 378 billion.
- Despite the higher prices for the alternative fuels, at least in the short to medium term, the significant reductions in energy consumption arising from the technologies will substantially reduce fuel costs compared to the baseline. The total fuel cost reduction to 2050 is EUR 395 billion.
- The balance between the different cost elements results in an increase in total costs to 2050 of EUR 33 billion.

Chapter 3 described the new technologies and operational measures that could be implemented to help aviation to meet the requirements of the European Green Deal. The inclusion of these technologies implies additional development costs, which are likely to be borne by the EU and Member States combined (through research programme funding) and manufacturers (through participation in research programmes and their own in-house R&D efforts). There are also likely to be additional costs for airlines in acquiring aircraft equipped with the new technologies[27]. Some of these costs may be passed on to citizens as consumers. This chapter presents estimates of the additional costs that will be incurred in adopting these technologies and operations measures, relative to the baseline scenario[28].

4.1. Cost methodology

This section gives a brief overview of the methodology used to estimate the costs to adopt these technologies (see Annex A3 for further details).

Most of the technologies described in Chapter 3 lack detailed information on their development and purchase costs, and on the implications of aircraft purchase costs, given their rapidly evolving nature. Where insufficient public information was available, the following approach was used to create estimates:

1. Development costs
    - The total funding of the Clean Sky, Clean Sky 2 and Clean Aviation programmes were combined. These programmes develop (some of) the technologies described in Section 3.
    - The overall energy consumption reduction of all technologies supported by these three programmes was calculated (see Annex A3.1).

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[27] Alternatively, the additional acquisition costs may be borne by aircraft leasing companies, which will expect to recover these costs through higher leasing rates.

[28] Recalling that the baseline scenario is based on the energy consumption for the aviation sector from the European Commission's Reference 2020 scenario (see Section 2).

  - The 'average development cost per % improvement' was calculated by dividing the total funding of the three programmes by the combined percentage energy consumption reduction of all technologies[29].
  - The development cost for a given technology was estimated by multiplying the calculated 'average development cost per % improvement' by the percentage energy consumption reduction for the particular technology.

2. Additional purchase costs
   - It was assumed that the development cost of a new technology would be recouped over a production run of 100 aircraft (i.e. assumed break-even point for a manufacturer[30]).

Consultation with stakeholders confirmed that in the absence of more detailed information on development and additional purchase costs, this approach gave reasonable estimates. However, it was noted that the Clean Sky, Clean Sky 2 and Clean Aviation programmes support the development of technologies up to technology readiness level (TRL) 6 or 7[31]. Therefore, the estimated development costs presented here should be considered those necessary to be supported through major research programmes (with EU and/or Member State funds). The additional development costs to take a new technology through to a new aircraft type are typically borne by the manufacturer and are both very uncertain and – usually – significantly higher. These additional manufacturer costs are not included in this analysis.

4.2. Development costs

The overall development costs were calculated by assuming that the costs for each technology are spread evenly over the period from 2020 to the entry-into-service date for the technology. All technologies that have been identified in this study are expected to be developed sufficiently for inclusion in new aircraft designs by 2040; as a result, no development costs are incurred after 2040. An exception is the production capability for SAF, where further details of the spread of investment over time (including continued investment in new production facilities) are available from the ReFuelEU aviation study[32] (European Commission, 2021i). That study derived estimated capital investments in new SAF production plants based on the forecast consumption of such fuels and presented them as average annual costs over 10-year periods (see Figure 4 in the impact assessment accompanying the proposal). The resulting development cost profiles are shown in Figure 4-1.

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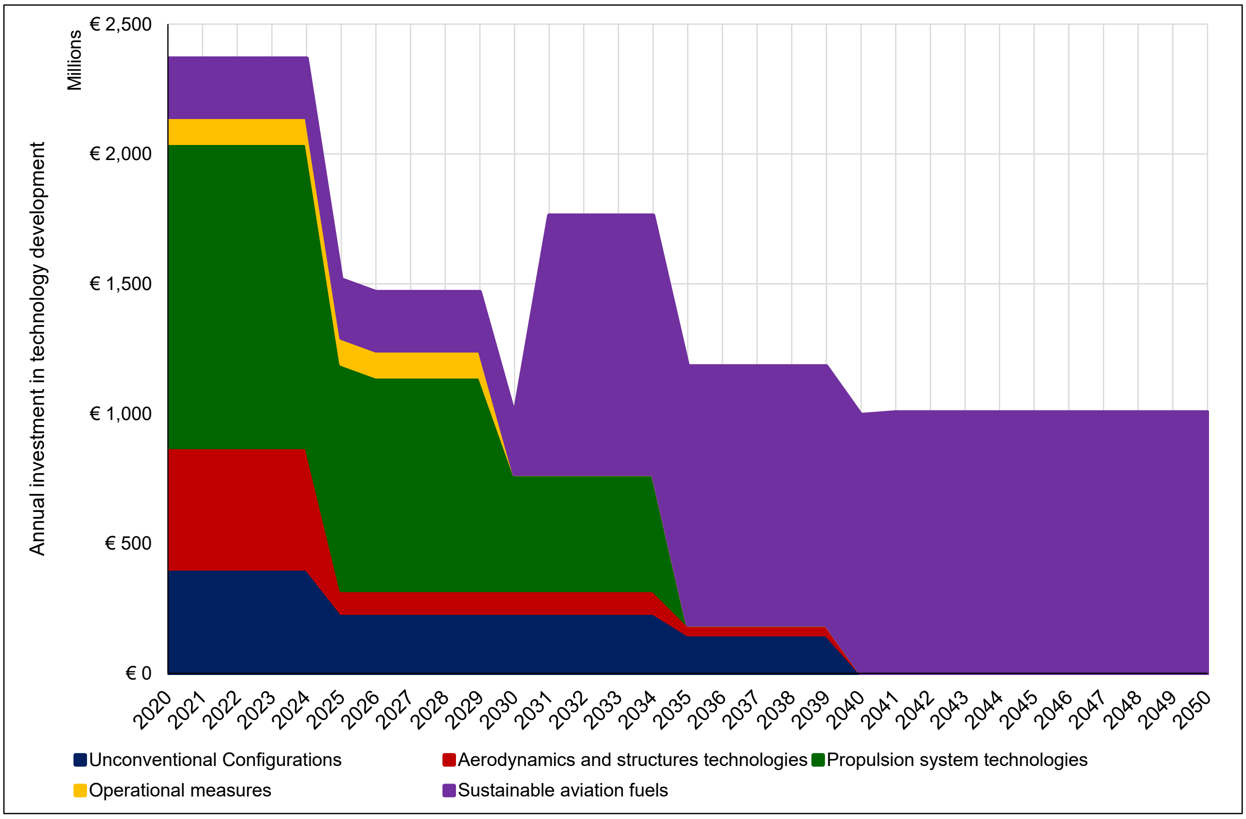
[29] The calculated value was EUR 117 278 000 per % reduction in energy consumption.

[30] The actual number of aircraft required to be sold for a manufacturer to break even on the programme depends on many factors, including the state of the market place and the discounts the manufacturer must offer to airlines. Our assumption of 100 aircraft for modelling purposes may be optimistic according to https://simpleflying.com/airbus-a350-break-even/

[31] 'Technology demonstrated in relevant environment (industrially relevant environment in the case of key enabling technologies)' and 'System prototype demonstration in operational environment', respectively; Annex A2 provides further information on the TRL scale.

[32] On 7 July 2022, the European Parliament adopted its position on new draft legislation for a SAF mandate throughout the EU. However, in doing so, the Parliament implemented significantly increased requirements, reaching 85% minimum percentage of SAF by 2050, compared to the 63% in the Commission's proposal. **All analyses in this report are based on the initial proposal from the Commission.**

Figure 4-1: Annual cost profiles for technology developments



Source: Compiled by authors based on information on technology development costs from the sources noted in Annex A2 or as described in Section 4.1.

The technologies included in these costs are currently in development, with the highest costs occurring in the early years, diminishing over time as the technologies reach production status. The largest single element of the technology development costs in the years up to 2030 is propulsion system technologies. These costs are driven by the continued development of technology for engines using conventional and drop-in fuels, in parallel with the development of electric and hydrogen-fuelled propulsion systems.

The main aerodynamics and structural technologies are expected to enter service in the next decade, with the development costs diminishing significantly in that time. By contrast, the development costs for unconventional configurations continue up to 2040 as they are not expected to enter service until then.

The total costs for the development of operational measures is relatively small, at approximately EUR 1.6 billion. This relates to the development of the capability for aircraft to fly at the optimum speed and altitude (and flight path), which is covered by the developments under the SESAR programme to 2031. The value is a close match to the total budget for SESAR from 2021 to 2031 (under the Horizon Europe programme) of approximately EUR 1.6 billion, of which EUR 600 million is provided by public funding (Horizon Europe) (see Section 5.2.1 for further details).

The nature of the development costs calculated for SAF is somewhat different, as the development and scaling-up of production capacity is the main cost driver. SAF development costs therefore continue further into the future, as the required production capacity continues to increase, and they ramp up substantially after 2030, leading to them becoming the largest single element of the total development costs to 2050.

The present value (PV[33]) for the total development investment can be calculated for different discount rates, with values to 2050 discounted to 2020[34], as shown in Table 4-1.

Table 4-1: PV for total technology development costs to 2050, under various discount rates

Discount rate	PV (EUR billion)
0 %	-EUR 50.4
3 %	-EUR 36.4
6 %	-EUR 28.1
9 %	-EUR 22.9

Source: Calculations of PV at different discount rates from the time histories of costs shown in Figure 4-1

The simple total of all development costs to 2050 is EUR 50.4 billion. Taking account the time value of money, using discount rates that may be appropriate to different stakeholder groups, values the total investment to between EUR 36.4 billion (3 % discount rate, appropriate to governments and specified by the Better Regulation Guidelines for impact assessments) and EUR 22.9 billion (9 % discount rate, appropriate to manufacturers).

These development costs are relevant for pre-competitive R&D activities that may be funded (at least in part) by the EU. They do not include the additional costs to industry to develop and certify the new aircraft types including these technologies. In addition, these costs reflect the European sector only. It is expected that industry (with government support) in other world regions (particularly North America, but also in the growing aviation industry in China, for example) will also invest in developing similar technologies that might subsequently be used on European flights.

4.3. Additional purchase costs

To estimate the costs to the airline industry to purchase aircraft equipped with the new technologies described in Chapter 3[35], the total European aircraft fleet operating in 2050 was estimated based on growing the existing fleet in line with the increase in transport demand[36]. The age profile of the fleet in 2050 (percentage of the fleet of a given age) was assumed to be the same as today[37], allowing calculation of the number of aircraft fitted with each technology[38]. These calculations were performed separately for the turboprop, regional jet, narrow-body jet and wide-body jet aircraft categories to allow for applicability of the various technologies. The number of relevant aircraft delivered each year following entry into service of the technology was then multiplied by the identified additional purchase

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[33] PV is an accounting method used to determine the current value of future costs and income, using different 'discount rates' to represent different views on the time value of money. For impact assessments, the European Commission's 'Better Regulation Toolbox' (Tool #61) recommends a discount rate of 4 %. Commercial organisations, whose performance may be measured in monetary terms, may choose a significantly higher discount rate, e.g. 9 % or 10 %. The four discount rates (including zero) used for the calculations of PV shown in Table 4-1, and other tables in this report, were selected to provide an even spread across a range covering no discount, a government perspective, a commercial perspective and an intermediate point of 6 %, selected by the authors to illustrate how PV varies with discount rate.

[34] The PV is calculated with costs discounted to 2020, rather than the present day, as that is the base year used here and, therefore, the analysis includes costs between 2020 and now.

[35] Covering unconventional configurations, aerodynamics and structures technologies, propulsion systems technologies, operational measures and alternative fuels and energy carriers; see Table 3-1 to Table 3-5 for more details..

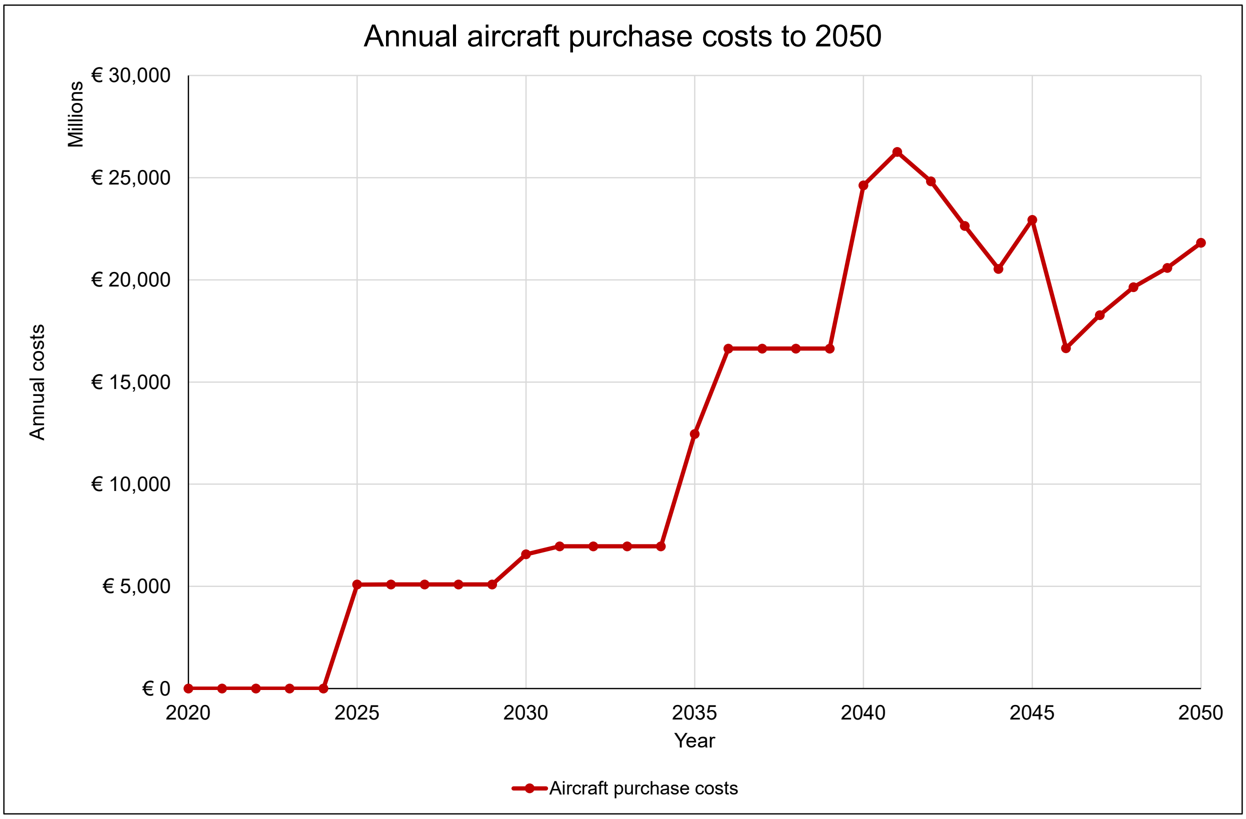
[36] Assuming a constant aircraft utilisation in passenger-km per year.

[37] Data for the age profile of the current fleet were obtained from Eurostat (Commercial aircraft fleet by age of aircraft and country of operator).

[38] Number of aircraft fitted with a technology were calculated from the number of aircraft delivered after the entry into service of the relevant technology, factored to allow for the fraction of deliveries likely to be fitted with the technology.

cost for the technology, to give an overall additional purchase cost, as shown in Figure 4-2. Further details of the methodology for calculating the additional purchase costs are given in Annex A3.2.

Figure 4-2: Additional aircraft purchase costs due to inclusion of new technologies to 2050



Source: Compiled by authors based on information from range of sources as described in Annex A3. Values presented are annual costs (undiscounted).

The PV for these additional costs can also be calculated for different discount rates, as shown in Table 4-2.

Table 4-2: Present values for total additional purchase costs to 2050, under various discount rates

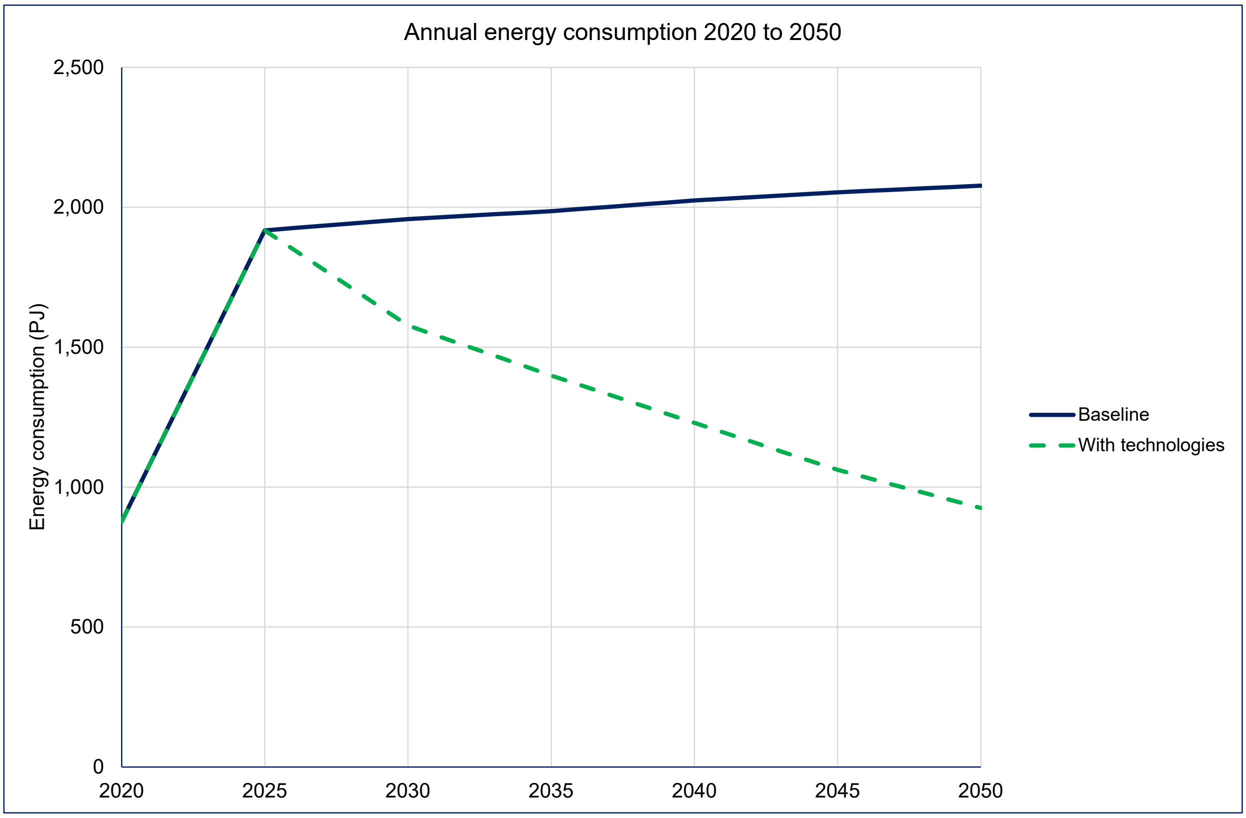
Discount rate	PV (EUR billion)
0 %	-EUR 377.6
3 %	-EUR 208.0
6 %	-EUR 120.9
9 %	-EUR 74.0

Source: PV calculation using various discount rates applied to annual costs shown in Figure 4-2.

4.4. Fuel consumption and emissions to 2050

The age profile of the fleet in future years and the years that aircraft entered service enabled an estimation of the proportion of the fleet incorporating the different technologies. A baseline (no new technology improvements) energy consumption profile was obtained by using the energy consumption for the aviation sectors (domestic and international) from the Reference 2020 scenario. The energy and emissions reductions associated with each technology were applied to the baseline to derive the energy and emissions in future years. Figure 4-3 shows the overall impact of the different technologies on fleet energy consumption.

Figure 4-3: Evolution of annual energy consumption under 'baseline' and 'with technologies' scenarios



Source: compiled by authors using demand data from the 2020 Reference Scenario (see Chapter 2) energy consumption data from the MIX scenario and energy efficiency reductions from technologies described in Chapter 3.

The annual energy consumption rises significantly between 2020 and 2025, representing the recovery from the impacts of the COVID-19 pandemic (see emissions in Figure 2-1 and Figure 2-2). Subsequently, the energy consumption rises gradually to 2050 under the baseline scenario. In the case with the technologies, the energy consumption peaks in 2025, then reduces towards 2050, by which point the energy consumption is 55 % lower than in the baseline case.

This energy consumption under the 'with technologies' case was converted to fuel consumption for the four identified drop-in alternative fuels[39] (three different biofuels plus electrofuels[40]) by 2050, using the percentage blends proposed as mandated in the ReFuelEU Aviation proposal (European Commission, 2021i).

The consumption of electricity and hydrogen was calculated using the percentages of the operating fleet in future years using these energy sources, based on the number of aircraft delivered following their initial availability and the assumed applicability of the technology to different aircraft categories, as described in Annex A3.3.

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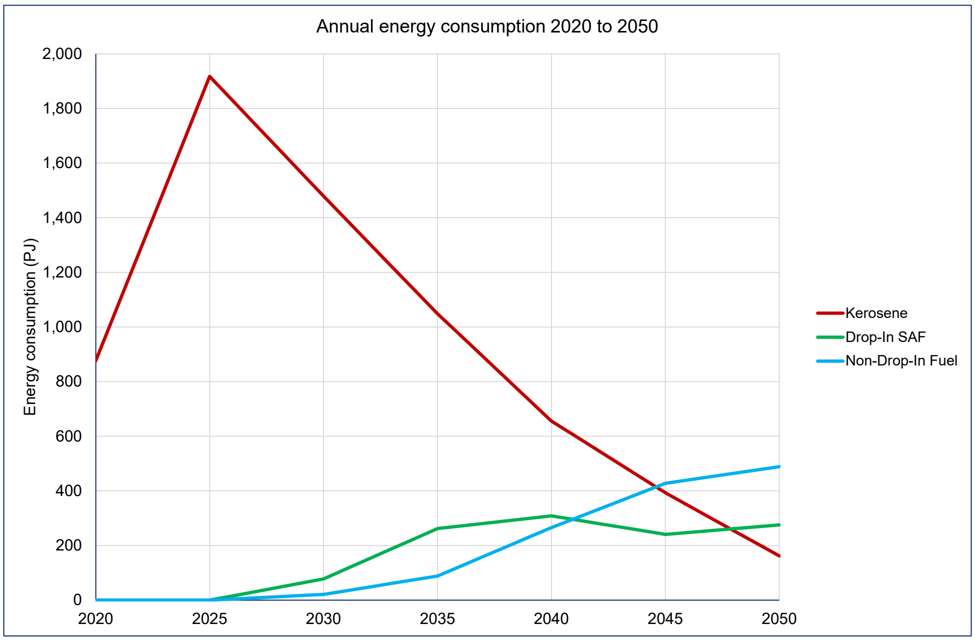
[39] HEFA-SPK, AtJ, Biomass gasification + Fischer-Tropsch (may also be produced with aromatic content), electrofuel (synthetic kerosene). Further information on drop-in fuels is given in Table 3-6 in Section 3.4.1

[40] The ReFuelEU Aviation proposal includes a separate blend percentage for electrofuels (28 %) contained within the 63 % overall SAF mandate in 2050. To derive the split of fuel consumption across the different drop-in fuels, this specific percentage was used for electrofuels; the remaining demand for (biofuel-based) SAF was distributed across the other three drop-in fuels in line with the splits presented in the ReFuelEU Aviation study.

Figure 4-4 shows the energy consumption to 2050 under the 'with technologies' scenario, split between conventional kerosene, drop-in alternative fuels and non-drop-in fuels (electricity and hydrogen).

Figure 4-4: Evolution of annual energy consumption to 2050, 'with technologies' scenario, split by conventional fuel, drop-in and non-drop-in alternative fuels



Source: Evaluation by authors, using total energy consumption shown in Figure 4-3, the blend percentages for drop-in fuels from the ReFuelEU Aviation study (see footnote 40) and the assumptions for the penetration of aircraft using electricity and hydrogen, as described in Annex A3.3.

Figure 4-5 and Figure 4-7 explore these calculations further. Figure 4-5 shows the calculated energy consumed by the different market segments across all the different fuels used in 2050. The total energy consumed is 9.26 x 10^8 GJ (926 PJ), approximately 58 % lower than the case without the energy efficiency technologies included in the analysis. The narrow-body and wide-body jets have the greatest shares of the total energy consumption (35 % and 41 %, respectively). In terms of fuels, liquefied hydrogen (LH2) has the greatest consumption, as it is used by the majority of the wide-body jet fleet. Electricity is used only by a single market segment, turboprops.

Aircraft market segment categories

The results of the analysis are split into four aircraft market segments:

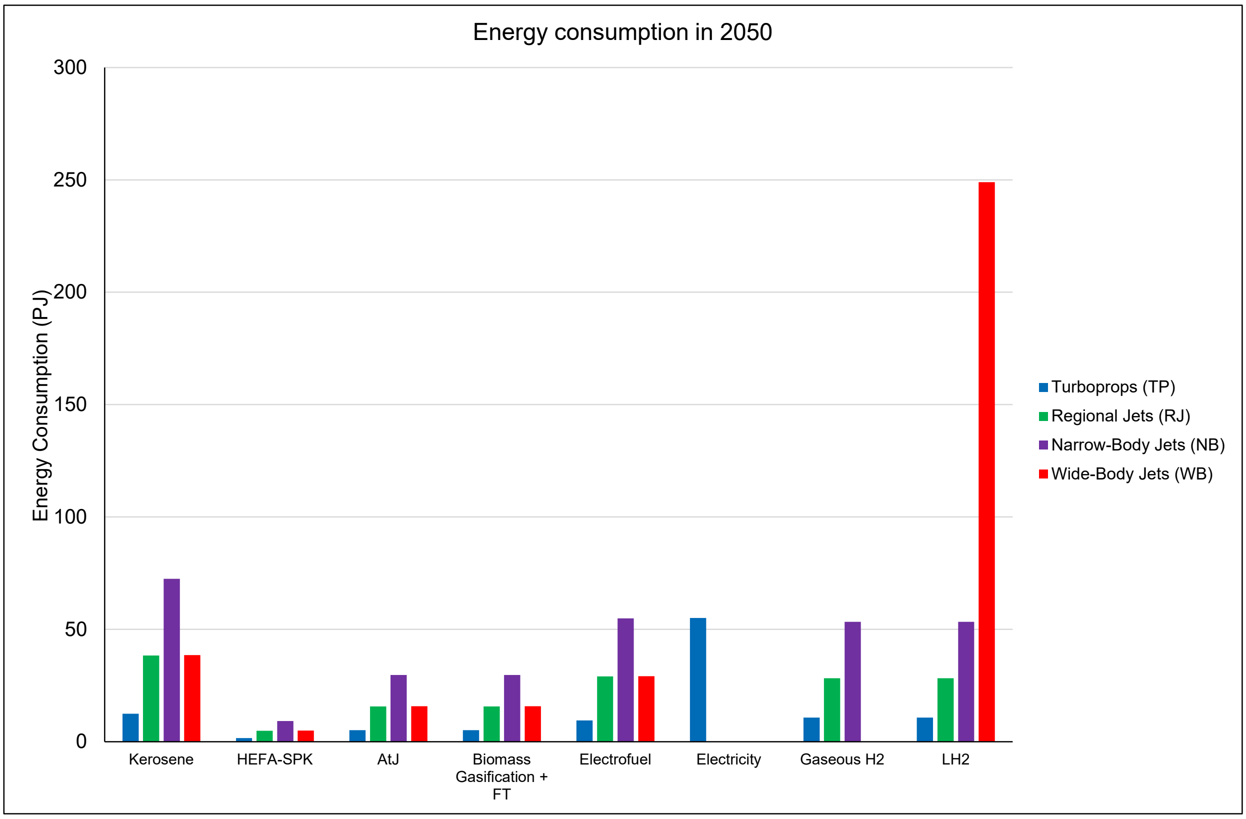
Turboprops – propeller-driven aircraft used for short-haul flights. Examples include the ATR ATR-72 and the Bombardier (now De-Havilland Canada) DHC-8 Q400.

Regional jets – jet aircraft with up to 130 seats, used primarily on short-haul to medium-haul routes. Examples include the Airbus A220 and the Embraer E-190E2.

Narrow-body jets – medium-sized aircraft with a single-aisle down the cabin with seats either side, used primarily on medium-haul routes. Examples include the Airbus A320neo and the Boeing 737-8.

Wide-body jets – larger aircraft with two aisles through the cabin, used primarily on long-haul routes. Examples include the Airbus A350 and Boeing 787-9.

Figure 4-5: Energy consumption in 2050, by fuel (energy carrier) type and market segment



Source: Compiled by authors using total energy consumption for 2050 shown in Figure 4-4, the blend percentages for drop-in fuels from the ReFuelEU Aviation study (European Commission, 2021i) and the assumptions for the penetration of aircraft using electricity and hydrogen, as described in Annex A3.3.

Table 4-3 shows the resulting total consumption by fuel type in 2050.

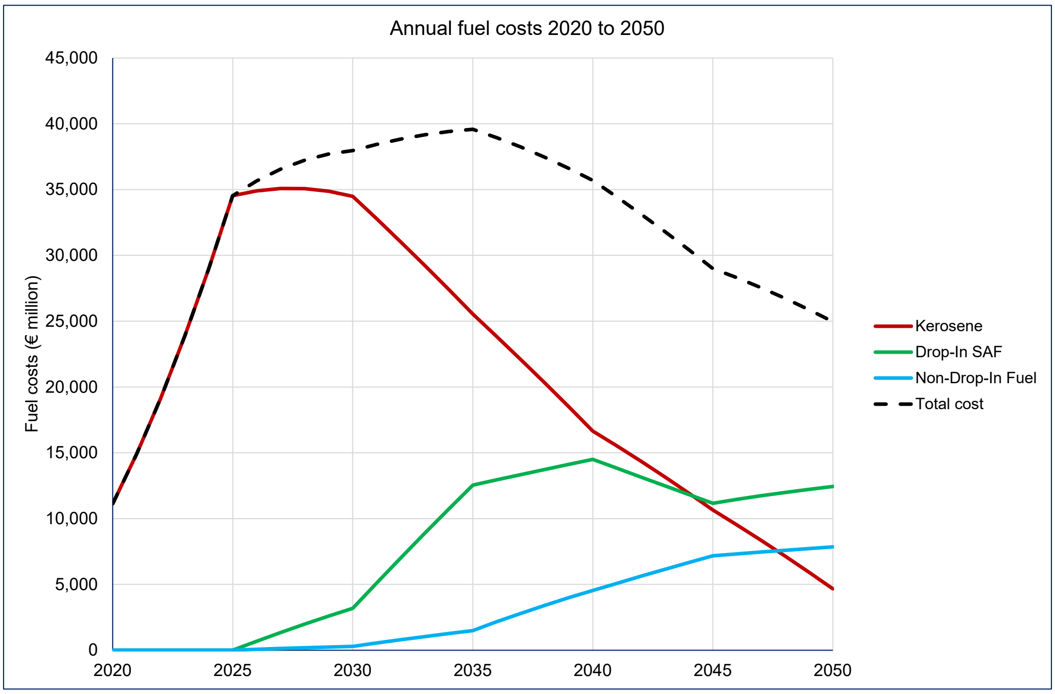
Table 4-3: Total consumption, by fuel type, 2050

Fuel type	Energy consumption (PetaJoules)	Fuel consumption (MT)
Kerosene	161.7	3.73
HEFA-SPK	20.5	0.47
AtJ	66.2	1.53
Biomass gasification + FT	66.2	1.53
Electrofuels	122.4	2.83
Electricity	55.0	N/A
Gaseous hydrogen	92.3	0.77
LH2	341.2	2.84
Total	**925.6**	**13.70**

Source: Evaluation by authors using the energy consumption shown in Figure 4-4.

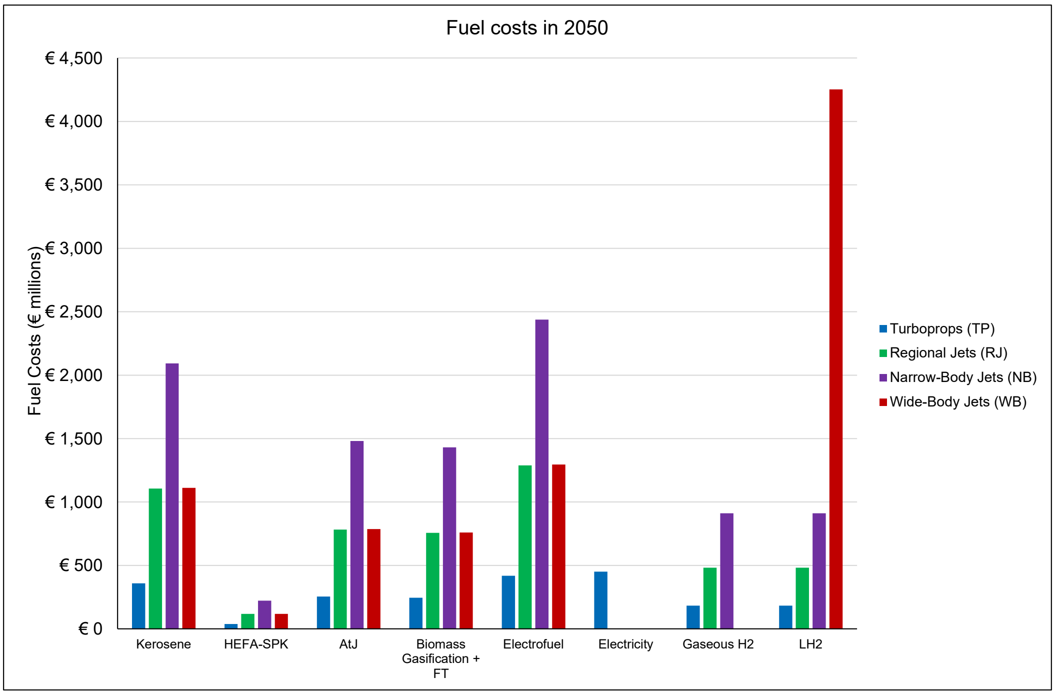
These fuel consumption values were converted to total fuel costs. The prices for most of the fuel types were obtained from the ReFuelEU aviation study (European Commission, 2021i), while those for electricity and hydrogen were obtained from a Ricardo study on decarbonisation options for the maritime sector (Ricardo, 2022). The resulting fuel costs from 2020 to 2050 are shown, by generic fuel type in Figure 4-6, with more detailed results for 2050, including fuel type and market segment, in Figure 4-7.

Figure 4-6: Evolution of annual fuel costs to 2050, split by conventional kerosene, drop-in alternative and non-drop-in fuel types



Source: Authors' evaluation using fuel consumption data from Figure 4-4 and fuel price data from ReFuelEU Aviation study (European Commission, 2021i) and Ricardo maritime decarbonisation (Ricardo, 2022) studies.

Figure 4-7: Fuel costs in 2050, by fuel (energy carrier) type and market segment



Source: Authors' evaluation using fuel consumption data from Figure 4-4 and fuel price data from ReFuelEU Aviation study (European Commission, 2021i) and Ricardo maritime decarbonisation (Ricardo, 2022) studies.

The reductions in energy consumption after 2025 lead to a peak in costs for conventional fuel by 2030. The costs of drop-in fuels increase from 2025, with those for non-drop-in fuels increasing from 2030, leading to a peak in total fuel costs in 2035 (Figure 4-6).

The total fuel cost in 2050, including all fuel types and aircraft categories shown in Figure 4-7, is approximately EUR 25 billion. Improved efficiency due to the technologies included in the fleet means that this is about 58 % lower than under a scenario without any additional technology (and using only fossil kerosene), even though the drop-in sustainable fuels are more expensive than fossil kerosene (the gap decreases substantially towards 2050[41]; the exemption for sustainable fuels under the EU ETS, and the expected increases in allowance prices, will also contribute to a closing of the gap in effective prices). As expected, given the energy consumption shown in Figure 4-5, hydrogen has the greatest portion of the total fuel cost, at about 30 % (adding the costs for gaseous and LH2 and dividing by total costs for all fuels). Electrofuels and fossil kerosene represent the next highest costs, at 22 % and 19 %, respectively.

The full effects of the introduction of technologies and alternative fuels on fuel costs have been calculated to 2050 as the difference from the costs under the baseline scenario without the additional technologies and assuming the use of only fossil kerosene[42]. Given the reduction in total energy consumption relative to the baseline (as shown in Figure 4-3), the costs with the technologies are lower than those without, so the net change in costs is negative. The full change in costs of fuel between 2020 and 2050 are shown in Table 4-4, again as PV discounted to 2020.

Table 4-4: PV for total savings in fuel costs to 2050, under various discount rates

Discount rate	PV (EUR billion)
0 %	+EUR 395.0
3 %	+EUR 206.3
6 %	+EUR 113.6
9 %	+EUR 65.9

Source: PV calculation using various discount rates applied to annual costs shown in Figure 4-6 and similar calculations for the baseline case.

4.5. CO_2 emissions

The emissions from aircraft in 2050 were calculated using the energy consumption by fuel type, shown in Table 4-3, together with assumed values for the emissions factors. For conventional kerosene, the values of 0.072 $kgCO_2/MJ$ (TTW) and 0.089 $kgCO_2/MJ$ (WTW) specified in ICAO Annex 16 Volume IV were used. For the other fuel types, the emissions reductions presented in Table 3-6 and Table 3-7 were applied to the values for conventional kerosene (where a range of reductions is given in Table 3-6, the mid-point of the range was applied). The calculated total CO_2 emissions for 2050, including both TTW and WTW, based on the fuel consumption results shown in Figure 4-5, are shown in Figure 4-8.

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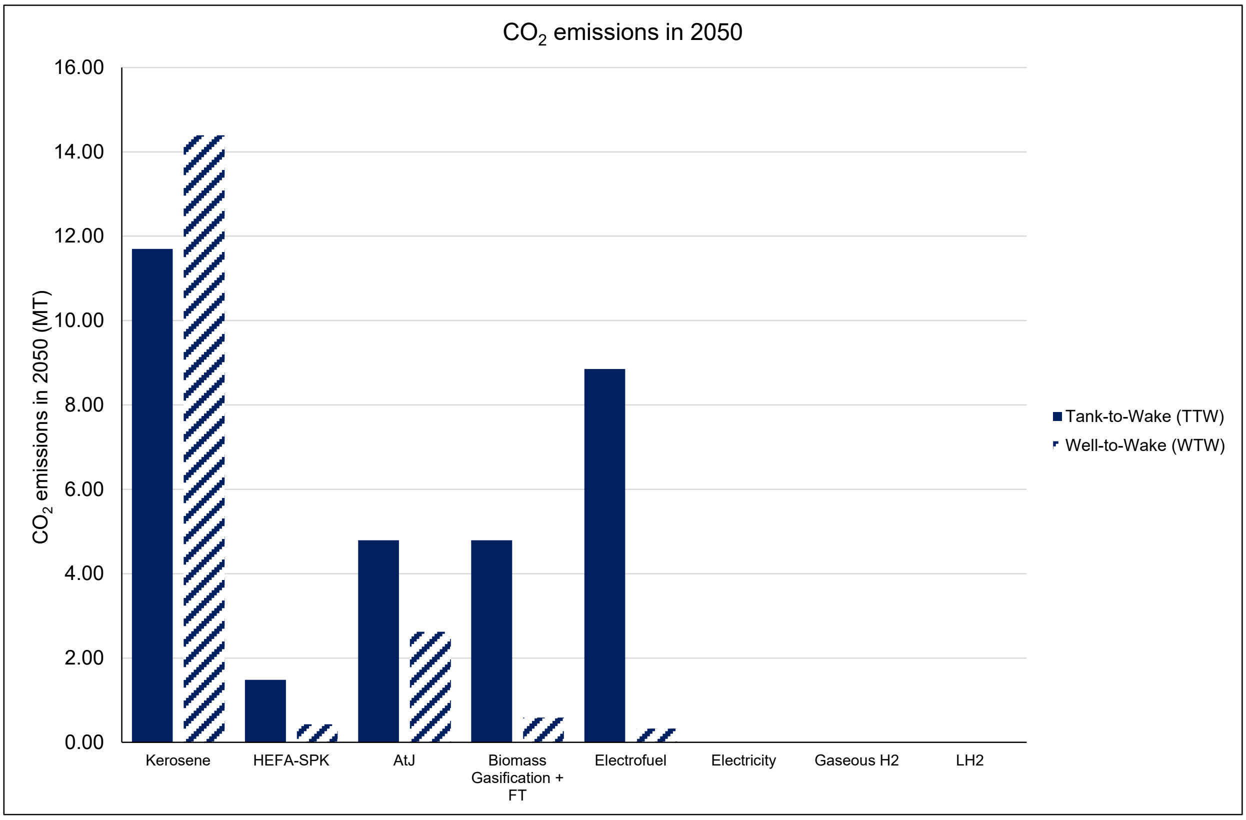
[41] In 2050, in a case without alternative fuels (solely fossil kerosene), but with the fuel efficiency technologies discussed, the fuel costs would be about EUR 27 billion, approximately 55 % lower than the baseline scenario.

[42] To simplify the analysis, the % penetration of each fuel (in the total energy demand) was calculated as a linear variation between the initial availability and the % use in 2050 as shown in Table 4-3.

Figure 4-8: CO_2 emissions calculations for 2050



Source: Authors' calculations using energy consumption from Table 4-3 and emissions factors from ICAO Annex 16 Volume IV.

For fossil kerosene, the WTW emissions are higher than the TTW emissions, as the former include the emissions during the production process, as well as those in the engine exhaust. For the other drop-in fuels, however, the production process includes the absorption of CO_2 from the atmosphere (either through direct capture, as in the case of electrofuel, or during the growth of the feedstock plants for biofuels). As a result, the WTW emissions are lower than the TTW emissions. The calculations for electricity and hydrogen in Figure 4-8 assume that sufficient renewable electricity is available for their production by 2050, leading to zero WTW emissions (TTW emissions are zero because they do not contain carbon). This assumption is significant when considering the high levels of hydrogen consumption shown in the preceding charts.

The total WTW emissions in Figure 4-8 is 18.4 MT, compared to the value from the MIX scenario for aviation in 2050 of 49.1 MT (see Figure 2-1). Based on the entry-into-service dates for the different technologies, and the associated reductions in energy consumption and emissions (see Sections 3.2 to 3.4), the WTW emissions in 2050 are comfortably within the targets needed to deliver the European Green Deal.

To provide additional insight into the impacts of the different measures, the total TTW and WTW emissions have been calculated taking account of the effects of the additional technologies (including operational measures), as well as together with the reductions from alternative fuels. These totals are compared to the baseline emissions in Table 4-5.

Table 4-5: Effects of technologies and alternative fuels on emissions in 2050

	Tank-to-wake (TTW) emissions (MT)	Well-to-wake (WTW) emissions (MT)	Change in WTW emissions relative to baseline[43]
Baseline	150.2	184.8	
With technologies	67.0	82.4	-55.4 %
With technologies and alternative fuels	31.6	18.4	-90.1 %

Source: Authors' calculations using demand data from the 2020 Reference Scenario, energy consumption data from the MIX scenario, energy efficiency assumptions for technologies and emissions factors from ICAO Annex 16 Volume IV.

Although, as noted above, the combination of the technologies and alternative fuels comfortably meets the requirements of the European Green Deal by 2050, the WTW emissions with the technologies and operational measures alone (82.4 MT) still exceed the target of 49.1 MT.

4.6. Electric and hydrogen-fuelled aircraft sensitivity analysis

Section 3.2.3 described the propulsion system technologies identified for future aircraft, including estimated entry-into-service dates for electric and hydrogen-fuelled aircraft (see Table 3-3). These entry-into-service dates are uncertain, given the need for new aircraft designs (as well as new propulsion systems), the expected limited size and range of the initial applications and the need for additional airport infrastructure for recharging/refuelling. The dates were derived from the literature, and represent the earliest dates that such technologies may enter service. The results presented in Section 4.4 show that these assumed entry-into-service dates lead to a large percentage of the total energy consumed by aviation in 2050 being for hydrogen fuel. This section considers the effects of the uncertainty associated with these technologies by assuming some delays to their entry into service.

Table 4-6 shows the technologies considered and the changes to the entry-into-service dates for this analysis.

Table 4-6: Entry-into-service dates for electric and hydrogen-fuelled aircraft under main and sensitivity analyses

Technology	Main analysis	Sensitivity analysis
Full electric propeller-driven aircraft	2030	2035
Hydrogen-fuelled gas turbine engine	2030	2040
Hydrogen fuel cell plus electric power for turboprop	2035	2040
Hydrogen fuel cell plus electric powered fans for jet propulsion	2035	2040

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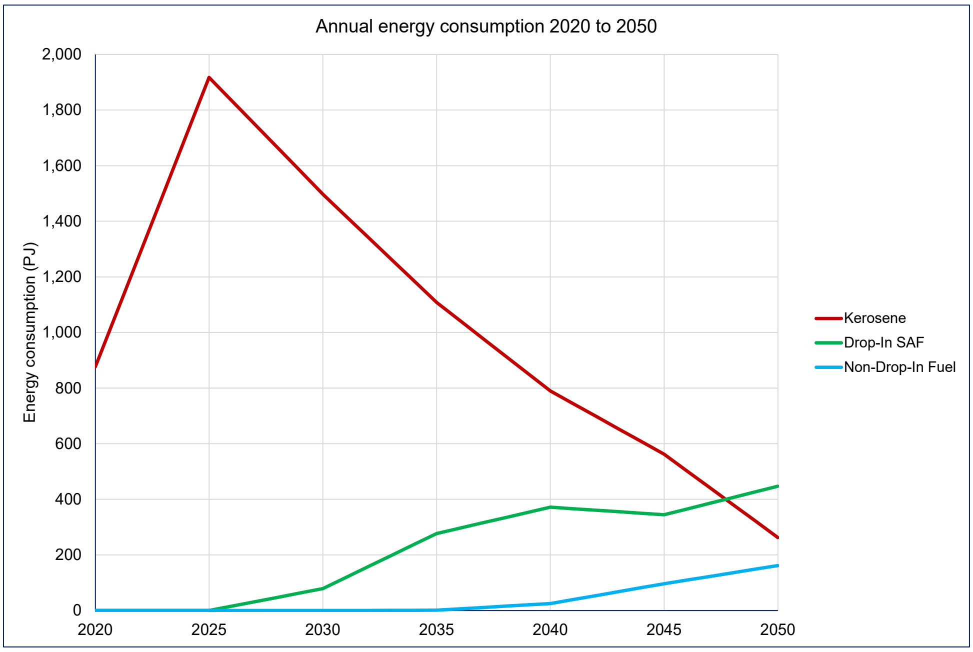
[43] The percentage changes are those relative to the baseline values shown in the table. Thus the emissions with technologies in 2050 (82.4 MT) represents a 55.4 % reduction relative to the baseline of 184.8 MT.

The full electric propeller-driven aircraft is delayed by five years to 2035, while the three hydrogen-fuelled options are all delayed to 2040.

The annual energy consumption to 2050, including these changes to the entry-into-service dates, is shown in Figure 4-9.

Figure 4-9: Evolution of annual energy consumption to 2050 for the sensitivity analysis, split by conventional fuel, drop-in and non-drop-in alternative fuels

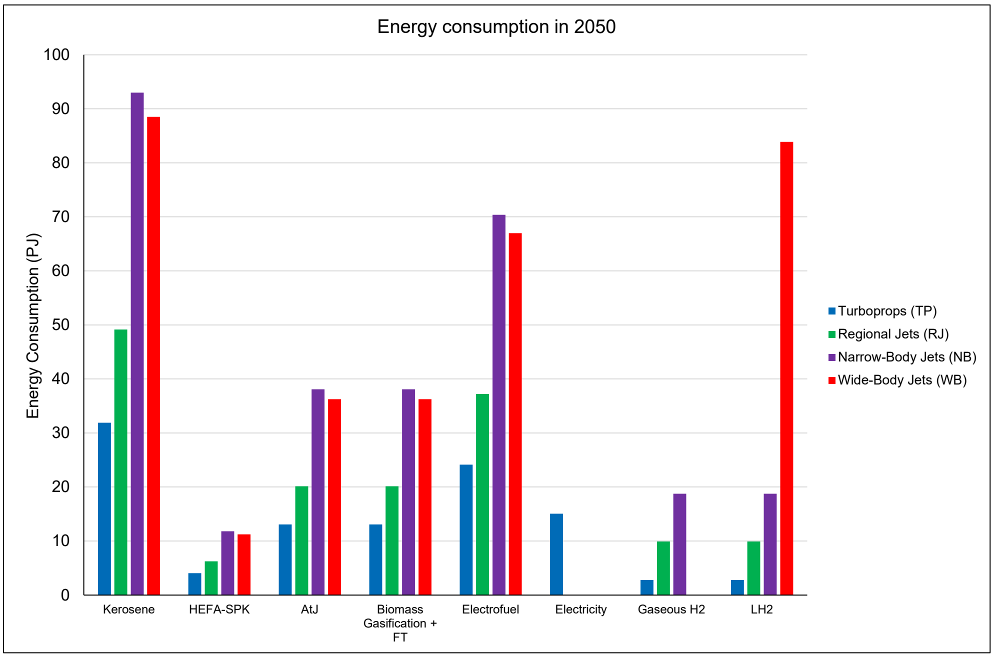


Source: Evaluation by authors, using total energy consumption shown in Figure 4-3, the blend percentages for drop-in fuels from the ReFuelEU Aviation study and the assumptions for the penetration of aircraft using electricity and hydrogen, as described in Annex A3.3, amended with the alternative entry-into-service dates from Table 4-6.

Compared to the main analysis (Figure 4-4), the growth in use of non-drop-in fuels (electricity and hydrogen) is significantly reduced, reaching only 162 PJ in 2050, instead of 489 PJ. Conversely, the growth in drop-in alternative fuels (advanced biofuels and electrofuel) is increased, reaching 447 PJ in 2050, compared to 275 PJ in the main analysis.

The split of the fuel consumption in 2050 by fuel type for the sensitivity case is shown in Figure 4-10, which can be compared to Figure 4-5 for the main analysis (note that the scale on the vertical axis is much smaller than in Figure 4-5, due to the significant reduction in the height of the LH_2 bar for wide-body aircraft).

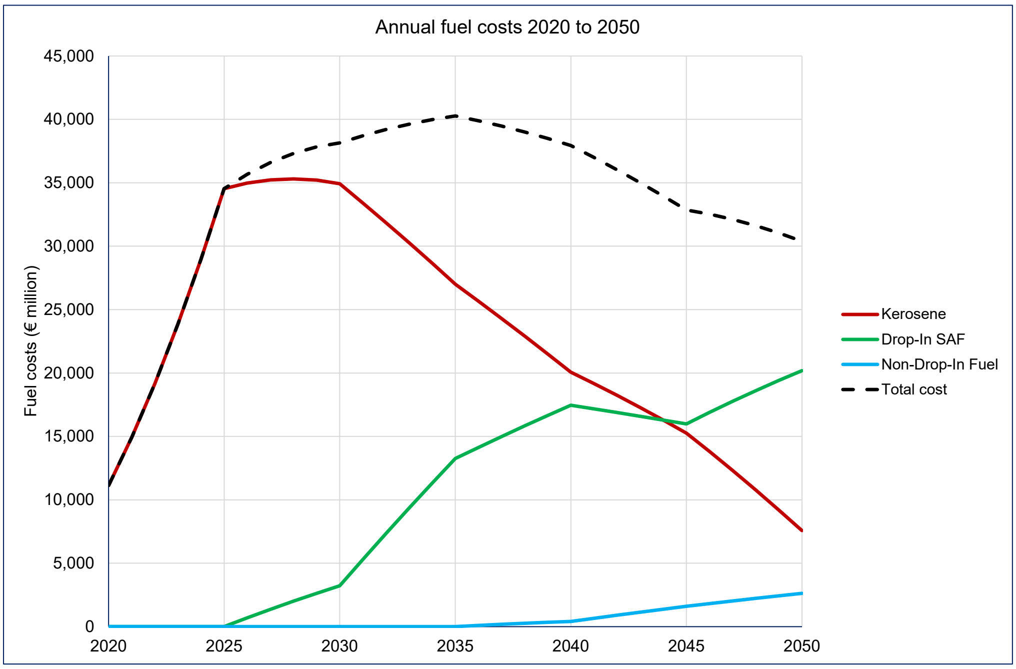
Figure 4-10: Energy consumption in 2050, by fuel (energy carrier) type and market segment for sensitivity case



Source: Compiled by authors using total energy consumption for 2050 shown in Figure 4-9, the blend percentages for drop-in fuels from the ReFuelEU Aviation study (European Commission, 2021i) and the assumptions for the penetration of aircraft using electricity and hydrogen, as described in Annex A3.3, amended with the alternative entry-into-service dates from Table 4-6.

The dominance of hydrogen as fuel (particularly for wide-body jets) is now matched by continued high use of conventional kerosene (62% higher than under the main analysis) and a significantly higher consumption of electrofuel, increasing from 122 PJ in the main analysis to 199 PJ (for all aircraft categories) in this sensitivity analysis.

Figure 4-11: Evolution of annual fuel costs to 2050, split by conventional kerosene, drop-in alternative and non-drop-in fuel types under the sensitivity analysis



Source: Authors' evaluation using fuel consumption data from Figure 4-9 and fuel price data from ReFuelEU Aviation study (European Commission, 2021i) and Ricardo maritime decarbonisation (Ricardo, 2022) studies.

Compared to the main analysis (Figure 4-6), the peak annual costs are increased slightly from EUR 38.9 billion to EUR 40.2 billion, with the peak still occurring in 2035. However, the reduction following the peak is less rapid, due to the continued high use of conventional kerosene and drop-in SAF, leading to a total fuel cost in 2050 of EUR 30.4 billion, about 22 % higher than the value under the main analysis (EUR 25.0 billion).

Table 4-4 presents the PV for total savings in fuel costs from 2020 to 2050, relative to the baseline, under different discount rates.

Table 4-7: PV for total savings in fuel costs to 2050, under various discount rates, for the sensitivity analysis

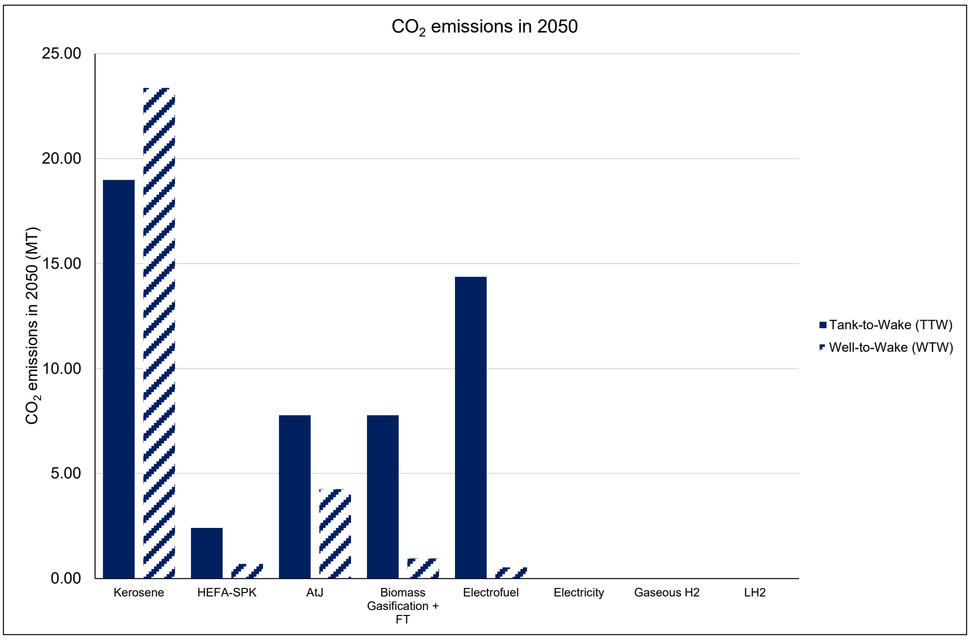
Discount rate	PV (EUR billion)
0 %	+EUR 344.0
3 %	+EUR 181.1
6 %	+EUR 100.7
9 %	+EUR 59.0

Source: PV calculation using various discount rates applied to annual costs shown in Figure 4-11 and similar calculations for the baseline case.

The change in fuel costs remains negative for all discount rates under this sensitivity case (and hence the PV is positive), indicating an overall reduction in fuel costs due to the large reductions in energy consumption, despite the increased consumption of the higher-priced fuels (mainly the drop-in SAF fuels). For example, the PV of fuel costs under the main analysis at a 6 % discount rate was +EUR 107.5 billion (Section 4.4), with the +EUR 93.7 billion calculated under this sensitivity analysis being some 13 % lower.

The calculated CO_2 emissions for 2050 under this sensitivity analysis are presented in Figure 4-12, by fuel type.

Figure 4-12: CO_2 emissions calculations for 2050, under the sensitivity analysis



Source: Authors' calculations using energy consumption from Figure 4-9, Table 4-3 and emissions factors from ICAO Annex 16 Volume IV, plus assumed reductions for alternative fuels, as described and as amended with the alternative entry-into-service dates from Table 4-6.

Summing the values for the different fuels in Figure 4-12, the total CO_2 emissions in 2050 under this sensitivity analysis are 51.3 MT (TTW) and 29.8 MT (WTW). The WTW emissions are lower than the TTW emissions because of the absorption of CO_2 from the atmosphere (or other industrial processes) during the production of the drop-in fuels (see Section 4.5). These emissions represent reductions of 66 % (TTW) and 84 % (WTW) in 2050 compared to the baseline.

The WTW emissions of 29.8 MT in 2050 under this sensitivity analysis is a significant increase on the 18.4 MT calculated for the main analysis, yet remains 40 % below the value of 49.1 MT from the MIX scenario for the European Green Deal objectives in 2050 (see Section 2). Those objectives for aviation, in terms of reductions in emissions of CO_2, will still be met by the technologies described here, even if the introduction of the step-change in fuel type to non-carbon-containing fuels is delayed.

4.7. Conclusions

The fuel consumption, emissions and costs described here were based on all technologies being adopted on new aircraft when they become available. Where multiple technologies cannot be combined on the same aircraft, they were applied to equal percentages of the fleet. For example, under the propulsion system technologies, the CROR engine and geared fan engine cannot be combined in the same engine, and each was assigned to 50 % of the aircraft built after the relevant entry-into-service dates. The results therefore present the most optimistic view of the potential improvements in efficiency and reductions in emissions from the technologies identified.

The expected overall costs were presented in the form of PV discounted to 2020. Table 4-8 presents the combined costs for technology development, aircraft purchases and fuel.

Table 4-8: PV for total change in costs to 2050, under various discount rates

Discount rate	PV (EUR billion)
0 %	-EUR 33.0
3 %	-EUR 38.1
6 %	-EUR 35.4
9 %	-EUR 31.0

Source: Summation of PV values for development costs, additional purchase costs and fuel costs, as shown in Table 4-1, Table 4-2 and Table 4-4.

When considering these overall costs, it should be noted that they do not include the costs to aircraft manufacturers for the final development and certification of new aircraft types (incorporating the technologies discussed in this report); the overall costs to the aviation industry would, therefore, be expected to be higher.

While the use of new fuels such as electrofuels and hydrogen will be expected to bring additional costs, these will be balanced by increases in aircraft efficiency. As a result, in the 2020-2050 period airlines are expected to save EUR 395 billion (undiscounted) in fuel costs compared to a situation in which they would use only fossil kerosene with less efficient aircraft. Overall, investments in decarbonisation measures will be slightly financially negative for the industry, with EUR 33 billion in additional costs expected between 2020 and 2050 (undiscounted).

As part of the study, interviews were held with stakeholders experienced in the development and application of technologies to aircraft design. These discussions identified that the initial efficiency improvements (or entry-into-service dates) for some of the technologies were optimistic and the amended assumptions were used in the sensitivity analysis.

The discussions also noted significant programme risks associated with incorporating new technologies in a new aircraft design, with manufacturers likely to be unwilling to incorporate several new technologies simultaneously in a new product. The main commercial aircraft manufacturers supplying aircraft in the EU market (Airbus, Boeing, Embraer) have all recently introduced new aircraft types or upgraded (reengined) types across all market segments. Given the time to develop a new aircraft type and the time required to recoup the investment, there is little scope for more than one (or perhaps two in a particular market segment) new generation of aircraft in each market segment before 2050.

While the technologies described here have the potential to enter service before 2050, it is unlikely that all will do so. Manufacturers of the next generation of aircraft will select from those technologies available (and demonstrated to a sufficient TRL) to meet airlines' requirements at the time of design. Development of all technologies is therefore expected to continue (and the costs described here will be incurred), but the estimated efficiency improvements and emissions reductions that will actually be achieved depend on the technologies that are eventually selected for investment at scale. The fuel costs may also be optimistic (fuel consumption may be higher than calculated), but the additional aircraft purchase costs may be overly cautious, as the aircraft may not include all the technologies assumed.

5. EU ROLE IN SUPPORTING DECARBONISATION

KEY FINDINGS

- The EU can support the decarbonisation of aviation chiefly through its regulatory and legislative role, and as a funding provider and enabler. EU legislation (current and proposed) takes a multi-faceted approach to the issue, with market-based measures (e.g. emissions trading legislation) to support the deployment of infrastructure, legislation to mandate uptake of SAF, and legislation on financial incentives.
- Legal barriers to decarbonisation of the aviation sector vary, including the lack of integration of the EU ETS with CORSIA, whose emission reduction ambition is lower than the EU ETS. In addition, the cost impact of the 'Fit for 55' package applicable to aviation (i.e. the EU-ETS and CORSIA, the end of the ETD exemption and ReFuelEU Aviation) might affect the demand for air travel and carbon leakage, potentially reducing CO_2 savings.
- Other barriers relate to support for the production and certification of SAFs to enable them to be produced at the appropriate scale. Synthetic biofuels can potentially deliver the highest GHG reductions (up to 100% if produced using renewable energy), but the technology to produce them is not yet mature. Regulatory support is needed to create an investment signal for the technology to develop, thus the aim of the ReFuelEU.
- Potential pitfalls of blending mandates introduced in ReFuelEU relate to their potential to incentivise cheapest eligible alternative fuels with less GHG reductions or to set targets that may exceed availability of sustainable SAF feedstock or the technological limits for deployment.
- Deployment of SAF may be promoted by GHG intensity targets, as in the proposal for the revision of the Renewable Energy Directive (RED) II. The effectiveness of such policies is entirely reliant on the quality of the underlying lifecycle assessment (LCA) methodology. Clear guidelines are needed to determine their GHG intensity on an LCA basis. The technology for hydrogen-powered aircraft is not yet available, but regulatory measures supporting its production are nevertheless important to provide the investment signal for the technology to develop.
- EU funding dedicated to aviation does not directly support the acquisition of more efficient aircraft, which is the area where greatest levels of investment will be needed. The EU could carefully extend the Taxonomy Regulation to the financing of such targeted purchases. This would incentivise quicker fleet replacement of aircraft, thus bringing efficiency improvements to the market more quickly.

5.1. Introduction

This section covers the legal framework that forms a crucial aspect of the EU role in supporting the decarbonisation of the aviation sector.

5.1.1. EU role

The existing legal framework to reduce emissions from the aviation sector is based on the EU shared competence attributed through Articles 4 and 192 of the Treaty on the Functioning of the European Union (TFEU) to intervene in all areas of environmental policy, in particular climate change.

Other measures are based on the EU shared competence on air transport (Article 100(2) TFEU), energy (Article 193 TFEU) or the internal market (Article 114 TFEU).

Within this context, the role of the European Parliament as the co-legislator is crucial to the design and formulation of ambitious amendments related to Commission proposals that respond to the climate emergency and prompt achievement of relevant emission reduction targets, such as the proposals for more ambitious targets within the Climate Law or the Renewable Energy Directive recast (RED II)[44] (European Commission, 2018).

The European Parliament also has the role of requesting the adoption of Commission proposals which might strengthen the EU's environmental ambition.

This study provides an overview of the EU regulatory framework needed for aviation to reach the European Green Deal objectives by 2050.

5.1.2. Existing and envisaged EU legislation

This sub-section examines the current legal and regulatory framework and relevant legislative initiatives introducing new measures to enable the achievement of the emission reduction targets for 2030 and 2050 in relation to aviation. It covers legislation regulating emissions reduction, in particular market-based measures (i.e. the EU ETS emissions trading system) legislation promoting sustainable fuel mandating the uptake of SAF, and legislation on financial incentives, including measures promoting deployment of infrastructure.

a. Policy background

Aviation is one of the fastest-growing sources of GHG emissions (see Section 2), which has led the EU to take action to reduce aviation emissions. Three different types of measures aim to address this objective: emission reduction market-based measures, legislation on aviation fuel, and measures to ensure appropriate financial incentives to support innovation and infrastructure development.

To deliver on the European Green Deal, the European Commission published its proposal for the European Climate Law, setting the goal of making Europe's economy and society climate-neutral by 2050 (European Commission, 2020a), which was amended to set a 55 % emission reduction target by 2030 compared to 1990 levels (European Commission, 2020b). The Climate Law (European Parliament, 2021) enshrines the 2050 climate ambition as a legally binding target with a 2030 milestone and requires sectors to prepare roadmaps towards climate neutrality.

The 'Fit for 55' legislative package adopted in July 2021 outlined the revisions and initiatives needed to meet the 2030 emission reduction target, several of which directly affect the aviation sector. It is worth mentioning the published Climate Action Progress Report 'Speeding up European climate action towards a green, fair and prosperous future' (European Commission, 2021f).

In addition, on 18 May 2022, the Commission published the Energy Package of measures, named REPowerEU, which presents measures to accelerate the use of hydrogen and clarify its regulatory framework complementing the Hydrogen and Decarbonised Gas Market Package published on 15 December 2021. By itself, REPowerEU calls for the substitution of fossil fuels and the acceleration of Europe's clean energy transition, including a reference to renewable hydrogen as the key to decarbonise industries and transport (such as aviation) veering away from natural gas, coal and oil.

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[44] Its power of scrutiny to oversee, together with the Council, the Commission's implementing and delegated acts (Articles 290 and 291 TFEU) provides an effective mechanism to support the achievement of legal objectives and targets.

To achieve decarbonisation objectives, in RePowerEU the Commission sets up ambitious targets for both the production and import of renewable hydrogen (10 million tonnes) by 2030. Regarding EU imports, the purchase of hydrogen was already included under the scheme of the EU Energy Platform proposed in the REPowerEU and endorsed by EU Heads of State on 25 March 2022, enabling common purchase of this fuel for all the EU Members[45]. Relevant measures have also been envisaged with regards to enhancement of hydrogen production and development of infrastructure in the EU such as: topping-up Horizon Europe investments on the Hydrogen Joint Undertaking (EUR 200 million) to double the number of Hydrogen Valleys or quick completion of the assessment of the first Important Projects of Common European Interest on hydrogen by the summer.

b. Legislation on emissions reduction

The relevant regulatory framework for the EU ETS for aviation in the EU comprises two Directives amending the EU ETS Directive 2003/87/EC: Directive 2008/101/EC and Directive 2009/29/EC.

Directive 2008/101/EC introduced aviation activities into the GHG emission allowance trading system within the EU from 2012. The current system is based on an EU-wide cap on CO_2 emissions, which are reduced annually following the ETS' linear reduction factor of 2.2 % (since 2021). Operating airlines are granted tradeable allowances for free to cover a certain number of emissions. Additional emissions require operating airlines to buy additional allowances in the carbon market at the market price.

The proposed amendments to the **EU ETS Directive** regarding aviation under the 'Fit for 55' package (European Commission, 2021g) establish a progressive phasing-out of the free allocation of allowances for airlines, with a progressive reduction in the number of aviation allowances auctioned by a certain percentage per year (yet to be agreed) from 2023, to reach full auctioning by 2027 (although the EP has proposed 2025 as the deadline for airlines to pay for their CO2 emissions[46]). The price of traded ETS allowances rose from 34 Euros in January 2021 to 80 EUR in December 2021 and picked to EUR 96 in February 2022 and being currently, on 26 August 2022, at EUR 90,31 representing a high increase on the EUR 25 average price in 2019 and 2020 and a rapid evolving price, difficult to predict and manage[47]. In the current system, that ongoing proposals aim to amend, the cost to airlines is balanced by the free allowances, the possibility of passing the cost to the consumer through pricing, and the benefit of a jet fuel tax exemption that is estimated at EUR 27 billion a year, higher than the ETS allowances cost (Transport & Environment, 2021a). The amendment to Directive 2003/96/EC (the Energy Taxation Directive, ETD) proposes to eliminate that tax exemption, thus, increasing the cost.

The current EU ETS design (to be amended) requires all airlines operating in Europe to verify and report their emissions and surrender allowances against those emissions annually. In practice, however, the so-called stop-the-clock decision meant that flights going beyond the EU's borders were excluded in 2012, an exclusion that was extended until 2023 by Regulation 2017/2392 so as not to interfere with the ICAO's development of an international offsetting scheme (CORSIA). Under CORSIA, the international airline sector is obliged (with some exceptions) to offset any emissions exceeding 2019 (baseline) levels of CO_2 emissions on international routes from 2021 onwards. More specifically,

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[45] The EU Energy Platform was established on 7 April 2022 to secure the EU's energy supply at affordable prices in the current geopolitical context and to phase our dependency on Russian gas. It is a voluntary coordination mechanism supporting the purchase of gas and hydrogen for the EU, pooling demand, coordinating infrastructure use and negotiating with the international partners. See at: https://energy.ec.europa.eu/topics/energy-security/eu-energy-platform_en

[46] European Parliament Decision 8 June 2022, on the proposal for a directive 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, amendment 19 (P9_TA(2022)0230).

[47] https://ember-climate.org/data/data-tools/carbon-price-viewer/

offsetting under CORSIA is possible on a voluntary basis since 2021 and will become mandatory in the year 2027.

The proposed amendments to the **EU ETS Directive** aim to ensure alignment with implementation of CORSIA for extra-EU flights and emissions pricing. The proposal requires the application of CORSIA to flights outside the EU ETS that depart from/arrive in countries that apply CORSIA. However, CORSIA 'does not propose to actually reduce emissions from aviation, but simply to compensate for any emission increases after 2020 through the purchase of carbon offsets.' Under the system linked to the proposed amendment, emissions from these flights continue to need to be offset once collective international emissions exceed 2019 levels. The eligible offset units need to originate from countries that participate in the Paris Agreement and in CORSIA. There is also the risk of double-counting, whereby the emission savings of a project are claimed by both the offsetting airline and the country where the project is based (Transport & Environment, 2021a). Offsets must be reliably accounted for to avoid being counted twice. The proposed amendments to the **EU ETS Directive** require the use of Member States' 2021 CORSIA notification to EU-based airlines of the offsetting for their 2021 emissions.

The current EU ETS for aviation was designed as a separated system to the ETS applied to industrial installations, and two types of emission allowances were used - European Union Allowances (EUAs) and European Union Aviation Allowances (EUAAs). Until 2020, the aviation sector was allowed to buy allowances from the stationary sector - which is currently characterised by a surplus - and to submit both types of allowances to comply with the regulatory system, whilst stationary (industrial) sources were bound to EUAs. This enabled aviation to buy additional allowances. Prices for EUAAs follow the prices of allowances in the stationary sector, thus if the stationary ETS is strengthened, leading to higher allowance prices, the aviation ETS is also strengthened (Graichen & Graichen, 2020). From 2021, in Phase IV of the EU ETS, stationary sources may also submit EUAAs, ensuring better integration of the systems and a more efficient ETS. Article 10(3) of the ETS Directive establishes that while Member States may determine the use of revenues generated from the auctioning of allowances, they are required to use those revenues to finance climate change/GHG emission reduction and energy efficiency projects.

c. Legal measures promoting sustainable fuel applicable to aviation

The **proposed** **ReFuelEU Aviation Regulation**, aims to ensure a level playing field for sustainable air transport by addressing undesirable practices such as 'fuel tankering' and to promote the uptake of SAF by strengthening supply and promoting demand.

Demand will be boosted by the introduction of a **specific target for renewable fuels in aviation, via a blending mandate** that requires the minimum proportion of SAF in aviation fuel to be increased every five years until 2050. This requirement will apply from 2025, with a transition period up to 2029, allowing fuel suppliers to report their SAF blending as a weighted average over all aviation fuel supplied across EU airports for that reporting period. Table 5-1 presents the proposed timetable for the SAF blending mandate targets, as per the initial Commission proposal[48].

Table 5-1: ReFuelEU Aviation proposal blending mandate: targets for renewable fuels in aviation

Target	Percentage/level	Year
Minimum share of SAF supplied at each EU airport	2 %	2025
	5 %	2030
	20 %	2035

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[48] On 07 July 2022 the European Parliament approved the blending mandate, but with increased targets compared to the Commission's proposal (up to 85 % by 2050, including a minimum of 50 % of synthetic biofuels). Interinstitutional negotiations "trilogues" to reach a final agreement on the specific details of the blending mandate are expected to start in September 2022 (Goulding Carroll, 2022).

	32 %	2040
	38 %	2045
	63 %	2050
Minimum share of synthetic biofuels within SAF	0.7 %	2030
	5 %	2035
	8 %	2040
	11 %	2045
	28 %	2050

Source: Article 4 and Annex I of ReFuelEU Aviation Regulation proposal.

The proposed recast of the Alternative Fuel Infrastructure Directive (2014/94/EU) into a proposal for a Regulation would facilitate decarbonisation of aviation through measures **on infrastructure for external electricity supply at airport gates** and remote stands for aircraft to use while stationary. Article 13(1)l) of the proposal requires Member States to develop a deployment plan for alternative fuels infrastructure in airports, other than for electricity supply to stationary aircraft, in particular hydrogen and electric recharging for aircraft.

RED II establishes a common framework for the promotion of energy from renewable sources, setting a binding EU target for the overall share of energy from renewable sources in the Union's gross final consumption of energy in 2030. RED II includes a 14% target for volume of renewable energy supplied to the transport sector by 2030, but this does not cover aviation. Nevertheless, fuel suppliers are incentivised to provide sustainable fuels to aviation via a 1.2x multiplier - any fuel supplied to this sector counts for 120% of its energy content.

RED II also has an impact on the development of **hydrogen**. Although the required technologies to use hydrogen-based fuels in aviation are not very mature, the Hydrogen Strategy identifies hydrogen as important to decarbonisation of the aviation sector in the long term (2030-2050) (European Commission, 2020d). Renewable hydrogen is thus included in the definition of renewable liquid and gaseous transport fuels of non-biological origin (RFNBOs) adopted in 2018 to determine how these fuels fit with compliance with the transport target. Under RED II, renewable hydrogen and hydrogen-based synthetic fuels produced from electricity of installations connected to the grid (even if the electricity mix has low shares of renewable electricity) are considered 100% renewable provided that certain conditions are met, including the additionality of the renewable electricity used. The Delegated Act on Renewable Fuels of Non-Biological Origin (RFNBO) adopted in 2021, pursuant to Article 27(3) of RED II, aims to clarify the conditions under which RFNBOs can be fully counted as made from renewable electricity.

The **proposed revision of RED II** significantly raises its overall ambition, with important consequences for aviation. Firstly, the fuel pool to which the transport sub-target applies is expanded beyond rail and road to cover all 'energy supplied to the transport sector', including aviation. The 14 % target for use of renewable energy in transport is strengthened by converting it to a 13% reduction target in GHG intensity. The sub-targets for **advanced biofuels and biogas** from the feedstocks in **Part A of Annex IX** to the Directive are lowered slightly and a new sub-target set for RFNBOs. The previously mentioned 1.2x multiplier for aviation fuel is maintained, but only concerns RFNBOS, excluding waste oil biofuels and recycled carbon fuels (RCFs)[49].

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[49] Liquid and gaseous fuels that are produced from (a) liquid or solid waste streams of non-renewable origin, or (b) from waste processing gas and exhaust gas of non-renewable origin.

The proposal adjusts the scope and content of the **certification system** for renewable and low-carbon fuels to include all fuels covered by RED II, including RCF. The **certification** of renewable and low-carbon fuels is addressed in two legislative proposals, within the Hydrogen and Decarbonised Gas Market Package [50]namely the Proposal of the Revised Gas Markets and Hydrogen Directive[51] and the Proposal of the Revised Gas Markets and Hydrogen Regulation[52] which are a review of the Gas Directive 2009/73/EC and Gas Regulation (EC) No 715/2009).

d. Legislation on financial incentives

To facilitate more informed investment choices in green activity[53], the EU legislator adopted Regulation (EU) 2020/852, the Taxonomy Regulation. It establishes criteria for determining whether an economic activity qualifies as **environmentally sustainable** for the purposes of establishing the degree to which an investment is environmentally sustainable.

By defining environmentally sustainable economic activities, the Taxonomy Regulation sets up a framework to facilitate sustainable investment and address economic activities that lead to significant GHG emissions and are considered to significantly harm environmental objectives.

Environmental, social and governance (ESG) criteria have become a crucial element of investment analysis in recent years. This trend is equally visible in 'mergers and acquisitions' transactions (Bain & Company, 2022) and on financial markets (O'Brien & Regan, 2021), where investors emphasise the environmental sustainability of the undertakings/financial products. The assessment of risks resulting from climate change or from the point of view of the environmental impact of investments is extremely complex, lacks coherent criteria, and is prone to greenwashing[54]. At the same time, results of such assessments often have a decisive impact on closing transactions and/or obtaining financing for investments. This prompted the need for legally binding, EU-wide harmonised criteria to determine whether or not an economic activity could be deemed sustainable. The Taxonomy Regulation is based on six environmental objectives:

1. Climate change mitigation;
2. Climate change adaptation;
3. Sustainable use and protection of water and marine resources;
4. Transition to a circular economy;
5. Pollution prevention and control;
6. Protection and restoration of biodiversity and ecosystems.

The assessment of whether or not an economic activity contributes to the achievement of these objectives is based on technical screening criteria (TSC). The criteria are not defined in the Taxonomy Regulation itself but are developed by virtue of delegated acts. Power to adopt such delegated acts was conferred to the Commission in the provisions of the Taxonomy Regulation. To date, only

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[50] Hydrogen and decarbonised gas market package webpage.

[51] Annex to the Directive.

[52] Annex to the Regulation.

[53] To increase transparency of green investments, a legal obligation was imposed on some entities (e.g. listed companies, banks) to report their policy on environmental issues as part of management reporting under Directive 2014/95/EU (Non-Financial Reporting Directive), while certain entities are subject to sustainability-related disclosure obligations under Regulation (EU) 2019/2088 (Sustainable Finance Disclosure Regulation).

[54] Giving a misleading impression about the environmental benefits of products, services, etc.

Commission Delegated Regulation (EU) 2021/2139 (European Commission, 2021o)[55] has been adopted (see discussion in Section 5.2.6).

5.1.3. Regulatory barriers affecting achievement of European Green Deal objectives

a. EU ETS

Several key barriers to aviation decarbonisation were identified in respect of the EU ETS for aviation.

All provisions regulating aviation under the EU ETS Directive, existing and proposed for amendment, refer to CO_2 emissions. The European Commission commissioned the EASA to develop a study to update the analysis of non-CO_2 effects of aviation on climate change[56], but concrete proposals for regulating aviation's non-CO_2 impacts have yet to be published, which might affect achievement of the decarbonisation objectives, given that the potential warming effect from the emissions of the relevant pollutants (NOx, soot particles, SOx and water valour) are not dealt with[57].

The emerging cost of allowances to airlines as a result of the proposed amendments to the EU ETS Directive is still being balanced by the offset through the jet fuel tax exemption. The current tax exemption on aviation fuel is equal to a public subsidy for airlines of EUR 27 billion (Transport & Environment, 2021a). On the other side, according to the European Aviation Safety Agency, the cost of ETS compliance during the third ETS period (2013-2020) has been very low for airlines, representing in 2017 about 0.3% of their operating costs for flights covered by the EU ETS. The price increase of ETS allowances does not affect much the cost of ETS compliance for airlines due to the free allowances allocation.

However, the proposed revision to the ETD seeks to remove the current tax exemption for fossil jet fuel used for intra-EU commercial flights, with a tax of EUR 10.75/GJ (corresponding to EUR 0.379/litre), and updated every year according to inflation, being imposed starting in 2023. While this is considered a major step towards decarbonising the aviation sector, it increases costs for airlines (and, by extension, consumers), whose EU ETS allowance costs were mitigated by the tax exemption. The increase in carbon prices from EUR 25 in 2020 to around EUR 90 in August 2022 has increased the cost per ticket, with expected additional costs as a result of the proposed jet fuel tax potentially affecting the demand for air travel. The impact of the 'Fit for 55' package applicable to aviation (in particular the EU-ETS and CORSIA, ETD/jet fuel tax and ReFuelEU Aviation) is expected to affect the demand for air travel, CO_2 savings and carbon leakage. The reduced demand for air travel, combined with higher SAF uptake and lower CO_2 emissions, will result in substantial CO_2 savings. There is however some risks related to carbon leakage, as some demand can shift to non-EU hubs (see sections 6.2 and 6.3 for more details).

CORSIA is less ambitious in its environmental objectives than the EU ETS for aviation. The latter defines the CO_2 emission cap for aviation as 95 % of the 2004-2006 average emissions, while the former only requires that CO_2 emissions exceeding the 2019 level be offset by the airline sector. CORSIA will only become mandatory by 2027, whereas the EU ETS has already been in force since 2012. The maintenance of two different systems with different conditions could lead to a complicated co- existence of measures and to a relatively high administrative effort for participating airlines and administering authorities alike. In addition to a lack of coherence, the possible competitive impacts of two parallel systems for the airlines should also be considered.

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[55] The TSC for the remaining four environmental objectives will be developed and adopted successively, with a view to ensuring their application from 1 January 2023.

[56] Published as a Staff Working Document on 23 November 2020.

[57] COM(2020) 747 final.

The current proposal extending the geographical scope of EU ETS for aviation to extra-EU flights will probably lead to higher CO_2 reductions compared to the current scheme. However, that extended scope will mean higher overall cost for air transport due to the EU ETS allowances cost and – from a demand perspective – increased air fares and air cargo rates. This may lead to a decreased demand for air services, depending on the price elasticities of demand. Carbon leakage by rerouting cargo and passengers to, from and via airports located outside the scope of a tightened EU ETS may be a further challenge.

Another issue relates to the EU ETS' relationship with CORSIA and the latter's effectiveness in relation to climate policy. CORSIA does not propose to actually reduce emissions from aviation, but simply to compensate for any emission increases after 2020 through the purchase of carbon offsets by airlines. Offsetting is a controversial and unproven way of tackling carbon emissions, as calculating the savings in carbon emissions generated by offsets is a very uncertain science. Eligible carbon credits may be generated by certified GHG reduction projects, such as reforestation, which, in return, should deliver measurable reductions in emissions. However, the environmental effectiveness of these projects has been questioned (Scheelhaase, Maertens, & Grimme, 2021).

There is a risk of double-counting, whereby the emission savings of a project are claimed by both the offsetting airline and the country where the project is based. This double-counting leads to over-estimating the emission-saving impact of a project and fails to accurately reflect real emission levels. In addition, CORSIA has no real compliance mechanism.

b. The EU ETS consistency with other systems

Recent developments linking the EU ETS to other systems outside the EU might further complicate coordination with the CORSIA system. In 2020, the EU ETS system was linked to the Swiss emissions trading system (Swiss ETS). As a result, emissions from flights between the EU (and also the European Economic Area) and Switzerland are subject to the EU ETS, while emissions from flights from Switzerland to the EU fall under the Swiss ETS, which also covers emissions from Swiss domestic flights. The EU ETS is not officially linked to the United Kingdom (UK) emissions trading system (UK ETS), which came into force on 1 January 2021 as a consequence of Brexit. A linking agreement with the UK, similar to that concluded with Switzerland, is expected to be negotiated shortly. Ensuring the integration of the EU ETS and CORSIA would be more complicated in the presence of other linked market systems.

c. RED

The effectiveness of the RED should complement emission reduction efforts, including in the aviation sector. While the proposed RED II revision raises its ambition with positive effects for aviation, insufficient ambition of its core objective from a 2030 and 2050 perspective in the proposed revision of RED II may potentially be a barrier to decarbonisation. The level of renewable target depends on the willingness of EU decision-makers. While the initial proposal might lack ambition, the Commission confirmed in the European Parliament in April 2022 that a complementary analysis of the impact assessment of the recast of the RED will consider a stronger target of 45 %, instead of the 40 % initially proposed[58].

Hydrogen is considered a renewable source of energy and RED II allows renewable hydrogen and hydrogen-based synthetic fuels produced from electricity of installations connected to the grid to be

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[58] ENDS Europe, 21 April 2022 states: Ms M. Wörsdörfer (Deputy Director General – Directorate General for Energy)) said the Commission welcomed many of the Parliament's proposed amendments to the RED, "in particular the even higher level of ambition for the renewables target for 2030 of at least 45% given the current circumstances". Amendments proposing a higher target for renewable heating and cooling would also be supported by the Commission, she said. "Our proposal can be considered as a baseline." https://www.endseurope.com/article/1753641/commission-assess-higher-2030-renewable-energy-target

counted as 100 % renewable under certain conditions (Art 7 and 19 Directive 2018/2001/EU). The required technologies to use hydrogen-based fuels in aviation are not yet mature, but the Hydrogen Strategy nevertheless identifies hydrogen as important to decarbonisation of the aviation sector in the long term. The proposal for revision of RED II further develops it by promoting the use of renewable fuels of non-biological origin, in line with the Energy System Integration Strategy and the Hydrogen Strategy[59].

Another challenge could come from the potential introduction in RED of hydrogen from fossil fuel production as mentioned by the Commission REPowerEU Action Plan in reaction to the difficulties and disruptions of the global energy market caused by Russia's invasion of Ukraine. In this plan the Commission reiterates its position that blending hydrogen into the fossil fuel natural gas grid requires careful consideration as it diminishes gas quality and can provoke increase in the overall system costs and the costs of heating for the residential sector. In addition, it is, in most applications, a less efficient alternative to direct electrification. However, the Commission underlines in the REPowerEU Action Plan that it is worth considering that blending up to around 3% by volume of renewable hydrogen in the gas grid may absorb about 1,3 million tonnes of hydrogen and replace 4,7 bcm natural gas[60]. Several authors consider that blending hydrogen from fossil fuels is not sustainable and would not facilitate achieving the decarbonisation target by 2050. It 'would send the wrong message and incentives in a legislative text that is meant to increase the ambition of renewables to deliver the European Green Deal' (Pickstone, 2022).

Member States' permitting processes for renewable energy projects represent another barrier to the deployment of the necessary sources of renewables to provide enough capacity to enable their full use in aviation. The Commission has published as part of its May Energy Package, (the REPowerEU Plan) a targeted amendment to the Renewable Energy Directive to recognise renewable energy as an overriding public interest for the purposes of the Habitats Directive until climate neutrality is achieved (proposed Article 16d)[61]. Shortened and simplified permitting processes should be developed for projects in 'go-to areas' with lower environmental risks. To complement this measure, the Commission has adopted a Recommendation[62] and Guidance to Member States on good practices to speed up permit-granting procedures for renewable energy projects[63], and is making available datasets on environmentally sensitive areas as part of its digital mapping tool for geographic data related to energy, industry and infrastructure. Impacts on biodiversity will require careful monitoring.

Proposals for legislation were adopted in 2021 to regulate the certification of renewable and low-carbon fuels and promote hydrogen production and use, including the Hydrogen and Decarbonised Gas Market Package[64] (Proposal of the revised gas markets and hydrogen directive[65] and Proposal of the revised gas markets and hydrogen regulation[66]).

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[59] Proposal for a Directive amending Directive (EU) 2018/2001, COM(2021) 557 final, Brussels, 14.7.2021

[60] Commission Staff Working Document Implementing the RePower Action Plan: Investment needs, hydrogen accelerator and achieving the bio-methane targets, Brussels, 18.5.2022 SWD(2022) 230 final

[61] Proposal for a Directive amending Directive (EU) 2018/2001 on the promotion of the use of energy from renewable sources, Directive 2010/31/EU on the energy performance of buildings and Directive 2012/27/EU on energy efficiency COM(2022) 222 final, 18.5.2022:
Art 16d states until climate neutrality is achieved, Member States shall ensure that, in the permit-granting process, the planning, construction and operation of plants for the production of energy from renewable sources, their connection to the grid and the related grid itself and storage assets are presumed as being in the overriding public interest and serving public health and safety when balancing legal interests in the individual casesfor the purposes of Articles 6(4) and 16(1)(c) of Directive 92/43/EEC, Article 4(7) of Directive 2000/60/EC and Article 9(1)(a) of Directive 2009/147/EC.

[62] C(2022) 3219 final (hyperlinks here but elsewhere also)

[63] SWD/2022/0149 final

[64] Hydrogen and Decarbonised Gas Market Package webpage.

[65] Annex to the Directive.

[66] Annex to the Regulation.

Additional barriers stemming from fuel options for aviation are discussed in the sub-sections below.

d. ReFuelEU Aviation proposal

This sub-section determines the regulatory barriers to effective deployment of SAF in the EU by examining whether all relevant policy levers are covered in the existing or proposed regulatory framework. It also examines if these measures address the main drawbacks of such policies.

The first type of lever to consider are the **blending mandates**, such as the ones included **in the ReFuelEU Aviation proposal.** These measures are key to drive demand for SAF and provide a clear policy signal to enable investment in developing the required supply chains and technologies.

A potential drawback of such measures is that mandates can inadvertently incentivise blending of the cheapest eligible alternative fuels instead of those providing most GHG reductions. Food-based and feed-based biofuels are an issue, but these are excluded from the definition of SAF in the ReFuelEU Aviation proposal, which covers:

1. Synthetic aviation fuels (also called e-kerosene, or RFNBOs).
2. Advanced biofuels produced from the feedstocks included in Part A of Annex IX of RED II (i.e. lignocellulosic biomass, non-food crop feedstocks, agricultural and forest residues, industrial wastes).
3. Advanced biofuels produced from the feedstocks in Part B of Annex IX, namely UCO and certain animal fats.

Synthetic biofuels have the potential to deliver the highest GHG reductions (up to 100% if produced using renewable energy), but remain expensive as the technology to produce them is not yet mature. These therefore require additional regulatory support to create a sufficient investment signal for the technology to develop. The ReFuelEU proposal addresses this though a sub-mandate for synthetic biofuels.

The category of advanced biofuels produced from Part A and B feedstocks, as well as the specific feedstocks within them, have different characteristics in respect of GHG reduction and sustainable availability (for example, availability of feedstocks for advanced biofuel is too limited, while synthetic fuels such as e-kerosene can potentially deliver the highest GHG reductions with up to 97 % if produced using renewable energy, see section 3.4.1 on Drop-in fuels). The potential of the different biofuels to reduce GHG emissions should be reflected in any future legislation (i.e. ReFuelEU Aviation proposal) so as to ensure the effectiveness of the blending mandate in delivering real emissions reductions.

Blending mandates must avoid **setting a target** that exceeds the available quantity of SAF feedstock that can be sustainably sourced or the technological limits for deployment, as this undermines the certainty of the policy[67].

A recent estimate of EU sustainable availability of SAF feedstocks projected that advanced SAF could cover 5.5% of jet fuel demand by 2030, but only under optimistic assumptions for the deployment rate of novel conversion technologies (ICCT, 2021a). In contrast, if Part B feedstocks are overly relied on, despite their sustainability limitations, the estimated jet fuel demand for advanced SAF coverage drops to only 1.9% of projected 2030 EU fuel demand. Another estimate places the sustainable availability of SAF from Part A feedstocks at 2.5% of total fuel demand by 2030, and at 1% for Part B feedstocks, which

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[67] See Table 4-1, Section 5.2.2. this is table 5.1 and section 5.1.2 or timetable put forward in the ReFuelEU Aviation proposal regarding the minimum share of SAF supplied at each EU airport from 2025 to 2050.

would require the remaining 1.5% to be met by e-kerosene if the proposed 5 % target was to be met (Transport & Environment, 2021b).

Several stakeholders suggested capping the use of Part B feedstocks under the definition of SAF in ReFuelEU aviation, given their competing use with the road sector which will not create additional GHG savings (Transport & Environment, 2021b)., while also introducing a sub-target for advanced biofuels from Part A feedstocks based on sustainable availability[68], and increasing the sub-target for e-kerosene. Capping Part B feedstocks would be coherent with RED II, which only allows these feedstocks to contribute to a limited extent (1.7% of total energy content) to the renewable energy target in the transport sector. This cap is reprised in the amendment proposal for RED II.

A second type of regulatory lever for the deployment of SAF is **GHG intensity targets**, as in the proposal for the revision of RED II. The advantage of this approach is that the fuels offering the greatest GHG reductions have the greatest compliance value, incentivising GHG performance in addition to volume supplied. As this approach considers lifecycle emissions, it can also promote improved production efficiency through reduced upstream emissions, encouraging continuous improvement. It is also technologically neutral, as it does not specify a method by which to achieve emissions reductions, but simply sets the reduction in GHG intensity to be achieved.

The effectiveness of such policies relies entirely on the quality of the underlying LCA methodology. If emissions from indirect land-use change (ILUC) are not adequately taken into account, this could incentivise compliance with GHG intensity targets through cheaper, less sustainable biofuels.

It is necessary to determine the well-to-wing (lifecycle) emissions of each SAF and establish their GHG reduction values in relation to conventional jet fuel. Although RED II currently provides a baseline GHG intensity value for fossil fuels (94 g wCO_2eq/MJ), coherence with the CORSIA system with a more conservative value applied for jet fuel (89 g CO_2eq/MJ) might require aligning the two frameworks (as indicated in the European Green Deal).

On the issue of ILUC-related emissions, food-based and feed-based biofuels are particularly problematic, as, when direct emissions are added to ILUC-related emissions, they generally have more GHG emissions than fossil fuels (e.g. palm oil generates up to three times more, or 300 %, emissions than fossil diesel (Transport & Environment, 2018)). The contribution of crop-based biofuels to the renewable energy target for transport was already limited under RED II, and several suggestions have proposed to further limit their contribution under RED III (ICCT, 2021b); (Transport & Environment, 2021c). However, biofuel suppliers providing aviation fuel would presumably not use these feedstocks to meet the GHG intensity target, as they are excluded from the ReFuelEU blending mandate. Nevertheless, **encouraging the development of more advanced and sustainable biofuel** pathways might have positive effects for aviation.

Clear **guidelines** should be established to **determine the GHG intensity** of biofuels from more advanced feedstocks on an LCA basis. Indeed, not all Part A and Part B feedstocks are equivalent in this regard, with some presenting more significant sustainability concerns (see Section 3.4).

Even where the LCA methodology is sound, GHG intensity targets may not be efficient in encouraging development of SAF based on more advanced feedstocks or technologies. Indeed, so long as a certain biofuel falls below the fossil fuel baseline GHG intensity value, suppliers can continue to use it to achieve compliance. This could be addressed in the proposed amendments to RED II, which introduce

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[68] See Transport & Environment: 0.3 % in 2025, 2.5 % in 2030; Advanced Biofuels Coalition LSB: 2.7 % in 2030, increasing to 30.5 % in 2050; European Waste-based & Advanced Biofuels Association (EWABA): no specific target provided.

sub-targets for Part A biofuels, starting at 0.2% in 2022, 0.5% in 2025 and 2.2% in 2030, as well as a 2.6% by 2030 sub-target for RFNBOs.

Renewable hydrogen can potentially deliver 100 % emissions reductions and is also included under the RFNBO sub-target. Although the technology for hydrogen-powered airplanes will not be available in the near future given the lengthy development period, measures supporting hydrogen production are nevertheless important to provide the requisite investment signal for this technology to develop. The RED III proposal further supports development of advanced biofuels and RFNBOs through application of a 1.2x multiplier, meaning that every contribution to the target made via these fuels will have its value amplified, providing a concrete incentive for suppliers to prioritise them.

Finally, a GHG intensity target introduces the potential risk of fraud in relation to the data for calculating the carbon intensity of renewable fuel (ICCT, 2021b). The current transport target under RED II requires 14 % of the *volume* of fuel supplied to be from renewable sources, and any fuel supplied that meets the relevant criteria will count towards that target. Biofuel facilities must demonstrate GHG savings of between 50-65%, depending on the age of the facility, for example. Facilities therefore have no incentive to claim higher savings above this threshold, since a fuel with 99% savings or 50% will have the same contribution to the target. However, with a GHG intensity target, this is no longer the case. LCA is a complex process and not all verification bodies yet possess the required expertise to identify intentional or accidental errors in the data reported by fuel facilities, pointing to a need for additional guidance from the Commission to assist voluntary schemes or auditors to verify data used in GHG emissions calculations.

e. Infrastructure requirements for SAF and hydrogen

The Impact Assessment for the ReFuel EU Aviation states that no specific refuelling station or dedicated infrastructure is needed for aviation to utilise drop-in SAF as they are interchangeable with conventional jet fuel. Stakeholders consulted for that impact assessment considered infrastructure development a minor challenge to the growth of SAF. This suggests that the main issue with SAF development is not the construction of infrastructure to link the demand and supply side, but, rather, a **policy framework that would scale-up production of SAF** by incentivising the construction of production plants.

Upscaling can be achieved through research and investment funding instruments (at EU and national level[69]), fiscal incentives, or more flexible and simpler permitting regulations (at national legislation level[70]). As measures to enhance development of infrastructure do not seem to be essential to the development of SAF, their absence cannot be considered a regulatory barrier.

This is not the case for hydrogen, the use of which will require investment in infrastructure, including new construction or repurposing of part of gas infrastructure. This predicament was addressed in the Commission's Hydrogen Strategy, published in July 2020, which outlines three phases of hydrogen ecosystem development in the EU and emphasises the decarbonation of aviation sector through hydrogen.

The Hydrogen Strategy does not identify specific policies to support the development of hydrogen infrastructure at airports, however, and the lack of existing incentives has left aircraft manufacturers non-committal about the development of hydrogen-powered aircraft because they are not confident

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[69] For example, the Green Fuels, Green Skies (GFGS) Competition run by UK Department of Transport or Jet Zero Council initiative. See Section 7.2.1 for more details.

[70] With exceptions such as the Environmental Impact Assessment (EIA) Directive (2011/92/EU), which established the environmental impact assessment procedure that must be carried out before other permits are granted for certain kinds of projects.

that large scale refuelling will be possible. The lack of relevant legal provisions to enhance the development of hydrogen infrastructure should be identified as a regulatory barrier and remediated.

Similar to the regulatory solutions to enhance fuel infrastructure provided for in the proposal for Alternative Fuels Infrastructure Regulation the following solutions could be envisaged as a legislative solution to be considered under the ReFuel EU Aviation proposal:

1. Introduction of an obligation to ensure the availability of infrastructure supplying hydrogen, which over time will convert into an obligation to provide supplies of green hydrogen; or
2. Development of a mechanism to promote the demand and supply-side for the use of hydrogen. The Commission Staff Working Document on 'Implementing the RePowerEU Action Plan: Investment needs, hydrogen accelerator and achieving the bio-methane targets' provides further analysis on this point"[71].

In relation to hydrogen, the Commission has announced that it will provide further guidance on applicable rules and procedures for the construction and operation of future infrastructure dedicated to the production storage and transport of pure hydrogen. This is further promoted through the initiative to streamline permitting procedures (European Commission, 2022g).

In addition, the Commission has confirmed the development of the Hydrogen Platform set under the hydrogen and gas markets decarbonisation package to enable scoping hydrogen market operation and technical issues as a first step towards setting up the European Network of Hydrogen Network Operators (European Commission, 2022g).

The Commission is also promoting the development of European hydrogen infrastructure priorities via the TEN-E process based on the TEN-E Regulation, leading to needs identification by March 2023 and a first list of Projects of Common Interest and Projects of Mutual Interest by end 2023 (European Commission, 2022g).

f. Taxonomy regulation

The taxonomy rules are applied taking into consideration specific criteria defined through non-legislative acts such as the Commission Delegated Regulation (EU) 2021/2139. This establishes the Technical Screening Criteria (TSC) for determining the conditions under which an economic activity qualifies as contributing substantially to climate change mitigation or climate change adaptation, and for determining whether that economic activity causes no significant harm to any of the other environmental objectives. Annex I to the Delegated Regulation contains the TSC that deal with climate change mitigation.

Several TSCs listed in the Commission Delegated Regulation (EU) 2021/2139 are relevant to leveraging green finance for aviation:

1. 3.2: Manufacture of equipment for the production and use of hydrogen;
2. 3.4: Manufacture of batteries;
3. 3.6: Manufacture of other low-carbon technologies;
4. 4.13: Manufacture of biogas and biofuels for use in transport and of bioliquids;
5. 6.17: Low-carbon airport infrastructure.

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[71] SWD(2022) 230 final

Most of the TSCs listed do not specifically refer to aviation, with the exception of TSC 6.17, which covers 'Construction, modernisation, maintenance and operation of infrastructure that is required for zero tailpipe CO_2 operation of aircraft or the airport's own operations, as well as for provision of fixed electrical ground power and preconditioned air to stationary aircraft.'

TSC 3.3 Manufacture of low-carbon technologies for transport classifies most forms of low-carbon transport modes as sustainable, and while it lists a large number of road vehicles, trains, and inland/maritime vessels, it does not make any reference to aircraft. This suggests that financing of low emissions aircraft technologies will not be classified as sustainable under the current Delegated Regulation.

In 2021, the European Commission commissioned a study to support the development of a methodology to assess the sustainability of aviation sector and project investments (Steer, 2021). The study noted that 'aviation faces challenges to demonstrate the sustainability of its activities', which explained the lack of green investment in the sector to date. The report highlighted that the scope of the Taxonomy Regulation will need to be extended if private investment is to become attractive. The study mapped the main aviation-related activities against the environmental objectives of the Taxonomy Regulation (Article 9) and made recommendations on activities that could usefully be developed into TSCs (see Table 5-2).

Table 5-2: Aviation economic activities for possible inclusion in the EU Taxonomy Regulation

Overall activity group	Sub-activities considered
Aircraft performance (and related technology)	• Sale, lease or operation of aircraft: ○ Passenger air transport ○ Freight air transport ○ Renting and leasing of air transport equipment • Aircraft manufacturing and technology development: ○ Manufacture of aircraft and related machinery ○ Repair and maintenance of aircraft ○ Manufacture of ATM equipment
SAF	• Fuel production, storage and distribution: ○ Production of efuels or other hydrogen-based synthetic fuels ○ Production of hydrogen (feedstock for efuels) ○ Transport of SAF via pipeline
ATM	• ATM R&D • ATM operational activities
Airport operations and ground-handling	• Airport People Movers[72] (APMs) • Airport operations and ground-handling • Cargo handling
Construction of airport infrastructure	• Utility and infrastructure for SAF

Source: (Steer, 2021).

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[72] Buses and similar vehicles that move people around airports, in particular those that transport passengers from the terminal to aircraft parked at remote stands.

The methodology set out in the study was reflected in the draft TSCs published in August 2021, with the manufacturing and leasing of aircraft added to previous drafts (Platform on Sustainable Finance, 2021). The TSCs in the final Delegated Regulation did not include any reference to aircraft technologies, but it is possible that they may be included in forthcoming revisions of the EU taxonomy rules.

In general, the current EU taxonomy rules frame the wider use of green finance to support the decarbonisation of the aviation sector so they need to be carefully designed to ensure accuracy in supporting the objective. While low-carbon airport infrastructure, batteries and (certain aspects of) SAF are included in the current TSCs, the manufacturing and purchase (or leasing) of new, lower emission, aircraft and associated aircraft technologies are not. Given the significant investment needs in cleaner (and potentially zero-emission) aircraft in the coming decades (see Section 4), these limits might, for example, prevent the European Investment Bank (EIB) from supporting certain investments. The financial sector continues to focus on green finance, and decarbonisation of the aviation industry should be part of that focus.

5.2. EU funding streams

The economy-wide European Green Deal Investment Plan (EGDIP) sets out the mobilisation of public and private financial resources for a green transition and puts sustainability at the core of investment decisions across all sectors (European Commission, 2020c). The EGDIP aims to mobilise at least EUR 1 trillion in sustainable investments from 2021-2030 through EU budget and associated instruments to decarbonise the entire EU economy, including the transport sector[73] (see Figure 5-1). The more relevant/promising instruments for decarbonising included in the EGDIP are described in more detail in the following sections.

The various sources for the EGDIP include public and public-private funding and financing for different R&D needs for aircraft/engine technology and innovative operational measures. Some instruments are loans, others are grants and still others are loan guarantees. The EGDIP aims to create an enabling framework for private investors and the public sector to facilitate sustainable investment, in part through the EU taxonomy.

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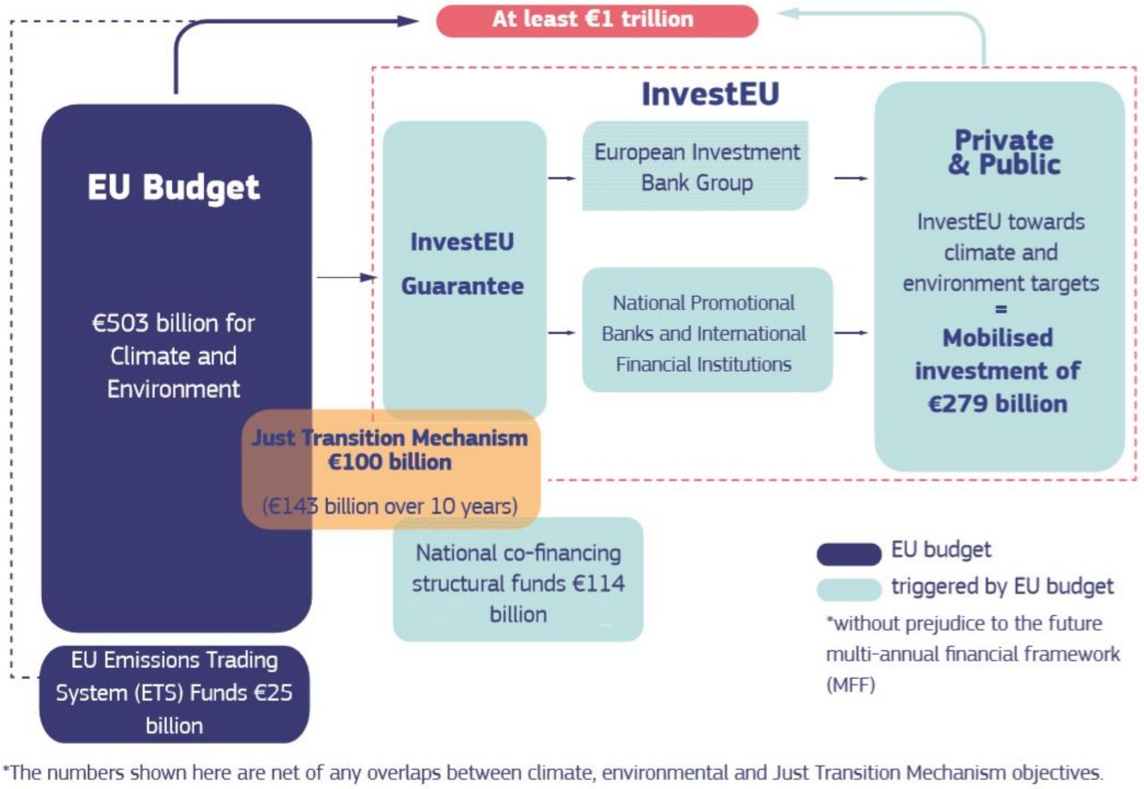
[73] Some estimates indicate that this level of investment might not be enough to achieve the decarbonisation goals set out in the European Green Deal. For example, an analysis from McKinsey & Company suggests that the EU will need to spend up to EUR 28 trillion (or EUR 800 billion per year) to achieve carbon neutrality by 2050 (Consultancy.eu, 2021).

Figure 5-1: Overview of European Green Deal Investment Plan financing



Source: (European Commission, 2020c).

The following sections explore how the different areas of the EGDIP contribute to funding R&D related to aviation:

- Section 5.2.1 focuses on the public funding streams expected through the EU budget (Horizon Europe, Connecting Europe Facility (CEF), cohesion policy and Recovery and Resilience Facility (RRF)).
- Section 5.2.2 discusses the Innovation Fund.
- Section 5.2.3 presents the InvestEU programme.
- Section 5.2.4 presents the Just Transition Mechanism.
- Outside of the direct EU remit, Section 5.2.5 explores how international and national financial institutions can leverage private and public financing, and how components of the InvestEU programme can use EU funds to trigger private financing.
- Section 5.2.6 reviews the opportunities established through the EU taxonomy to attract private capital investments in sustainable aviation.

Table 5-3 summarises these different funding streams. It includes a description of the type of instrument (loan, grant, loan guarantee) and the potential areas of aviation decarbonisation that it can support.

Table 5-3: Summary of funding streams

Funding stream	Type of instrument	Potential areas of support in aviation
Clean Sky/Clean Sky 2/Clean Aviation	Grant	Aircraft technology development
SES/SESAR	Grant	ATM
CEF	Grant	Airport infrastructure ATM
Cohesion policy	Grant	Airport infrastructure
RRF	Grant, loan	Aircraft technology development Airport infrastructure ATM SAF and hydrogen
Innovation Fund	Grant	SAF and hydrogen
InvestEU	Loan guarantee	ATM SAF and hydrogen
Just Transition Mechanism	Grant, loan, loan guarantee	Limited
International and national financial Institutions	Grant, loan, loan guarantee	Fleet replacement costs Airport infrastructure ATM SAF and hydrogen
Green finance	Loan	Aircraft technology development Fleet replacement costs Airport infrastructure ATM SAF and hydrogen

5.2.1. EU budget

The European Commission has proposed that 30 % of the post-2020 Multiannual Financial Framework (MFF) resources are to be dedicated to climate-related expenditures. This amounts to at least EUR 503 billion of the EU budget as climate-related funding. Of the instruments included in this figure, the most relevant for aviation are the Horizon Europe framework programme for research and innovation, CEF, cohesion policy, and the Innovation Fund. More recently, the RRF was established to help the EU to emerge stronger and more resilient from the COVID-19 pandemic, as well as to provide funding for the green transition, including transport.

a. Horizon Europe

Horizon Europe is the EU's key funding programme for research and innovation. Its goals include tackling climate change and boosting the EU's competitiveness and growth. The programme facilitates collaboration and strengthens the impact of research and innovation. It has a budget of EUR 95.5 billion, at least 35 % of which is to support climate objectives. Horizon Europe is the current programme in the series of Framework Programmes for Research and Technological Development (FP).

Horizon Europe and its predecessors encompass funding for research in aviation. The Clean Sky/Clean Aviation research programmes (with funding of almost EUR 10 billion over two decades), focussing on innovative aircraft technologies, and the SES initiative, focusing on ATM (with funding of over EUR 5 billion over two decades), are two key initiatives benefitting from Horizon Europe funding – see the next two sub-sections for more details about these programmes.

Besides the aviation-specific programmes, the Horizon Europe also supports research and innovation projects on hydrogen. Projects are managed by the Fuel Cells and Hydrogen Joint Undertaking, a public-private partnership supported by the European Commission. The European Hydrogen Valleys Partnership initiative under the Commission's Smart Specialisation Platform facilitates cooperation between European regions seeking to develop the production and utilisation of hydrogen (European Parliament, 2021a).

i. Clean Sky, Clean Sky 2 and Clean Aviation

The Clean Sky, Clean Sky 2 and Clean Aviation research programmes are public-private partnerships with funding support coming from the EU and from industry.

The general objectives of these programmes are to reduce the ecological footprint of aviation by accelerating the development of climate-neutral aviation technologies through innovation, the competitiveness of manned and unmanned air transport in the Union, and ATM services' markets (Clean Aviation JU, 2022). The programmes also aim to ensure that aeronautics-related research and innovation activities (particularly breakthrough technology initiatives) contribute to competitiveness, aviation safety and security requirements, and that aviation remains a secure, reliable, cost-effective and efficient means of passenger and freight transportation.

The programmes have the specific objective to integrate and demonstrate disruptive aircraft technological innovations able to decrease net emissions of GHGs by no less than 30 % by 2030, compared to 2020 state-of-the-art technology, while paving the way for climate-neutral aviation by 2050 (Clean Aviation JU, 2021a). A further specific objective is to ensure that technological and industrial readiness of innovations can support the launch of disruptive new products and services by 2035, with the aim of replacing 75 % of the operating fleet by 2050.

As per Council Regulation (EU) No 558/2014, the Clean Sky 2 (2014-2021) budget totalled around EUR 3.949 billion. The EU financial contribution to the Clean Sky 2 Joint Undertaking to cover administrative costs and operational costs was up to EUR 1.755 billion. Contributions from members other than the EU (stakeholders from industry and national research institutions) were expected to be at least EUR 2.194 billion.

More recently, Council Regulation (EU) 2021/2085 established the Clean Aviation Joint Undertaking (2021-2028), with a total budget of EUR 4.1 billion. EU appropriations to cover administrative costs and operational costs are to be up to EUR 1.7 billion. Other members of the Clean Aviation Joint Undertaking will make a total contribution of at least EUR 2.4 billion.

Table 5-4 presents an overview of the funding for the different Clean Sky/Aviation programmes.

Table 5-4: Overview of Clean Sky/Aviation programmes funding

Research initiative	Timeline	FP	Public funding	Private funding
Clean Sky	2007-2014	FP7	EUR 0.8 billion	EUR 0.8 billion
Clean Sky 2	2014-2021	Horizon 2020	EUR 1.8 billion	EUR 2.2 billion
Clean Aviation	2021-2028	Horizon Europe	EUR 1.7 billion	EUR 2.4 billion

Source: (European Council, 2007) for Clean Sky; (European Council, 2014) for Clean Sky 2; (European Council, 2021) for Clean Aviation.

In total, these programmes will receive almost EUR 10 billion in funding over two decades, 44 % of which is public funding. While these R&D programmes are expected to continue, the level of public funding after the 2028 period cannot be predicted at this point.

ii. Single European Sky and SESAR

The SES initiative was established in 2004 to increase the efficiency of ATM and air navigation services. The technological and industrial dimension of the SES (i.e. the development and deployment of the new European ATM system) was set up in 2007 as the SESAR Joint Undertaking. The development phase of the SESAR programme (2008-2024) was estimated to cost EUR 3.7 billion, evenly split between the EU, EUROCONTROL[74] and industry (SESAR JU, 2017).

Between 2008 and 2016, the SESAR 1 programme received EUR 0.7 billion from the EU plus EUR 1.4 billion from Eurocontrol and the industry, for a total of EUR 2.1 billion. The subsequent SESAR 2020 (2016-2024) received EUR 1.6 billion in total funding, including EUR 596.3 from the EU. Per Council Regulation (EU) 2021/2085, SESAR 3 has a forecasted budget of EUR 1.6 billion, with the EU portion being slight bigger than that the industry and Eurocontrol allocations (EUR 500 million each). SESAR 3 is planned to fund projects from 2021 to 2031, with a three-year overlap with SESAR 2020. Table 5-5 presents an overview of the funding for these programmes.

Table 5-5: Overview SESAR programme funding

Research Initiative	Timeline	Framework programme	EU funding	Other funding
SESAR 1	2008-2016	FP7	EUR 0.7 billion	EUR 1.4 billion
SESAR 2020	2016-2024	Horizon 2020	EUR 0.6 billion	EUR 1.0 billion
SESAR 3	2021-2031	Horizon Europe	EUR 0.6 billion	EUR 1.0 billion

Source: (SESAR JU, 2020b) for SESAR 1 and SESAR 2020; (European Council, 2021) for SESAR 3.

For SESAR 3, research will focus on nine 'flagship areas' (SESAR JU, 2020):

1. Connected and automated ATM;
2. Air ground integration and autonomy;
3. Capacity-on-demand and dynamic airspace;
4. U-space and urban air mobility;
5. Virtualisation and cyber-secure data sharing;
6. Multimodality and passenger experience;
7. Aviation Green Deal;
8. Artificial intelligence (AI) for aviation;
9. Civil/military interoperability and coordination.

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[74] EUROCONTROLl, the European Organisation for the Safety of Air Navigation, is an international organisation with 41 member states within and outside the EU. Its aim is to make aviation in Europe safer, more efficient, more cost-effective and to minimise its environmental impact (EUROCONTROL, 2022).

While these research areas are all likely to improve the efficiency of the ATM system – and thus support decarbonisation - flagship areas #1 and #7 are particularly important in this respect. Flagship area #1, connected and automated ATM, is at the crux of the SES and involves further advancements in the technologies required for more efficient airspace across the EU. Flagship area #7, Aviation Green Deal, focuses on delivering decarbonising gains via advancements in ATM. Areas of research include the optimisation of flight trajectories with a focus of fuel savings, 'formation flying' where aircraft fly closer together (much like migrating birds) to reduce fuel use, and environmentally optimised climb and descent operations (SESAR JU, 2020).

In addition to EU funding on R&D, the deployment of the operational improvements of the SESAR programme to actually implement a 'single European sky' will require significant investment from the industry (i.e. air navigation service providers). The total investment is expected to be up to EUR 28 billion between 2015 and 2035, with the EU contribution only 10 % of the total investment (SESAR JU, 2017). As the R&D portion of SESAR eases, the focus will shift to deployment and the majority of the funding will come from industry. Nevertheless, the EU will play a role in funding the deployment stage, as some EU programmes funding infrastructure support ATM funding and are likely to continue to do so.

b. Connecting Europe Facility

CEF is the main EU funding programme specifically for transport infrastructure (as well as energy and digital services, with transport representing around 78 % of its budget for the 2021-2027 period). Its goals are to deliver sustainable and efficient trans-European networks. The European Climate Infrastructure and Environment Executive Agency (CINEA) manages the CEF Transport budget.

Between 2007 and 2020, CEF supported a multitude of aviation projects. These were generally divided into work or studies on airports, and improvements in operational and/or environmental efficiency in ATM (e.g. deployment of SESAR technologies in Member States such as Belgium, Hungary and Portugal) (CINEA, 2022a). A list of aviation projects supported by CEF was provided to the study team by CINEA and were analysed for this study. Some trends are evident in the funding periods 2007-2013 and 2014-2020:

- Total spending in aviation projects across the 27 EU Member States (EU-27) doubled, in nominal terms, between the two funding periods, from EUR 1.59 billion (for 36 projects) to EUR 3.15 billion (for 63 projects).
- The EU contribution multiplied three times between the first and second period, from EUR 468 million to EUR 1,468 million across the EU-27. This translated into an increase in the average EU contribution, from 29 % in the 2007-2013 period to 47 % in the 2014-2020 period.
- The majority of EU funding was provided to ATM-related projects. In the 2007-2013 period, only 10 % of EU funding went to airport projects (11 of 36 projects). In the 2014-2020 period, 98 % of funding went to ATM projects (55 of 63 projects[75]).

For the current funding period (2021-2027), the CEF budget will total EUR 25.8 billion to support transport infrastructure projects (CINEA, 2022b). Of this, EUR 11.3 billion will be earmarked for countries eligible to receive support from the Cohesion Fund (CF). The most recent 2021 CEF Transport call closed with 447 project proposals requesting EUR 14.5 billion in co-funding, with available funding of EUR 7 billion. From a total of 134 projects that were selected for funding, only five related to aviation

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[75] Some of the 55 ATM projects related to ATM improvements at airports (e.g. new towers or other ATM equipment).

(all on ATM-related projects), with a combined EU contribution of EUR 47.6 (total project values have been not specified, so non-EU funding shares are now known). According to an official at CINEA, as of March 2022, no grants for aviation projects were signed for this round of funding[76].

Previous rounds of CEF funding appear to indicate that funding for aviation is mostly granted to ATM projects related to the deployment of the SES (see Section 5.2.1a.ii). No evidence was found that these priorities will shift in the 2021-2027 period, meaning that CEF funding for aviation projects will likely continue to be directed towards ATM projects. This has benefits for decarbonisation of the aviation sector, as a more efficient ATM allows flights to be optimised for minimum fuel consumption and emissions (see Section 3.3).

c. Cohesion policy

EU cohesion policy contributes to strengthening economic, social and territorial cohesion in the Union (European Commission, 2022a). Two of the key instruments of EU cohesion policy are the CF and the European Regional Development Fund (ERDF). The CF and the ERDF are expected to invest at least EUR 108 billion in climate and environment-related projects between 2021 and 2027. The ERDF receives a certain level of co-financing from national authorities (15-50 %), with less developed regions receiving greater EU contributions (EU-Learning.net, 2022). Funding through these instruments does not solely rely on the EU budget.

The ERDF and CF can support the deployment of sustainable transport infrastructure. They have previous supported investment in ATM (as part of the work on the SES), as well as airport infrastructure to change the negative environmental impact of airports.

Article 7(1)e of Regulation (EU) 2021/1058 on the European Regional Development Fund and on the CF notes that investments in airport infrastructure are only permitted for outermost regions or existing regional airports, and that those investments must go towards environmental impact mitigation measures or towards security, safety, and ATM systems as part of SESAR. In other words, no financial support is possible for alternative fuels infrastructure at airports, except where it is covered under the environmental impact mitigation measures.

Cohesion policy has funded some initiatives supporting the decarbonisation of aviation. An example of a project funded by the ERDF is the Sustainable Aviation Fuels Innovation Centre established by the University of Sheffield to support and promote the production and characterisation of SAF (Barton, 2021).

An analysis of total CF and ERDF funding during 2014-2020 shows that aviation projects received only 0.6 % of the spending during that period (for a total of EUR 1.7 billion of EU spending in these aviation projects; total investment represented EUR 1.8 billion) (European Commission, 2022f). Although not insubstantial, this is nevertheless dwarfed by the EUR 268 billion the EU spent on transport projects during the period (total investment of EUR 324 billion) – as per authors' calculations using the data made available by the European Commission (European Commission, 2022f). Given the focus of cohesion policy, changes allowing for wider use of these funds in aviation are not expected and current funding levels for aviation are unlikely to increase.

d. Recovery and Resilience Facility and the National Recovery and Resilience Plans

The NextGenerationEU fund is the EU recovery plan out of the COVID-19 pandemic. It is worth EUR 723.8 billion in loans and grants (at current prices), at least 30 % of which must be spent on

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[76] Results on ATM/SESAR grants are expected in June 2022, after the publication of this study.

combating climate change. The RRF is the key instrument of NextGenerationEU and aims to 'mitigate the economic and social impact of the coronavirus pandemic and make European economies and societies more sustainable, resilient and better prepared for the challenges and opportunities of the green and digital transitions' (European Commission, 2022b).

Member States can access these funds following the submission of National Recovery and Resilience Plans (NRRPs) and can use the money on aviation (and transport in general) initiatives. However, the use of the RRF to fund aviation initiatives is severely limited by the 'do-no-significant-harm' (DNSH) assessment. As the DNSH guidance states, 'on the basis of DNSH to climate change mitigation, only measures related to low-carbon airport infrastructure such as investments in energy-efficient airport buildings, on-site renewable grid connection upgrades of airport infrastructure and related services are likely to be compliant' (European Commission, 2021l). The application of the DNSH assessment limits Member States' capacity to use the RRF to support investments in aviation and precludes support for investments such an expansion of airport capacity. A review of the Commission's analysis of the NRPPs of 24 Member States[77] showed that only five Member States (Belgium, Croatia, France, Italy, Spain) outlined investments in aviation in their NRPPs, all of which include aspects targeting climate change mitigation. These investments total EUR 1.6 billion, 85 % of which comes from France, which is supporting R&D in zero-emission aircraft technologies and solutions. Table 5-6 outlines the investments on aviation in the NRPPs of these five Member States.

Table 5-6: Aviation measures across the Member States' NRPPs

Member State	Aviation investment	Budget (EUR million)
Belgium	R&D support of the aeronautics sector	25
Croatia	Alternative fuels infrastructure at Zadar airport	5.3
	Capacity building for solar energy at Zadar airport	0.5
France	Support to R&D to the aeronautics sector	1,370
Italy	Digitalisation of ATM	110
Spain	SES: digitalisation	107
Total		**1,608**

Source: Authors' elaboration based on the aviation measures with climate impacts available on the "Staff Working Documents" that the European Commission produced about the NRPPs of each Member State. These documents are available at: (European Commission, 2022b).

The application of the DNSH assessment is not as limiting for land-based transport modes, which have clear and readily available means of decarbonisation (e.g. electrification of transport modes is explicitly referenced by the Commission as being compatible with the DNSH principles (European Commission, 2021l)). Of the 24 Member States' NRPPs reviewed by the Commission, investments in transport infrastructure and transport vehicles totals over EUR 67 billion[78]. This includes investment in charging infrastructure for road vehicles, building or renewal of rail infrastructure, and supporting the purchase of trains, buses and electric cars.

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[77] As of 20 April 2022, these Commission's reviews of the NRPPs (Staff Working Document) were not available for Hungary, the Netherlands and Poland. See (European Commission, 2022b) for available reviews.

[78] Includes investments in alternative fuels (biofuels, hydrogen, etc.) aimed directly at the transport sector, but does not include more general investments in alternative fuel production and infrastructure, even where those investments might also have a transport use.

5.2.2. Innovation Fund

The Innovation Fund is financed outside the EU's long-term budget, with its funding coming exclusively through the EU ETS (European Commission, 2022c). Established by the ETS Directive, the Innovation Fund aims to support the demonstration of low-carbon technologies in energy-intensive industries, renewable energy, energy storage, carbon capture and storage, and industrial carbon capture and use. The Innovation Fund is expected to provide around EUR 38 billion[79] of support for the demonstration of innovative low-carbon technologies over the 2020-2030 period (European Commission, 2022c).

According to the Commission Delegated Regulation (EU) 2019/856 (Innovation Fund Regulation), Innovation Fund support will be provided in the form of a grant of up 60 % of the additional costs linked to the innovative low-carbon technology applied. The Innovation Fund grant is not considered State aid. To cover the remaining 40 % of relevant costs and all other costs, a project applicant can combine the Innovation Fund grant with any other public support in line with the applicable rules, including public support by a Member State (i.e. State aid).

The Innovation Fund is one of the world's largest funding programmes for the development of innovative low-carbon technologies. To date, funded projects include research on hydrogen, biofuels and carbon capture and storage (European Commission, 2021b), which could eventually support the aviation sector to reduce its environmental impact. Only one project directly supported aviation decarbonisation – the 'PIONEER – airPort sustaInability secONd lifE battEry storage' project, which installs second-hand batteries (first used in electric cars) at Rome Fiumicino Airport to store electricity produced using solar photovoltaic panels. This project received EUR 3 million from the Innovation Fund and is scheduled to finish construction by 2024 (ENEL, 2021).

A call is ongoing for new large-scale projects, with a total budget of EUR 1.5 billion (European Commission, 2022d). Over time, as aviation becomes one of the few sectors in the economy where decarbonisation pathways are not yet fully developed, more and more projects with potential applications to aviation (or perhaps focusing exclusively on aviation) are likely to be funded.

5.2.3. InvestEU

The EGDIP outlines how the InvestEU Fund can leverage EU budget guarantees to partially cover the risk of financing and investment operations. InvestEU combines 13 centrally managed EU financial instruments and the European Fund for Strategic Investments into a single instrument (European Commission, 2021c). The aim of the fund is to support investments needed for the green transition but that entail more risk than the private sector alone can bear. InvestEU intends to mobilise EUR 650 billion from 2021 to 2027, of which 30 % is targeted for climate investments. Regulation (EU) 2021/1078 sets out investment guidelines for implementing partners, i.e. the EIB, National Promotional Banks and Institutions (NPBIs) and international financial institutions.

The InvestEU Fund aims to mobilise public and private investment through an EU budget guarantee of EUR 26.2 billion backing the investment projects of the EIB Group and other financial partners. Two 'policy windows' of the InvestEU Fund may be relevant for aviation: EUR 9.9 billion for Sustainable Infrastructure, and EUR 6.6 billion for Research, Innovation and Digitisation (European Commission, 2021d). The InvestEU Regulation provides that the InvestEU fund as a whole will target at least 30 % of investment contributing to climate objectives, with 60 % under the Sustainable Infrastructure policy

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[79] Depending on the carbon price: EUR 38 billion at a carbon price of EUR 75/tCO_2. The amount of funding available for the Innovation Fund is thus highly dependent on the price of carbon on the EU ETS market. For a discussion of the impacts of the price of carbon on the aviation sector see (Adler, Boonekamp, & Konijn, 2022).

window. The InvestEU detailed rules indicate that the Fund can support investments in the digitalisation of transport (including SESAR), as well as the supply of alternative fuel supply points (European Commission, 2021m).

The EIB will also undertake other financing and investment operations (see Section 5.2.5).

A further instrument to consider is the Green Transition Investment Facility, currently under negotiation, which will add to the InvestEU resources (EIB, 2021a). The first two policy areas considered under the Facility are clean energy/low-carbon innovation and future mobility. The Green Transition Investment Facility is expected to receive a contribution from the Innovation Fund (see Section 5.2.2). A proposal from the European Commission for an SAF blending mandate across the EU (as part of the ReFuelEU Aviation Regulation) also establishes that any administrative fines resulting from the enforcement of the provisions of that initiative[80] should be transferred to the Green Transition Investment Facility to top-up the EU guarantee (European Commission, 2021i).

5.2.4. Just Transition Mechanism

The Just Transition Mechanism is a tool to ensure that the transition towards a climate-neutral economy happens in a fair way and does not leave behind those regions and communities most exposed to the transition challenges (European Commission, 2022e). Mobilising at least EUR 100 billion in investments between 2021 and 2027, the Mechanism comprises three pillars: the Just Transition Fund, the Just Transition Scheme and the public sector loan facility.

The JTF is expected to generate financing of EUR 30-50 billion. It will primarily provide grants and will include contributions from the ERDF and Member States through co-financing. The scope of support of the JTF is defined in Article 8 of Regulation (EU) 2021/1056, with Article 8(2)(d) including 'investments in the deployment of technology as well as in systems and infrastructures for affordable clean energy, including energy storage technologies, and in greenhouse gas emission reduction', which could potentially be applied to aviation. However, the scope does not include airport infrastructure, as confirmed by the Commissioner for Cohesion and Reforms to the European Parliament in 2020 (European Parliament, 2021b), and it is not clear if any other aviation-related investments would be eligible. The objectives of the JTF are to focus on regions of the EU that are highly dependent on fossil fuel mining/extraction or carbon-intensive industries[81], further restricting the potential applicability of the JTF to support aviation decarbonisation. In addition, those regions might not be served by aviation (although they could have a role in the overall aviation supply chain, e.g. production of SAF).

The Just Transition Scheme will provide guarantees under the InvestEU programme (see Section 5.2.3) to mobilise up to EUR 45 billion in investments. It will also provide an InvestEU advisory hub that will act as a central entry point for advisory support requests. The public sector loan facility will combine EUR 1.5 billion of grants from the EU budget, with EUR 10 billion of loans from the EIB. This will leverage public financing to mobilise EUR 25-30 billion in investments. While these additional tools could potentially be applied in a wider range of projects than the JTF, they are also to be applied in the same priority regions as the JTF, potentially precluding their use in aviation investments (Department of the Environment, Climate and Communications, 2021).

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[80] These fines can be imposed on airlines if they do not comply with the requirement to uplift 'at least 90 % of the yearly aviation fuel required' at each EU airport (this is to avoid the practice of 'tankering' where airlines refuel aircraft at airports with cheaper fuel), and on fuel suppliers if they do not comply with the minimum blending rates for SAF imposed by the proposed regulation (see Table 5-1).

[81] For an initial list of regions eligible for the JTF, see (European Commission, 2020f).

5.2.5. International and national financial Institutions

Beyond the InvestEU Fund, international and national financial institutions have other financing and investment operations that may be relevant for aviation decarbonisation. These are expected to increasingly align with European Green Deal objectives, providing a role for international and national financial institutions in financing the deployment of infrastructure to advance the decarbonisation of the aviation sector, and funding technological research.

The following sub-sections explore the potential role of the EIB, NPBIs and international financial institutions.

a. European Investment Bank

The EIB has financed the deployment of different SES initiatives (EIB/SESAR, 2017), supported research in cleaner aircraft engines (EIB, 2021b) and focused its support of airports on improving their efficiency and environmental footprint (Morgan, 2020). Between 2016 and 2020, the EIB signed finance contracts with a value of EUR 36.7 billion for transport climate action (EIB, 2021c).

In 2019, the EIB announced that it would support EUR 1 trillion of investments in climate action and environmental sustainability between 2021 and 2030 (EIB, 2019a), guided by its Climate Bank Roadmap (EIB, 2020a). The Climate Bank Roadmap points to an ongoing lack of clarity on the pathway to decarbonising aviation, with the EIB's investments accordingly limited to the decarbonisation and resilience of infrastructure, roll-out of zero direct emission aircraft, SAF R&D, and the digitalisation of aviation. No investments will be made in airport capacity expansions (similar to the DNSH assessment of the RRF, see Section 5.2.1.d) and conventionally fuelled aircraft. Nevertheless, in late 2021 the EIB agreed to loan EUR 90 million to support Bologna's airport development plan, which includes 'additional terminal and landside capacity in order to accommodate traffic growth' (EIB, 2022a).

Between 2013 and 2022, of EUR 90 billion directed at the transport sector across the EU-27, only some EUR 4.5 billion was spent on aviation, all of it on airports, and most including a component of capacity expansion (EIB, 2022a). This paradigm shift in EIB support across the airport sector will therefore significantly change the support to EU airports. Given the difficulties associated with decarbonising aviation – including the lack of clarity on the pathway to decarbonising aviation noted by the Climate Bank Roadmap - the share of EIB's transport funding directed at aviation will likely remain limited, with a focus on the decarbonisation of other transport sectors.

b. National Promotional Banks and Institutions

NPBIs support government targets at a national or regional level by investing in projects, funds, and companies (EIB, 2022b). They often act as financial intermediaries for EIB investments directed to small-scale projects. The EIB and the five largest European NPBIs launched a Joint Initiative on the Circular Economy (EIB, 2019b) and cooperated in the fight against COVID-19 (EIB, 2020b), through the informal '5+1' group that includes the NPBIs from France (*Groupe Caisse des Dépôts* and Bpifrance), Germany (KfW), Italy (*Cassa Depositi e Prestiti*, CDP), Poland (*Bank Gospodarstwa Krajowego*) and Spain (ICO). It is not yet clear if this agreement will lead to any direct support for aviation decarbonisation, but it is nevertheless an indication of the overall direction of funding towards sustainable finance, which could eventually include aviation.

Some examples of the funding made available to aviation from these NPBIs include the German bank KfW providing financing for airlines and leasing companies (KfW, 2022), and France's *Groupe Caisse des Dépôts* supporting the aviation sector with loans (Caisse des Dépôts, 2020). However, no overarching strategies could be found that indicate the types of funding, if any, that aviation decarbonisation activities might receive in the future from NPBIs. Like EIBs, support for the aviation sector is expected to shift away from climate-harming activities such as airport expansion, and instead focus on initiatives to support decarbonisation.

c. International financial institutions

The EGDIP suggests that 'Other International and National Financial Institutions will play an increasing role in financing sustainability in line with EU policy objectives', but it is unclear whether these international financial institutions might play a role in the decarbonisation of aviation in the EU. For example, while the World Bank has a presence in some of the Eastern EU Member States (The World Bank, 2022a), it does not appear to support any aviation-related investments in those Member States. As such, it the role of international financial institutions is expected to be limited.

5.2.6. Green finance

Green finance or sustainable, finance are terms used for financing or investing based on environmental and sustainability principles. As an area of growing interest, it can be leveraged to support investments in decarbonisation.

Green finance can encompass multiple aspects, such as the concept of 'stewardship', where institutional investors or assets managers procure ownership of companies to 'steward' them towards more sustainable decisions[82]. While this aspect of green finance has gained prominence in sectors such as oil (Somerset Webb, 2022), it has only limited presence in the aviation industry (airlines and airports). However, as other sectors of the economy decarbonise, more interest from green investors could be directed towards aviation.

A common and clear definition of 'green' is crucial to raise the profile of green finance and support its growth. The EU taxonomy plays a major role in putting green finance at the heart of the overall financial system, by establishing a unified classification system to determine which activities can be considered as green investments.

The importance of the EU taxonomy is two-fold:

- For the private sector, being able to classify certain kinds of investments as 'green' can have several benefits, such as reputation (a company can claim to invest a certain percentage of their capital in green investments, backed by the taxonomy classification), and the ability to offer green products (e.g. banking or asset management can offer proven green bonds to their customers, potentially offering them an advantage in a growing market) (UNCTAD, 2021)[83]. This could, in theory, nudge those asset managers to offer more green products in the future, thus supporting more investment in sustainable goods and services.
- For the public sector, the EU taxonomy allows transparency in decisions as to whether public investments can be considered to support sustainability goals. For example, the EIB considers the EU taxonomy rules in its assessment of the environmental, climate and social considerations of the investments it supports (EIB, 2019a). This will have implications for investment decisions under the InvestEU funding stream (see Section 5.2.3), for which the EIB is the main implementing partner.

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[82] The concept of stewardship can be defined as '[investors promoting] the responsible allocation, management and oversight of capital to create long-term value for clients and beneficiaries leading to sustainable benefits for the economy, the environment and society' (see discussion in (HM Government, 2021)).

[83] From 2022, EU banks will have to report their 'green asset ratio', a measure of how much of their investment balance sheets complies with the EU taxonomy. This is also expected to prompt banks to increase their investments in green finance (Furness, 2021).

Although aviation is included in the EU's Taxonomy Regulation, the lack of clear criteria defining sustainable financing in the context of aviation may be a barrier to access financing (see Section 5.1.3.f). The 2021 Steer report highlighted the need to develop TSC for all aviation-related activities to be included in the EU Taxonomy Regulation, and proposed that those criteria should align with or exceed existing targets and standards set by the ICAO (Steer, 2021).

Failure to fully include the aviation sector and related sectors in the EU taxonomy constitutes a regulatory barrier hindering its recourse to private capital. As mentioned in the Steer report, by 2020, 'green labelling' had attracted more than EUR 700 billion investment in green assets and projects. An inability to fully participate in this funding limits the potential of sustainable finance for aviation.

5.2.7. Conclusions

This chapter explored the funding streams provided by the EU to date and their potential role in supporting large-scale decarbonisation, either as direct funding programmes or as financing streams that the EU enables via regulatory action.

Existing programmes have typically funded R&D needs for aircraft and ATM-related technologies (under the Clean Sky/Clean Aviation and SESAR programmes), as well as deployment of ATM technologies (under CEF and EU cohesion policy). While these are key areas in the pathway to decarbonisation, much of any future investment will be needed in two areas where EU support has been limited: commercial availability of new fuels, and purchase of more efficient aircraft.

The major issue in respect of new fuels is the need to support production at scale in the case of SAF, and production at scale and availability of infrastructure in the case of hydrogen. The EU has funded R&D for these fuels (e.g. via the Innovation Fund) and some Member States have plans to use the RRF funds to support the growth of the sector, but major investment is needed if they are to become commercially available at scale. While it is expected that the majority of that investment will come from the private sector, the EU could create the necessary regulatory conditions for commercial offerings to be more widely available, as well as offering financial support (loans or grants) to spur investment in the sector.

Airlines operate in a commercial setting and competitive market, making it generally inappropriate for the EU to directly fund new, more efficient aircraft, as well as likely to contravene rules on State aid (see Annex A4). Rather, this is a role for the private sector. Aircraft are expensive assets with a lifespan of decades, and as such the replacement of an airline's fleet is once-in-a-generation event, where improved efficiency is just one of many factors. The EU could, however, promote the uptake of more efficient aircraft and the shortening of that replacement cycle via the inclusion of aircraft in the Taxonomy Regulation (see Section 5.2.6).

Table 5-7 summarises the different funding streams, their applicability, and past/future (time period vary depending on the instrument) expenditure in aviation. The last column shows the amount of that aviation expenditure that is funded by the EU.

Table 5-7: Summary of aviation expenditure and EU funding streams

Funding stream	Potential areas of support in aviation	Total aviation expenditure (EUR billion)	EU contribution (EUR billion)
Clean Sky/Clean Sky 2/Clean Aviation	Aircraft technology development	EUR 9.7	EUR 4.3
SESAR	ATM	EUR 5.3	EUR 1.9
SES	ATM	EUR 28	EUR 2.8*

Funding stream	**Potential areas of support in aviation**	**Total aviation expenditure (EUR billion)**	**EU contribution (EUR billion)**
CEF	Airport infrastructure ATM	EUR 4.7	EUR 1.9
Cohesion policy	Airport infrastructure	EUR 1.8	EUR 1.7
RRF	Aircraft technology development Airport infrastructure ATM SAF and hydrogen	EUR 1.6	EUR 1.6
Innovation Fund	SAF and hydrogen	-	-
InvestEU	ATM SAF and hydrogen	-	-
Just Transition Mechanism	Limited	-	-
International and national financial Institutions	Fleet replacement costs Airport infrastructure ATM SAF and hydrogen	EUR 4.5	-
Green finance	Aircraft technology development Fleet replacement costs Airport infrastructure ATM SAF and hydrogen	-	-

*Note: this figure may overlap with the figures under the CEF and cohesion policy, as those funding streams were used to fund the deployment of SES infrastructure. Cells in grey and no value listed indicate areas where it is not possible to estimate at this point how much money will be spent on aviation measures; please see the respective sections earlier in the chapter for details.

Source: authors' elaboration.

6. POTENTIAL CHALLENGES

KEY FINDINGS

- The main barriers for aircraft manufacturers and air carriers to adopt decarbonisation technologies relate to their risk adversity in the context of high capital costs, slow fleet replacement, and high uncertainty. Airlines also have a limited capacity to absorb additional costs in a highly competitive market.
- The application of decarbonisation policies at EU level tend to focus on intra-EU (or intra-EEA) flights, thus the burden of these policies may be higher on EU carriers and airports compared to non-EU players. There may be a demand switch from EU hubs to non-EU hubs, especially from peripheral EU airports to nearby non-EU airports. These demand effects would disproportionally affect EU carriers and airports if similar policies are not implemented in other regions.
- The effects on connectivity are expected to be limited, and to apply mostly to small and peripheral airports.

6.1. Main barriers

This section analyses the implementation barriers for manufacturers and air carriers to adopt decarbonisation technologies. Several issues were identified:

- **High capital costs of new aircraft designs.** The purchase of aircraft equipped with new technologies would imply additional capital costs for air carriers. As per the estimates in Section 4.3, the total costs to airlines of purchasing aircraft between 2020 and 2050 may be EUR 377.6 billion higher, compared to a situation with no technology developments.
- **Slow fleet replacement rate and long investment cycles**. The longevity of the fleet means that it takes longer for air transport companies to introduce newer, more sustainable aircraft into service. This can be compounded by the time it takes aircraft to pass rigorous national and international safety standards. Policies can be created to support quicker fleet replacement rates, for example, by including aircraft purchases under the umbrella of the Taxonomy Regulation (see Section 5.2.7) or by supporting innovative solutions such as 'scrappage schemes' to incentivise fleet replacement (an option that would need to be carefully designed to avoid issues with State aid) (Kaminski-Morrow, 2020).
- **Lack of certainty about which solutions will become the frontrunners.** Given the long investment cycle, aircraft manufacturers and air carriers are very risk averse. This means that the industry may defer investment until a technology becomes a clear frontrunner and can be deployed at scale to avoid sunk costs[84]. One of the functions of large public and private research programmes is to streamline the technological landscape and seize economies of scale.

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[84] A cost already incurred that cannot be recovered.

- **Lack of certainty about hydrogen infrastructure deployment at airports.** Sufficient deployment of refuelling infrastructure in airports is essential to support the uptake of low-carbon technologies and fuels for aviation. Again, however, the uncertainty in respect of the likely infrastructure frontrunner adds another layer of complexity. A clear roadmap on technology choices and their most suitable market segments will be key to plan infrastructure needs accordingly.

- **Airlines' limited capacity to absorb extra costs.** The aviation market in the EU is highly competitive, with profit margins rather thin compared to other sectors. This limits the capacity of air carriers to absorb additional costs derived from decarbonisation measures. Those additional costs are likely to be passed on to air transport users, which may have an impact on demand. The COVID-19 pandemic worsened the financial situation of air carriers, despite government support measures, further limiting the capacity of air carriers to invest in a more modern fleet and implement decarbonisation technologies.

6.2. Competitiveness of EU air carriers compared to non-EU carriers

Competitiveness can be defined as the ability of aviation companies in a region to maintain profits and market share. Regional (rather than global) policies might disproportionately affect businesses operating in that region, and this may lead to a competitive disadvantage (OECD/IEA, 2008).

Decarbonisation policies in the aviation sector usually apply to both EU and non-EU carriers. This is the case for the EU ETS for intra-EU flights, the proposed SAF mandate and the proposed fuel tax on intra-EU flights, for example. However, as EU carriers are likely to have a greater proportion of intra-EU flights than non-EU carriers, those impacts may differ (ATA/Clarity, 2018):

- Airlines with more affected routes will have a larger overall policy-related cost burden (volume effect). They will therefore have a reduced ability to cross-subsidise[85] affected routes from profits on unaffected routes (cross-subsidisation effect), placing them at a disadvantage on routes between the EU and a third country, for example. In addition, on a given intra-EU route, EU carriers that serve both intra-EU and extra-EU routes might have better overall profitability than EU carriers that serve only intra-EU routes.

- Airlines with hubs in policy-affected regions (the EU, here) will face greater costs than those with external hubs. If costs are passed on to fares, then ticket prices via these hubs will increase, potentially leading to a shift in market share towards other airlines (the hub effect). That could be the case where an EU airline operating long-haul flights from an EU airport competes on a similar route with a non-EU airline connecting via a non-EU hub airport.

Impact assessment studies in the context of 'Fit for 55' policy initiatives for aviation suggested very limited effects on EU carriers' competitiveness. For example, the SAF mandate included in the ReFuel Aviation initiative (European Commission, 2021i) is expected to lead to a limited ticket price increase by 2030 (+1 %). Such a price increase is not itself expected to justify a switch in customer behaviour from direct flights to connecting flights, or even to select an alternative hub connection.

However, other studies (Adler, Boonekamp, & Konijn, 2022) on the overall effect of the 'Fit for 55' package for aviation (EU ETS, CORSIA, EU tax on kerosene in the ETD, SAF mandate in the ReFuel Aviation initiative) suggest a more significant effect. They estimated a demand drop of 10 % for intra-

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[85] Cross subsidisation is the practice of charging higher prices to one type of consumer to artificially lower prices for another group.

EEA flights and a reduction by 1.4 % in demand for extra-EEA destinations if the complete cost increase was passed on to consumers. These demand effects would disproportionally affect EU carriers until similar policies are implemented in other regions. However, other regions are also developing their own SAF and decarbonisation policies (e.g. the US, see Section 8), which would mitigate the impact.

6.3. Competitiveness of EU airports compared to non-EU airports

Aviation decarbonisation policies with an EU scope may impact the competitiveness of EU airports through the hub-switching effect described above. EU hub airports with large international traffic could be put at competitive disadvantage if passengers, for economic reasons, choose to re-route and connect via neighbouring non-EU hubs. The extent to which hub switching may occur also depends on a number of additional factors, including slot availability at airports and passenger preferences.

A recent study on the effect of 'Fit for 55' on aviation (Adler, Boonekamp, & Konijn, 2022) found that the number of passengers traveling to a non-EEA destination, either directly or via an EEA hub, would decrease by 2.7 % in 2030, while the number of intercontinental passengers travelling through non-EEA hubs would increase by 1.9 %. Hubs close to the EU (e.g. Istanbul (IST), Moscow Sheremetyevo (SVO)) would see a significant increase in traffic volumes. Traffic gains in extra-EU hubs would primarily come from lost traffic in peripherical EU hubs (e.g. Madrid, Helsinki or Larnaca), while more central EU hubs (e.g. Amsterdam, Frankfurt) would be less affected (Adler, Boonekamp, & Konijn, 2022).

6.4. Connectivity

Another potential effect is the switch to a non-EU airport to travel from/to a final origin/destination in the EU via a land connection.

Air connectivity can be broadly defined as the ability and ease with which passengers and freight can reach destinations by air. Air connectivity plays a crucial role in enhancing economic growth by facilitating tourism and inward foreign direct investment and supporting trade in goods and services (ITF, 2018). Air connections are particularly important where there are no substitutes, as is the case for remote locations and islands.

Potential increases in ticket prices as a result of decarbonisation policies in the aviation sector could reduce demand for air transport (either no travel or switch to other modes). In principle, this could potentially lead to lower flight frequencies on some routes, as they become financially unviable for air carriers to operate. However, this effect may be limited for a number of reasons (Ricardo, 2021):

- Any decrease in demand compared to the baseline would be offset by an overall demand growth trend. Hence, demand levels and frequency of services are not expected to be lower than current levels on average.
- For routes/peripheral regions where connectivity is a real issue, there is generally a public service obligation (PSO) in place that ensures a minimum level of connectivity.
- For routes with high frequencies, a reduction in the number of flights may not be a major issue from a connectivity point of view, as a potential reduction of flights would have only a marginal effect on travellers' choices.

There is a risk, however, that routes to smaller airports with no PSO would be the first to be cut, particularly those served by low-cost carriers, which tend to be associated with price-sensitive demand. To safeguard air connectivity for the benefits of EU citizens, businesses and regions, it is thus important to avoid imposing undue burden on air transport operations at small airports in EU peripheral regions.

7. BEST PRACTICES AROUND THE WORLD

KEY FINDINGS

- Three global case studies were analysed in detail to demonstrate the potential for decarbonising aviation.
- Each case study is examined in light of one of the three themes:
  - SAF: Green Fuel Green Skies;
  - Technologies and associated infrastructure: Airbus, Air liquid and VINCI airport's hydrogen hub;
  - ATM: US Nextgen.
- These collaborative initiatives/programmes met the key concerns about uncertainty of market dynamics, in terms of both deployment of innovations and solutions, and their management in the medium and longer term.
- Collaboration and involvement of key stakeholders are at the core of these initiatives, and a continuous commitment on expansion of stakeholder involvement is key for their success. However, lack of relevant policy mechanisms and financial instruments across the market limit the potential for 'buy-in' from the public and private sectors.

7.1. Introduction

This task aimed to identify, analyse and present best practice in aviation decarbonisation measures and financial instruments, and to inform policy-making in the EU.

It used desk research and an in-depth review of potential case studies on the decarbonisation of aviation through the strategic and structured establishment of national or international policy programmes. These programmes may individually or collectively impart progress, through innovation or collaborative networks and clusters. The three case studies are presented in Section 7.2 and focus on:

- **Context:** This section sets the scene for the aviation-driven environmental concern against which the promising case study was implemented. This is followed by a general introduction to the case study, its categorisation under the three themes, sectoral, spatial (geographical) and temporal (time-relevant) scope.
- **Design and implementation:** The nature and processes associated with these case studies are described in greater detail, defining their design, collaborative framework (relevant stakeholders), existing and planned programme of work, implementation timelines, financial and policy instruments put in place, key outcomes, and efficiency of the measures.
- **Key lessons and best practices:** This section details the experiences gained from the implementation of these case studies, drawing out their key strengths, risks and weaknesses, particularly highlighting relevant policy and financial mechanisms that enabled the case study's success, practices of stakeholder network development and cooperation, and strategies for development, including provision of funding streams,

shortening implementation times and supporting demonstrators to strategically improve the technology readiness level of promising technologies.

- **EU replicability:** This section reports the process by which relevant approaches could be replicated in the EU, informed by the detailed analysis the case studies. It includes the identification of the policy and financial support that would be needed, existing implementation barriers and adaptable best practices to successfully apply these case studies in the EU.

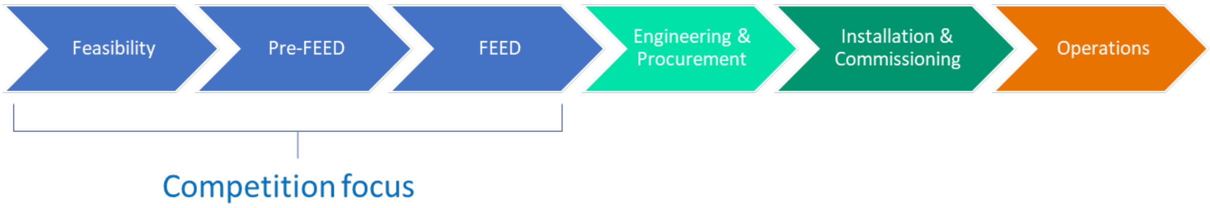
7.2. Case studies

7.2.1. UK: Green Fuels, Green Skies (GFGS) Competition

Context: SAF in the UK are expected to generate an annual revenue between GBP 0.7-1.7 billion (EUR 0.8-2 billion), partially through intellectual property export and provision of engineering services. As part of its aim to decarbonise aviation in the near-term, the UK Department for Transport undertook a number of initiatives focused on SAF deployment, including the Advanced Biofuels Demonstration Competition and the Future Fuels for flight and freight competition. The GFGS Competition followed those initiatives, as part of the national 'Ten-Point Plan for Green Revolution'. This was designed to drive the deployment of innovative SAF production at a commercial scale, supporting the pioneering of new technologies to convert waste streams such as household and forestry waste into SAF (UK Department for Transport, 2021).

Design and implementation: The GFGS competition included total grant funding of GBP 15 million (EUR 18 million) to be awarded through a single competitive funding round. It focused on projects within large-scale SAF production, notably their early-stage development, commonly referred to as front-end engineering design (FEED, see Figure 7-1). Overall, the competition prioritised the projects closest to developing first-of-a-kind (FOAK)[86] commercial scale SAF production plants. Following a rigorous review of applications, promising projects with the potential to reduce overall lifecycle emissions of candidate SAF by about 70 % (compared to conventional jet fuel) were selected and funded. The level of funding varied according to the maturity of the project, i.e. how close it was to commercial-scale SAF deployment (UK Department for Transport, 2021)).

Figure 7-1: Project lifecycle stages for a SAF plant and GFGS competition focus



Source: (UK Department for Transport, 2021).

Key lessons and best practice: The competition supported developers with crucial early-stage capital and activities relevant to the development of FOAK commercial and demonstration scale SAF plants. Support activities included stakeholder briefing sessions to take the interested parties through the application process and provide guidance on the standards for the measurement of lifecycle GHG

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[86] FOAK is a commonly used term in the manufacturing sector to denote the scale-up of a pilot production to semi-commercial or commercial production.

emissions for reporting purposes. Another good practice was that the competition leveraged private investment in the sector by supporting projects within the reach of 'investor ready' status. Since 2017, the initiative has helped to draw investor trust and thus investment in SAF production, increasing the TRL of the production technologies while removing some of the risk from FOAK initiatives. The GFGS competition was initiated in parallel with UK Clearing House[87], providing a coherent flow of support for early-stage SAF developers and producers. This could potentially allow more SAF to be available in greater quantities in the near future, supporting the decarbonisation of aviation activities.

EU replicability: The UK and EU markets face similarities in the challenges for commercial scale SAF deployment. In the EU, investing in SAF refineries is perceived as high risk, partly due to the lack of demonstrable SAF production, routes at commercial scales, and high development and capital costs (European Commission, 2020e). Another key deterrent is the consideration of SAF for medium to long-term decarbonisation of aviation, where producers perceive a limited life span for SAF stock and infrastructure, as they will eventually need to compete with hydrogen and electric propulsion systems (ICCT, 2021a). The prevalence of these risks and the demand to promote the EU SAF markets (from European Green Deal initiatives) makes the replicability of initiatives – at EU and Member State level - both feasible and crucial. Such initiatives could provide the necessary financial and technological boost to SAF production projects within the fringes of commercial deployment. Integration of an EU Clearing House concept is now being discussed for implementation by the EASA, which is expected to provide the appropriate regulatory framework and guidance to remove risk from close-to-commercial-scale SAF production and fast-track wider-level SAF uptake (EASA, 2019).

7.2.2. Airbus, Air Liquide and VINCI airport collaboration

Context: Aviation is globally acknowledged as 'hard-to-decarbonise', owing to the stringent technical performance and policy requirements around fuel specifications. These regulatory requirements extend to SAF, requiring them to be produced as drop-in fuels and relying on their carbon sequestering or displacement capacity in case of blending with biofuels or other RFNBO. Despite this regulatory 'status quo', there is wider acknowledgement of aviation's need to explore radical zero-carbon fuels, with the aim of delivering net-zero consistent environmental performance (ICCT, 2022). There is significant interest in hydrogen among aviation communities facing stringent national environmental targets, and this zero-carbon fuel has become a key aspect of mid-term (2030-2035) and long-term (2035 and beyond) strategies for large-scale aviation decarbonisation. With virtually no carbon emissions from its combustion, and potentially demonstrating 'zero-lifecycle' carbon when produced using renewable energy (green hydrogen), hydrogen demonstrates promising operational performance by eliminating the technical limitations (e.g. flight range restrictions, limited battery evolution) commonly associated with battery-electric power.

To accommodate the future role of hydrogen in encouraging zero-emission air travel in Europe and to mitigate the high risk associated with deployment of SAF refineries in general, Airbus, Air Liquide and VINCI airports established a partnership to promote the use of hydrogen by building a European airport hydrogen network. This initiative is in line with the cleaner energy systems strategies for scaling-up the production of hydrogen through the Commission's Hydrogen Roadmap to 2050 (European

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[87] The UK Clearing House Task Force, inspired by the US Clearing House, was set up by the Knowledge Transfer Network (KTN) in the UK to support SAF producers through the early stages of fuel testing and then to support the development and uptake of militarystandard sustainable fuels in UK aviation (KTN, 2021).

Commission, 2020d) and Airbus's ambition for the introduction of zero-carbon aircraft concept, *ZEROe*[88], to the market by 2035 (Airbus, 2022).

Design and implementation: Airbus and Air Liquide partnered with VINCI airports, which own and operate 52 airports in 12 countries. Lyon-Saint Exupéry airport was chosen for the pilot study and is expected to see a series of the hydrogen project implementations from 2023 onwards.

There is limited information on the overall investment costs, but the hydrogen gas distribution station is planned for deployment in 2023. This is expected to supply hydrogen for Lyon-Saint Exupéry's ground operations, such as buses, trucks, handling equipment and other heavy goods vehicles used around the airport. This phase is funded by the consortium of the three companies and is intended to evaluate the airport's adaptability and dynamics as a hydrogen hub. The second phase (2023-2030) involves the addition of liquid hydrogen infrastructure for refuelling hydrogen aircraft. This is in line with the Airbus's launch of ZEROe, which may establish a strong demand for on-site supply of liquid hydrogen. From the third phase (2030 onwards), this liquid hydrogen infrastructure is expected to be transformed into a more complex production and distribution facility to produce hydrogen onsite, while supporting its storage and mass distribution suitable for wider supply and distribution across the VINCI airport network. The production and distribution unit to be installed in Lyon St-Exupéry is expected to improve the commercial competitiveness for green hydrogen by widening demand - and thus supply - to the surrounding airport mobility services, particularly buses and shuttles to the airport, logistics and ground service equipment services.

Key lessons and good practices: Key takeaways from this collaboration are the degree of shared interest and practical implementation of initiatives among the different stakeholders of the hydrogen infrastructure and aviation community. It relies on Airbus's technical expertise of the engine-airframe configuration that is hydrogen compatible, Air Liquide's know-how on the hydrogen value chain (production and distribution), and VINCI's insights into site operations across a global test bed of airport networks. VINCI Airports also aim to support the infrastructure's initial performance evaluation and, eventually, progressive integration of hydrogen distribution hubs. VINCI Airports contribute by providing the land needed to install the hydrogen storage and distribution units, as well as participating in the purchase of the solar photovoltaics to produce that carbon-free electricity that is then used to produce hydrogen. As per an interview with the study team, VINCI Airports are also committed to developing the hydrogen demand on their airport platform (particularly through ground service equipment and mobility services) (VINCI Airports, 2022). Some of the key perceived risks are the current lack of commercial interest and associated lack of substantial commitment from third parties in adopting hydrogen technology. This is required to boost the competitiveness of hydrogen production and its daily operations. Another challenge identified by VINCI in an interview with the study team was the lack of clear evaluation and definition of a policy framework that creates the demand for hydrogen and partaking/sharing of overall hydrogen costs (VINCI Airports, 2022).

EU replicability: A similar collaboration is the Groningen Airport Eelde and the New Energy Coalition, where the airport seeks to produce green hydrogen on-site to support ground and aviation fuel operations (Groningen Airport Eelde, 2021). Other examples include the H2 Hub Airports' initiative by the 'Choose Paris Region' partnerships of public and private stakeholders that work with local representatives to promote international businesses (Choose Paris Region, 2022). This collaboration was funded by a mix of stakeholders from the hydrogen value chain and the aviation community.

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[88] The Airbus *ZEROe* series is the hybrid-hydrogen zero-emissions commercial aircraft expected to be powered by liquid hydrogen-oxygen in a modified gas-turbine and via fuel-cells to generate electrical power, thus improving the overall efficiency of the propulsion systems. Having reached a demonstrator stage, this technology is, according to Airbus, expected to be operational in 2035 (Airbus, 2022). See Section 3.2.3 for further information on the feasibility and timelines of hydrogen-powered aircraft.

With observed growth in progressive zero-carbon initiatives across Europe, these consortia identified several key demands for support:

- The need for a clear concise evaluation for support and transition from current aviation fuels to green hydrogen;
- Identify and prioritise the policy, financial instruments and stakeholders' framework needed to initiate this transition in the short to medium term (2023-2030).

7.2.3. US: Nextgen or the Next Generation Air Transportation System

Context: The 29 million square miles of US airspace caters to more than 45,000 flights and 2.9 million airline passengers per day. In the early 2000s, the Federal Aviation Administration (FAA) established 'NextGen' to tackle the need to increase airspace capacity and reduce congestion. NextGen is a multi-billion dollar upgrade of the aviation infrastructure in the US, funded and deployed by the FAA, with the aim of transforming the US air traffic system to provide safer and more efficient ATM. NextGen is a dynamic programme that is dedicated to modernising US airspace though a series of interlinked programmes, portfolios, systems, policies and procedures. These programmes are not restricted to a single goal or product, but, rather, take a holistic view of new technologies, procedures, operations and policy development to improve the safety, efficiency, capacity, access, forecasting and resilience of US airspace, while reducing the environmental impact of aviation.

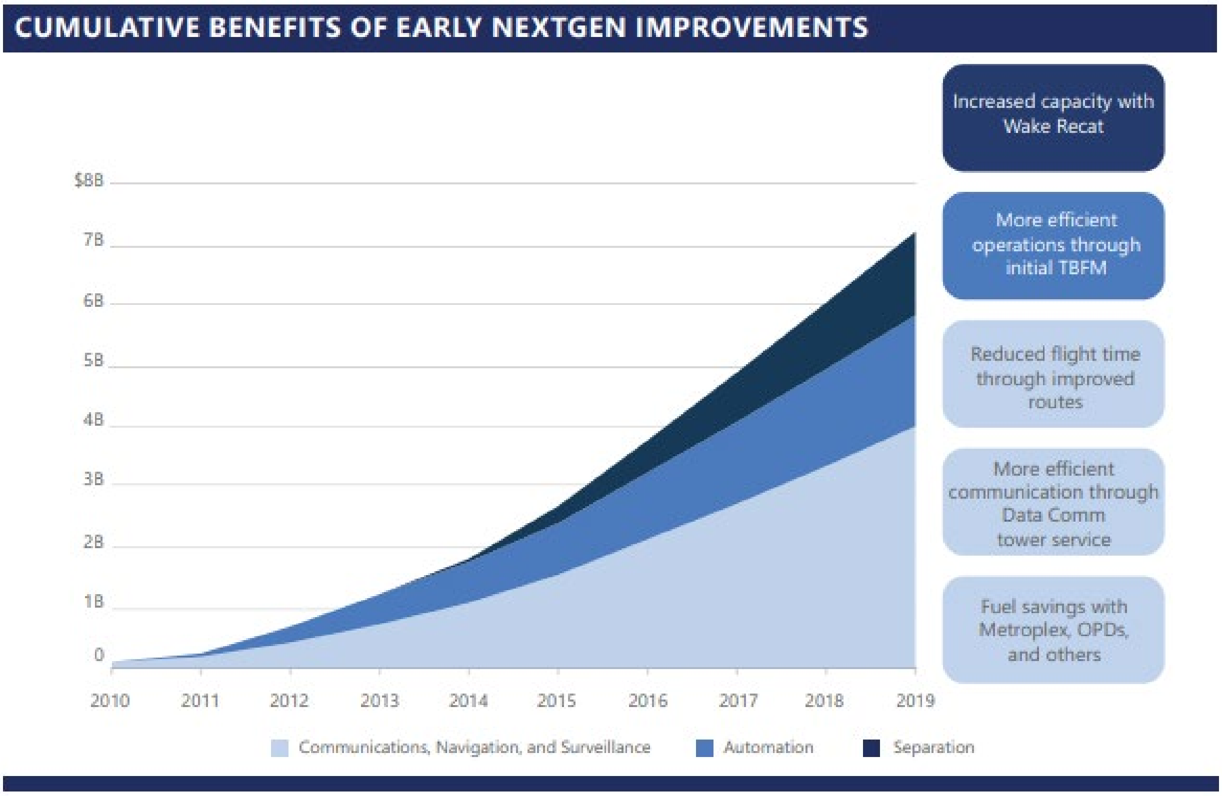
Design and implementation: As a multi-agency programme, NextGen draws stakeholders from its own industry and from across the various US government departments. To meet its long-term (20-year) goal, the FAA works with the national and international aviation communities to identify capabilities of integrating existing aircraft equipage. It has partnered with SESAR in the EU, and has similar links with aviation stakeholders from Japan and Singapore. There are strategic research and developments timelines, closely followed by periodic technology refreshes. The initial implementation of all major schemes is planned for 2025. Some early implementation of selected technologies delivered savings in excess of USD 7 billion (EUR 6.6 billion), most of which (57 %) resulting from savings in passenger travel time. By the 2030s the combined benefits are expected to surpass USD 100 billion (EUR 94 billion) (see Figure 7-2) (FAA, 2022).

Some of the key programmes included in NextGen are:

- Trajectory based operations: a long-term goal of NextGen is to develop a cutting-edge ATM method for strategic planning and optimisation of air and ground systems. This is supported by information exchange between the relevant parts of the infrastructure. This programme links with the technology updates that support aircraft to fly precise paths and time-based management, improving forecasting models and making them more environment- and time-efficient.
- Data Communications (Data Comm): this corresponds to digitisation and efficiency improvements in communication between ground ATM services and airspace.
- Performance-based navigation (PBN): a customised set of specifications for different parts of airspace, with specific characteristics that allow equipped aircraft to fly shorter, more efficient paths, reducing fuel consumption and engine emissions, while improving time management capabilities.

- Automatic Dependent Surveillance – Broadcast (ADS-B): ADS-B enables real-time display of air traffic, increasing situation awareness for improved safety through the use of satellite technology (rather than radar) to identify and monitor aircraft.
- Decision Support System Automation: supports the optimisation of traffic flow across US airspace, with three different systems, each catering to the different sets of air and ground system users across the airport and aircraft operators.
- System-wide information management: a digital data-sharing platform for non-sensitive information such as aeronautical, surveillance and weather data.
- Weather: NextGen weather is responsible for upgrading forecasting, modelling capabilities and translating weather information into airspace constraints.
- Some of the other NextGen improvements involve new FAA policies and operational procedures to improve capacity and efficiency, such as ‘wake re-categorisation’, which focuses on revising wake turbulence separation standards to improve airport capacity[89].

Figure 7-2: Cumulative benefits of early implementation of selected technologies



Note: Vertical axis scale is USD billion (USD 0 billion – USD 88 billion). ‘TBFM’ refers to ‘Time-based flow management’. It is a system of tools used to manage flows of traffic based on time to maximise efficiency and optimise flow of traffic (for example, by avoiding having aircraft in the air “on hold” while they wait permission to land). ‘OPDs’ refers to ‘Optimised Profile Descents’, where aircraft glide down from cruising instead of the older, and more fuel-consuming, ‘stair-step procedure’, where aircraft repeatedly level off and power up the engines during the descent.
Source: (FAA, 2020).

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[89] ‘Wake turbulence separation standards’ are the minimum separation between aircraft on a runway. As an aircraft uses a runway, it generates turbulence in its wake. That turbulence consists of a pair of counter-rotating vortices that can persist for several minutes behind the generating aircraft. Before another aircraft can use the runway, the vortices must be known to have dissipated or they could negatively impact the following aircraft (EASA, 2017).

Key lessons and best practice: Unlike the FAA, which controls NextGen's schedules and uniformly implements them nationally, the EU has complex levels of governing bodies (e.g. EU, EUROCONTROL, EASA, nationally-segmented airspace control). However, the FAA faced similar uncertainties in NextGen implementation, including future funding uncertainties, limited industrial/ societal acceptance, gaps in projected and actual benefits due to discrepancies in scenario modelling and other factors, and the need for potential air traffic control restructuring. This led to programme delays and lower uptake of new capabilities, (US Department of Transportation, 2018), which was further exacerbated by the global pandemic.

These issues occurred despite collaboration with industry to prioritise, support implementation and track the benefits of the programmes (US Department of Transportation, 2021). In addition, severe gaps in performance tracking and reporting procedures led to transparency concerns. Addressing these key concerns would improve data quality and transparency, which is critical for securing industry trust and thus long-term collaborative commitment and investment. Other lessons include issues with inconsistencies in modelling accuracy, lack of preparation for 'high-risk' scenarios, and supporting risk mitigation measures. The FAA subsequently adopted mitigation strategies, focusing on deploying the most promising technologies, assessed through the use of performance metrics, and implementing an interim process to adjust benefit projections and identify implementation analyses to prioritise improvements (US Department of Transportation, 2021).

EU replicability: Stakeholders in the EU, such as EUROCONTROL and the different air navigation service providers could potentially follow a strategy similar to NextGen, i.e. map and establish a stakeholder network to feed into the prioritisation of improvements in the early stages, comprising airspace and ground system operations and management. That would also align with the long-term vision for the SES. These collaborations could capitalise on the partnership with NextGen and utilise its decades of recorded experience and strategies. These lessons could help address both expected and unforeseen risks stemming from implementation challenges and provide updates to the benefits projections, and analysis. Embedding transparency in reporting and analysis will reduce financial uncertainty and support long-term collaborative commitment and investment from industry.

8. COMPARATIVE ANALYSIS WITH THIRD COUNTRIES

8.1. Introduction

KEY FINDINGS

- The analysis of technology research programmes found little difference in aircraft technological priorities among main aviation markets, although Asian countries (China, Japan) tend to focus their developments on hydrogen.
- The US is setting out an ambitious SAF policy package that combines funding research, tax credits for producers, and supporting efficient regulatory approval.
- The analysis of policy instruments found that the US, Canada and Brazil tend to rely on fuel standards (i.e. setting carbon intensity targets for fuel sold and allowing regulated entities to trade credits) to promote low-carbon fuel production, particularly SAF. China is piloting an ETS for aviation, which may be applied at national level.

This section describes the R&D efforts and policies being put in place in major aviation markets (US, China, Brazil, Canada, Japan) and how they compare with those of the EU.

In 2019, more than 65 % of EU emissions from aviation were from extra-EU flights (Figure 2-2). This makes international cooperation crucial to effectively meet climate goals for aviation. At United Nations (UN) level, responsibility for mitigating emissions from international aviation lies with the ICAO, which has agreed two ‘aspirational goals’ for the international aviation sector (ICAO, 2022a):

- 2 % annual fuel efficiency improvement by 2050;
- Carbon-neutral growth from 2020 onwards (the “CNG 2020” strategy), later revised to using 2019 as the baseline year because of the COVID-19 pandemic.

It aims to achieve this through a so-called basket of measures, including:

- Aircraft-related technology and standards;
- Improved ATM and operational improvements;
- Development and deployment of SAF;
- Market-based measures.

The ICAO is also exploring the feasibility of a long-term global aspirational goal for international aviation CO_2 emission reductions (ICAO, 2022b). At the same time, the International Air Transport Association (IATA) approved a resolution for the global air transport industry to achieve net-zero carbon emissions by 2050. The IATA considers a potential scenario in 2050 in which 65 % of emissions are abated through SAF, 13 % through new propulsion technology, such as hydrogen, and 3 % through efficiency improvements. The remainder (19 %) could be dealt with through carbon capture and storage and offsets (IATA, 2021b).

The role of governments and cooperation at international level is essential to support this transition. As major emitters, the decarbonisation efforts of the US, China, Brazil, Canada and Japan are key to meeting global goals for international aviation. With the exception of Airbus, these countries also host the main aircraft manufacturers (Boeing in the US, COMAC in China, Embraer in Brazil, Bombardier in Canada, and Mitsubishi in Japan). As such, they are likely to become frontrunners in developing decarbonisation technologies for aviation.

8.2. Main research areas

8.2.1. Aircraft technologies

There is significant scope for government-supported research and innovation in aviation due to its strategic position for defence and its close ties with aerospace. Public research programmes in the aviation sector are well placed to solve pressing societal challenges, such as the development of low-carbon aircraft technologies, as these require coordination between many stakeholders, as well as consistency and complementarity of public and private investments to drive systemic change. Horizon Europe is a good example of a similarly ambitious EU research programme in the field of aviation (see Section 5.2.1).

The **US** has a long tradition of ambitious research projects, such as the Defence Advanced Research Projects Agency (DARPA), the National Aeronautics and Space Administration (NASA), and US Department of Defence and Energy programmes that provide funding for the network of National Laboratories and Research Centres, including its Advanced Research Projects Agency-Energy (ITF, 2021).

For example, the Department of Energy announced that it would provide USD 33 million (EUR 31 million) in funding for carbon-neutral hybrid electric aviation, as part of two ARPA-E programmes[90]. ASCEND projects work to develop an innovative, lightweight and ultra-efficient all-electric powertrain, with advanced thermal management systems that help to enable efficient net-zero carbon emissions for single-aisle passenger commercial aircraft. REEACH projects seek to create innovative, cost-effective and high-performance energy storage and power generation sub-systems for electric aircraft, with a focus on fuel-to-electric power conversion technologies (Department of Energy, 2020).

NASA is engaging with industry, academia and other agencies through the Sustainable Flight National Partnership (NASA, 2022c). This will focus on three main areas: advanced vehicle technologies, efficient airline operations, and SAF. NASA plans to test the following technologies by 2026: transonic truss-braced wing, hybrid thermally efficient core, electrified aircraft propulsion, composite aircraft manufacturing, ATM-exploration project and SAF. In June 2022, announced that it was seeking private partners to develop a “sustainable flight demonstrator”, a large-scale demonstrator with an advanced airframe configuration, as well as related advanced technologies that are yet to be defined (NASA, 2022b).

In **China**, the Civil Aviation Administration of China (CAAC) is responsible for setting the aviation industry development strategy and for developing major civil aviation scientific and technological projects. As part of the 14th Five-Year Plan (2021-2025), the CAAC developed the first Green Development Roadmap for the aviation industry. The Roadmap states that carbon intensity of aviation operations will continue to decline by 2025 and aviation emissions will peak by 2035 (State Council, 2022).

COMAC is a state-owned company that develops aircraft, from regional jets to larger wide bodies, mainly for the Chinese market. In March 2019, COMAC announced a successful test flight of its

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[90] ARPA-E advances high-potential, high-impact energy technologies that are too early for private sector investment.

Lingque-H hydrogen fuel cell demonstrator. The Lingque-H aircraft, with a wingspan of six metres and supplemented by lithium batteries, can have different tails and types of landing gear. Lingque-H was jointly developed by COMAC in cooperation with State Grid, Shenzhen-based Gree, and the School of Aeronautic Science and Engineering at Beihang University (Chinessima, 2021). Given the lack of information, the level of maturity of these technologies is uncertain and difficult to compare against similar developments in the EU, such as the Airbus ZEROe demonstrator, which is expected to achieve a mature TRL for a hydrogen-combustion propulsion system by 2025 (Airbus, 2022).

Canada's National Research Council (NRC) 'Low-emission Aviation' programme aims to establish a collaborative ecosystem that will stimulate the aviation industry's green transition and support other government departments to develop green technology policies and regulations. The main research areas are aircraft technology integration, electrical systems, hydrogen applications and battery safety (Government of Canada, 2021).

The Green Aviation Research and Development Network (GARDN) is an industry-led consortium of 40 public and private sector partners, including industry heavyweights like Bombardier Aerospace, Pratt & Whitney Canada, Esterline CMC Electronics and Bell Helicopter Textron Canada. GARDN targeted the 'valley of death'[91] in the innovation supply chain, which includes prototyping, testing and demonstrating early-stage, pre-competitive research on next-generation aircraft, engines and avionics[92] systems. The consortium received CAD 26.4 million (EUR 19.4 million) of funding between 2009 and 2021 (Government of Canada, 2021).

Japan has a world-leading position in hydrogen, with strong activity in its industrial sector. Japan is developing hydrogen storage, pumping and combustion research, seeking to transfer technology from space and hypersonic successes under the Japanese Aerospace Exploration Agency (JAXA) programmes. It also aims to have an industrial gas turbine running on 100 % hydrogen by 2025 (Aerospace Technology Institute, 2022).

8.2.2. Operational measures

At international level, the ICAO-led Aviation System Block Upgrades (ASBUs) is a package of capabilities (modules) that sets out a framework for harmonising avionics capabilities and the required ATM ground infrastructure, as well as automation. The ASBUs provide a roadmap to assist air navigation service providers to develop their individual strategic plans and investment decisions, with the goal of global aviation system interoperability (CANSO, 2018). The implementation of ASBU Block 0 (2013- 2019) and Block 1 (2019-2025) is expected to reduce CO_2 emissions by 1.5-2.9 % in 2025 compared to 2015 levels (ICAO, 2019). Regional ATM improvement programmes are aligned at ICAO level under the ASBU framework.

NextGen in the **US** (equivalent to SESAR in the EU) aims to modernise communication and navigation infrastructure to improve position and information time, thereby increasing efficiency, reducing delays and improving safety. Implemented in 2007, NextGen is about halfway through an investment and implementation plan, and is expected to be completed between 2025 and 2030 (see Section 5.3.3).

In **China**, the CAAC 13th Five-Year Development Plan (2016-2020) included the implementation of the Strategy for Modernising Air Traffic Management, focusing on safety, capacity, efficiency and services

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[91] The 'valley of death' is the period in the development of a product or service when a significant increase in investment is required, making the risk of failure much more likely to outweigh any potential future return.

[92] Avionics refers to the electronic systems and equipment specifically designed for use in aviation (e.g. communications, navigation, display).

in an attempt to meet the demands on ATM from the continuous and ever-increasing growth of air transport (ICAO, 2016).

Many other air navigation improvement programmes are at varying stages of implementation, such as CARATS in **Japan** and SIRIUS in **Brazil**.

8.2.3. Sustainable Aviation Fuels

With broad acceptance that SAF will be required in substantial quantities to decarbonise the aviation sector, research programmes and policy action to enable this energy transition are the subject of increasing focus.

In the **US**, the Departments of Energy, Transport and Agriculture together launched a government-wide Memorandum of Understanding (MOU). The 'SAF Grand Challenge' attempts to reduce cost, enhance sustainability, and expand production and use of SAF, while 1) achieving a minimum of a 50 % reduction in lifecycle GHG emissions compared to conventional fuel, and 2) meeting the goal of supplying sufficient SAF to meet 100 % of aviation fuel demand by 2050.

Through this MOU, the Parties intend to accelerate the research, development, demonstration and deployment needed for innovative solutions and technologies, as well as the policy framework to enable an ambitious government-wide commitment to scale-up production of SAF to 35 billion gallons per year by 2050. A near-term goal of 3 billion gallons per year was established as a milestone for 2030. New and existing funding is supporting SAF production to the tune of USD 4.3 billion (EUR 4.1 billion) (The White House, 2021).

The US Congress introduced the Sustainable Skies Act in May 2021, which will use targeted tax credits to scale-up production of SAF. The tax credit starts at USD 1.5 (EUR 1.42) per gallon (3.79 litres) for blenders that supply SAF with a demonstrated 50 % or greater lifecycle GHG savings and rewards higher GHG achievement up to the maximum of USD 2 (EUR 1.90) per gallon. The legislation requires eligible SAF to use the full set of ICAO sustainability criteria as one of the safeguard provisions to ensure its environmental integrity. A complementary proposal also includes a USD 1 billion (EUR 0.9 billion) grant over five years to expand the number of SAF production facilities in the US (IATA, 2021a).

Specification approval is one of the most challenging barriers to entry for SAF. Any new SAF must be shown to behave sufficiently similarly to conventional jet fuel if it is to gain approval, be considered suitable for use, and further categorised as a 'drop-in' product. The process of approval is necessarily rigorous and can be expensive and lengthy, delaying the deployment of new SAF to the market. In response to this obstacle, the US set up a Clearing House to provide support on the approval process, carry out/coordinate the tests required, and fund producers to review the research report on the tests done (EASA, 2019). The US Clearing House is run by the University of Dayton Research Institute and funded by the FAA. In 2021, the Clearing House was awarded funding of USD 3.6 million (EUR 3.4 million) (The White House, 2021).

EASA identified the US Clearing House as a significant means of supporting the SAF approval process (EASA, 2019). It offsets many of the costs, barriers and risks faced by potential fuel vendors and forms a centralised hub that guides SAF producers through all activities to achieve approval for use. It aims to eventually support the deployment of SAF from new production processes, cheaper, faster and with less risk. This would support the uptake of SAF, releasing all of the benefits in decarbonisation potential they present.

The EU faces similar challenges, barriers and risks as the US, and an EU clearing house would have many parallels with the US Clearing House. A study carried out by EASA on the potential 'Sustainable Aviation

Fuels Facilitation Initiative' assessed the feasibility and design of a similar initiative in the EU (EASA, 2019).

Brazil's Renovabio Programme provides low-interest loans of up to BRL 100 million (EUR 19 million) to biofuel producers via the National Bank for Economic and Social Development. A grace period of 24 months is granted and interest rates are linked to CO_2 emissions reduction targets set by the programme (BNDES, 2021). In turn, the Brazilian Network of Biokerosene and Sustainable Hydrocarbons for Aviation (RBQAV) aims to lead research and innovation efforts in the sector through partnerships between research institutions, private companies and government institutions, thereby supporting the development of the aviation biokerosene sector at the national level. The network will support the creation of public policies and enabling actions for the production of biokerosene and renewable hydrocarbons, in line with the RenovaBio Programme (RBQAV, 2022).

In **Canada**, GARDN (see Section 8.2.1) redefined its mandate in 2020 to focus exclusively on leading a pan-Canadian SAF initiative. Its mission will be to support the supply of domestically produced SAF in every airport in Canada (SKIES, 2020).

8.3. Main policy developments

8.3.1. Aviation carbon pricing schemes

At international level, CORSIA is the main aviation carbon pricing scheme for international flights (see Section 5.1.2). Under CORSIA, airlines can reduce or offset increases in international air transport emissions exceeding a baseline value. Airlines can also reduce emissions using lower carbon CORSIA-eligible fuels and offset them by purchasing emission units consisting of carbon credits or offsets. As of 2021, 88 countries decided to participate in the pilot phase from 1 January 2021, including all G7 countries. However, some important partners, such as China, India and Russia, are not participating. The second phase of CORSIA will run from 2027 to 2035 and apply to all states (European Commission, 2021g).

In **China**, a national ETS came into effect in 2021, which initially covers the power sector and does not yet include (domestic) aviation in its scope. Under the national ETS work plan, the eight pilot ETS' operating in China will gradually be integrated into the national ETS.

Shanghai's ETS is the first of the eight Chinese ETS pilots to include aviation. The Shanghai pilot ETS applies to CO_2 emissions from the industrial, buildings and transport sectors. Emission allowances under the cap are primarily distributed via free allocation. For most industries, transport sectors and water suppliers, free allocation is based on each entity's historical carbon intensity and actual production data. For complex industries, airports and buildings, free allocation is based on historical emissions. Small emitters are exempt from the Shanghai pilot ETS (The World Bank, 2022b).

As part of the 14th Five-Year Plan, China's Ministry of Environment plans to enrol the aviation sector in the national carbon market by 2025, as one of its eight targeted sectors (S&P, 2022).

South Korea (International Carbon Action Partnership, 2022) and **New Zealand** (New Zealand Government, 2016) have ETSs, although both only cover emissions from domestic aviation. As part of a new trans-Atlantic agenda, the Commission has emphasised that the EU and **US** 'should work closely together on emissions trading, carbon pricing and taxation' (European Commission, 2020g).

8.3.2. Taxation of aviation fuel

The 1944 Convention on International Civil Aviation (the Chicago Convention) bans the taxing of fuel on board an aircraft when it arrives in the country but does not restrict taxing the fuel loaded onto the aircraft in that country. The ICAO explicitly supports the non-charging of fuel levies on international transport, as stated in its non-binding resolution on 'Policies on User Charges & Taxation' (ICAO, 2000).

Most national governments exempt jet fuel for commercial airline use sold on their territory from tax through bilateral air services agreements negotiated between countries. The exemption extends to international carbon taxes, which effectively tax fuel use (ITF, 2021).

There are no legal obstacles to taxing jet fuel used on domestic routes, including under carbon taxes. As of 2019, however, very few countries applied carbon and/or fuel excise taxes to jet fuel. Those that did included Argentina, Armenia, Australia, Canada, India, Ireland, Japan, Norway, Myanmar, Saudi Arabia, Switzerland, Philippines, Thailand, Vietnam and the US (OECD, 2019).

8.3.3. Fuel standards and blending mandates

Low-carbon fuel standards (LCFS) support the deployment of alternative fuels by setting a decreasing lifecycle-based carbon intensity target for fuel sold and allowing regulated entities (fuel suppliers, companies producing, importing, distributing or selling fuel) to trade credits to achieve the target (ITF, 2021).

LCFS originated in California in the **US**. The regulation in California was updated in 2019 to acknowledge SAF as an eligible fuel to generate credits. The GHG benefits of SAF are quantified through LCA modelling that calculates the emissions avoided compared to conventional jet fuel. These credits can incentivise SAF production, as they can then be sold to other obligated parties under the LCFS (IATA, 2021a). The US Congress has expressed interest in a nationwide LCFS (House Select Committee on the Climate Crisis, 2020).

In **Canada**, the Clean Fuel Standard will require liquid fossil fuel primary suppliers (producers and importers) to reduce the carbon intensity of the liquid fossil fuels compared to their 2016 carbon intensity levels. In 2022, the carbon intensity reduction requirement will start at 2.4 gCO_2e/MJ. It will gradually increase over time, reaching 12 gCO_2e/MJ in 2030 (Government of Canada, 2022).

In **Brazil**, RenovaBio sets national decarbonisation targets for the fuel sector for 2019-2029 to foster production and participation of biofuels in the country's transport energy matrix. Fuel distributors must prove compliance with mandatory individual targets through the purchase of 'decarbonisation credits', a financial asset tradable on the stock exchange, derived from the certification of the biofuel production process based on the levels of efficiency achieved in relation to emissions. RenovaBio establishes that for a biofuel to be eligible, the biomass cannot come from areas where native vegetation was suppressed (Ministério de Minas e Energia, 2021).

Fuel-blending mandates are an alternative policy instrument to reduce the carbon intensity of fuel. They can require blending by volume or lifecycle GHG emission reductions. Biofuel-blending mandates are already common for road transport fuels (ITF, 2021). For example, Brazil´s standards require a 27 % blend of ethanol in gasoline (IEA, 2021) and 10 % of biodiesel (S&P, 2021). As yet, however, SAF mandates are only being considered in the EU.

8.4. Overview

Table 8-1 summarises the main findings from the analysis of R&D efforts and decarbonisation policies in major aviation markets:

- Research on aircraft and avionics technologies is well embedded in national research institutions and programmes, especially in the US and the EU.

- There is little difference in aircraft technological priorities among the main aviation markets, although Asian countries (China, Japan) tend to focus their developments on hydrogen.
- The US is setting out an ambitious SAF policy package that combines funding research, tax credits to producers, and supporting efficient regulatory approval of new SAF. The Clearing House is an effective solution to supporting the SAF approval process.
- The US, Canada and Brazil tend to rely on fuel standards to promote low-carbon fuel production, particularly SAF.
- China is piloting an ETS for aviation, which may be applied at national level.

Table 8-1: Overview of policy developments in aviation in major third countries

Policy development	EU	US	China	Brazil	Canada	Japan
Research funding programmes	✓	✓	✓	✓	✓	✓
Regional/national carbon pricing schemes	✓	✗	✓	✗	✗	✗
Fuel taxation	✗	✓	✗	✗	✓	✓
Fuel standards and blending mandates	✓	✓	✗	✓	✓	✗

Source: authors' elaboration.

9. CONCLUSIONS AND POLICY RECOMMENDATIONS

9.1. Conclusions

9.1.1. Technological readiness

This study considered a wide range of technologies in development that will support the aviation sector to move towards decarbonisation. These technologies covered three different areas of improvement:

- Aircraft technologies;
- Operational measures;
- Sustainable Aviation Fuels.

In terms of **aircraft performance**, technologies were identified that could lead to reductions in energy consumption (thus **lower emissions) of up to 50 %**[93]. While progressive efficiency improvements are expected to continue, a number of issues will likely impact the ability of new technologies to significantly reduce the emissions of aircraft at a wide scale. Firstly, there are **significant programme risks associated with implementing new technologies in a new aircraft design**, and aircraft manufacturers might be reluctant to try all new technologies in a single new aircraft. Secondly, the main commercial aircraft manufacturers supplying aircraft in the EU market recently introduced new or upgraded aircraft types across all market segments, suggesting **limited scope for a large number of new technologies to be incorporated in new products before 2050**. Finally, aircraft are long-lived assets that are only replaced once in a generation. As such **many of the aircraft using current technologies, as well as those delivered in the coming decade, are likely to still be flying in 2050**. Together, these factors will diminish the impact of new aircraft technologies on decarbonisation of aviation by 2050.

In terms of **operational measures**, the EU has worked on the SES for the past two decades. When fully deployed, this will offer **fuels savings of 9-11 %,** as aircraft will fly at optimum speed and altitude. Other measures include improvements in operations while aircraft are on the ground. Although these improvements can represent savings of up to 100 % of emissions during ground operations, it nevertheless represents a small portion of total flight emissions.

One area that offers substantial potential is **novel fuels**, including drop-in fuels, hydrogen and electricity, as they can offer emissions reductions of between 20 % and 100 % (measured on a WTW basis). While hydrogen and electricity will require novel aircraft types and might not be commercially available before 2040 for all types of aircraft, **drop-in fuels can help aviation to reduce emissions now**. The main constraints on drop-in fuels are **price and availability**, with the two issues being connected. For these drop-in fuels to become more attractive, their production rates must increase, which at the same time should help support lower prices (given the potential for economies of scale).

9.1.2. EU legal framework

The EU's legislative role will continue to be central to supporting the decarbonisation of aviation. The main areas of action to date are:

- Market-based measures to support emissions reduction;

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[93] Specifically that for full electric propeller-driven aircraft shown in Table 3-3.

- Aviation fuel;
- Financial incentives.

Perhaps the most influential EU action was the creation of the **EU ETS for aviation, a market-based measure**. This scheme requires all airlines operating in the EU to verify and report their emissions and surrender allowances (some of which these airlines currently get for free) annually against those emissions, with the goal of incentivising reductions in emissions. However, the application of the full scope of the EU ETS covering EU flights to/from outside the EU/EEA was frozen in favour of an international emission reduction system. The **EU ETS is proposed to be amended, removing free allowances and integrating it with the ICAO CORSIA scheme**, which may improve its effectiveness. However, CORSIA does not propose to actually reduce emissions from aviation, but simply to compensate for any emission increases after 2020 through the purchase of carbon offsets. Under the proposed amendment, emissions from these flights continue to need to be offset once collective international emissions exceed 2019 levels.

In terms of **aviation fuel**, the main EU actions relate to two proposals submitted in July 2021 as part of the 'Fit for 55' package of proposals. Firstly, the revision to the ETD proposed to impose **a tax on fossil kerosene used as jet fuel of EUR 10.75/GJ (corresponding to EUR 0.379/litre)** in 2023. Secondly, the proposed ReFuelEU Aviation Regulation will impose a **blending mandate** requiring the minimum proportion **of SAF in aviation fuel** to be increased every five years from 2025 until 2050 (when a 63 % blend rate will be required). These two initiatives together offer **huge potential to shift demand away from fossil-based kerosene and into sustainable fuels**. The scalability of production and price of these novel fuels remains a problem, however.

The impact of the 'Fit for 55' package applicable to aviation is expected to affect the demand for air travel, CO_2 savings and carbon leakage. The anticipated reduced demand for air travel, combined with higher SAF uptake and lower CO_2 emissions, will result in substantial CO_2 savings.

In addition, **RED should complement emission reduction efforts,** including in the aviation sector, **provided that the new targets for 2030 and 2050 are sufficiently ambitious**. While RED II allows renewable hydrogen and hydrogen-based synthetic fuels produced from electricity of installations connected to the grid to be counted as 100 % renewable under certain conditions, the required technologies to use hydrogen-based fuels in aviation are not yet mature. The proposal for revision of RED II further develops it by promoting the use of renewable fuels of non-biological origin[94]. A challenge could come from the potential introduction in RED of hydrogen from fossil fuel production.

Finally, in terms of **financial incentives**, the main EU tool is the Taxonomy Regulation, which defines environmentally sustainable economic activities and thus sets a framework to facilitate sustainable investment and address economic activities that lead to significant GHG emissions. The **Taxonomy Regulation already covers a number of activities that can support the decarbonisation of the aviation sector**, including the production of hydrogen and biofuels, and the construction of low-carbon airport infrastructure. **Significantly, the Taxonomy Regulation excludes the purchase, lease and manufacturing of aircraft**, which will be an important expenditure area to support lower emissions in the sector.

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[94] Proposal for a Directive amending Directive (EU) 2018/2001, COM(2021) 557 final, Brussels, 14.7.2021, which is in line with the Energy System Integration Strategy and the Hydrogen Strategy.

9.1.3. Investment needs and EU funding support

The **development of new aircraft technologies, purchase of new aircraft equipped with those technologies, and uptake of sustainable aviation fuels will all impose costs on the aviation industry.** While R&D costs are expected to be relatively small (EUR 50 billion between 2020 and 2050, undiscounted), **the *additional* costs of purchasing new, more efficient aircraft**[95] **are expected to reach EUR 378 billion in the 2020-2050 period** (undiscounted). This could impose a **substantial burden** on an industry that already has significant capital expenditure. In terms of **fuel consumption**, while the use of new fuels such as electrofuels and hydrogen will bring additional costs, these will be balanced by increases in efficiency. Accordingly, **in the 2020-2050 period airlines are expected to *save* EUR 395 billion** (undiscounted) in fuel costs compared to a situation in which they would use only fossil kerosene with less efficient aircraft. Overall, **investments in decarbonisation measures will be slightly financially negative for the industry**, with EUR 33 billion in additional costs expected between 2020 and 2050 (undiscounted).

In terms of **EU funding**, **existing programmes typically funded R&D needs for aircraft and ATM-related technologies** (under the Clean Sky/Clean Aviation and SESAR programmes), **as well as the deployment of ATM technologies** (under CEF and cohesion policy). While these are key areas in the pathway to decarbonisation, an important share of future investments will be needed in two areas where **EU funding has been limited: commercial availability of new fuels, and purchase of more efficient aircraft.** The EU can play a role in creating the necessary regulatory conditions for the commercial offerings in respect of new fuels to be more widely available, but also in terms of financial support (loans or grants) that could be offered to spur investment. Although State aid rules prevent EU or Member State direct funding of new aircraft acquisition, **the EU could promote the uptake of more efficient aircraft** and shortening the aircraft replacement cycle by **including aircraft in the Taxonomy Regulation**. This would support quicker reductions in emissions.

9.1.4. Decarbonisation challenges

The main barriers to aircraft manufacturers and air carriers adopting decarbonisation technologies are their **risk adversity in the context of high capital costs, slow fleet replacement, and high uncertainty**. Airlines also have **limited capacity to absorb additional costs** in a highly competitive market.

As the application of decarbonisation policies at EU level tends to focus on intra-EU (or intra-EEA) flights, the burden of these policies may be higher on EU carriers and airports compared to non-EU players. There may be a demand switch from EU hubs to non-EU hubs, especially from peripheral EU airports to nearby non-EU airports. These **demand effects would disproportionally affect EU carriers and airports until similar policies are implemented in other regions**.

The effects on **connectivity** are expected to be limited to **small and peripheral airports**.

9.2. Policy recommendations

The results of this analysis allow for several policy recommendations in respect of technology, legislation and funding:

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[95] These additional costs represent the extra burden to acquire new aircraft that include the new technologies described, i.e. the cost beyond what it would cost to buy aircraft with current technologies.

- **A combination of actions** in deployment of new aircraft technologies, market-based measures and wider use of SAF **will be needed if aviation is to have a chance to achieve its ambitious decarbonisation goals**. As such, **the EU should continue to pursue a multifaceted approach and act in all areas**. While some measures might have more significant impacts than others, all singular aspects will be important, in view of the overall effort needed.
- **The EU should continue to support R&D of new technologies for aircraft, ATM and SAF, so that innovative technologies with decarbonisation potential can continue coming to the market**. Earmarking revenues from the EU ETS (similar to the Innovation Fund) or the new proposed tax on aviation fuel to fund these programmes could be explored at EU or Member State level.
- **Increasing the production of drop-in sustainable fuels and hydrogen in the coming decades will be crucial** to enable their increased uptake and, in the case of drop-in SAF, to achieve the blending mandates proposed in the ReFuelEU Aviation proposal. **Without large-scale production of sustainable fuels, it will be impossible to achieve a high level of emissions reduction**. The EU will need to play a role in this market to ensure that all types of SAF are produced at the necessary volume. The availability of hydrogen refuelling infrastructure at airports will also be essential.
- **EU regulatory action will also be needed** in SAF certification (including coordination with other economic blocks) to ensure that feedstocks are prioritised for aviation (and other sectors where decarbonisation is not possible without drop-in fuels) and to create the conditions for investment in production capacity (and potentially support that production capacity directly).
- **Experiences in other countries offer potential lessons in promoting the uptake of SAF**. From the UK's GFGS competition to foster the production of SAF at a commercial scale, to the US' ambitious SAF policy encompassing funding research, ambitious fuel standards, tax credits to producers, and the regulatory Clearing House, these experiences demonstrate the tools available for policy-makers to support the decarbonisation of aviation. These programmes can offer important lessons for the EU.
- Furthermore, furthering the **integration of CORSIA into EU ETS** focusing on the reduction of emissions (rather than just offsetting) will promote technological development and achievement of 2050 carbon neutrality.
- Additional regulatory action could be taken to incentivise investment in aviation decarbonisation. **The Taxonomy Regulation should be expanded to include other emission reduction activities,** such as the sale or lease of (lower emission) aircraft, aircraft manufacturing and technology development, and production, storage and distribution of SAF. This will incentivise the private sector to invest in the sector and consider more aviation activities in the growing field of green finance.

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ANNEXES

11. A1 – AIRCRAFT ENERGY CONSUMPTION

The aims of technology developments associated with the decarbonisation of aviation are, ultimately, to reduce emissions of greenhouse gases resulting from their operation. At a high level, this can be achieved by reducing their energy consumption (for transporting the same number of passengers or cargo the same distance) or by reducing the emissions associated with that consumption of energy (or a combination of the two).

Considered simplistically, the fuel (or energy) consumption of an aircraft, while flying at a constant speed and altitude, can be written as:

$$Fuel\,flow\,rate\,\left(\frac{kg}{s}\right)=\frac{Fuel\,flow\,rate}{Total\,thrust}\times {}^{1}\!\Big/\frac{Aircraft\,Weight}{Total\,thrust}\times Aircraft\,Weight$$

In this equation, the fuel flow rate (in kg/s) is the fuel flow rate for each engine, multiplied by the number of engines and the total thrust is the thrust produced by each engine multiplied by the number of engines (assuming that each engine is operating the same). As the aircraft is flying at a constant altitude and speed (i.e. in the cruise segment of the flight), the total thrust (in Newtons, N) must equal the airframe drag (or air resistance, also in N) and the lift produced by the wings must equal the aircraft weight (both also in N). Using these equalities then allows the equation to be expressed as:

$$Fuel\,flow\,rate=\ Specific\,Fuel\,Consumption\times {}^{1}\!\Big/\frac{Lift}{Drag}\times Weight$$

The specific fuel consumption (SFC) is the fuel flow rate to the engines (in kg/s) divided by the thrust produced (in N); as all engines are operating the same, the SFC value for an engine is the same as for the complete aircraft. Therefore, this term represents the contribution of the engine efficiency to the fuel consumption. The key element of the second term (Lift/Drag, or L/D) presents the lift developed by the wings (in N) divided by the airframe drag (or air resistance, also in N), thus representing the contribution of the aircraft aerodynamics. The final term on the right hand side is the aircraft weight (in N). From this, it can be seen that reductions in fuel consumption of an aircraft can be achieved through improvements in engine efficiency (SFC), aerodynamics (L/D) or weight. Research programmes to improve aircraft fuel efficiency address all three elements.

12. A2 – FULL SET OF TECHNOLOGIES IDENTIFIED

As described in the main report body (section 3), the analysis has identified a wide range of aircraft and engine technologies, operational measures and alternative fuel options. The tables in this annex list the technologies identified through this review.

For aircraft and engine technologies, and the operational measures, which can, in general, be used with conventional or alternative fuels, the descriptions are accompanied by their expected reductions in energy consumption in use. For the alternative fuels shown in Table 12-6, the descriptions are accompanied by the expected reductions in CO_2 emissions. These reductions include those in the engine exhaust ('tank to wake' or TTW) and the full fuel lifecycle ('well to wake' or WTW)[96]. For drop-in alternative fuels, the chemical composition is almost identical to that of conventional fuel, so the TTW emissions show no reductions, but the WTW emissions may show significant reductions.

As well as a brief description of the technology, the tables also include the market segment (or segments) that the technology is relevant to and the current technology readiness level (TRL) of the technology. The latter is based on the TRL scale used in monitoring Horizon Europe projects:

Table 12-1: TRL scale used in Horizon Europe programme

TRL	Description
TRL 1	Basic principles observed
TRL 2	Technology concept formulated
TRL 3	Experimental proof of concept
TRL 4	Technology validated in lab
TRL 5	Technology validated in relevant environment (industrially relevant environment in the case of key enabling technologies)
TRL 6	Technology demonstrated in relevant environment (industrially relevant environment in the case of key enabling technologies)
TRL 7	System prototype demonstration in operational environment

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[96] Tank-to-wake (TTW) refers to the CO_2 emissions resulting from the combustion of the fuel in the engine. For aircraft engines, these are proportional to the fuel consumed (with the constant or proportionality depending on the fuel chemistry). Well-to-wake (WTW) refers to the CO_2 emissions for the full lifecycle of the fuel, including extraction from the well (or growing of crops, etc., for biofuels), processing/refining, transport to the airport, as well as combustion in the engine. For conventional fuels, WTW emissions are higher than TTW. For sustainable alternative fuels, WTW emissions are lower than TTW as they include the negative emissions that occur when the plants absorb CO_2 from the atmosphere.

TRL	Description
TRL 8	System complete and qualified
TRL 9	Actual system proven in operational environment (competitive manufacturing in the case of key enabling technologies; or in space)

Source: (Enspire.science, n.d.)

Finally, the following tables include the estimated reduction in energy consumption through the application of the technology (or the reduction in GHG emissions in the case of alternative fuels).

Table 12-2: Unconventional aircraft configurations technologies identified

Technology	Description / Reference(s)	Market segment	Technology Readiness Level	Reduction in energy consumption
Blended Wing Body (BWB)	Airframe design in which the wing and fuselage are 'blended' together, with a large area wing and no tail surfaces. Provides reduced overall drag and mass for the same passenger (or freight) carrying capacity. More appropriate to long-range aircraft than short-to-medium range aircraft. Has been in development for considerable time, but significant challenges remain, hence TRL still only 3-4. (Clean Sky, 2021), (IATA, 2019)	Long-range, wide-body	TRL 3-4	30%
Boundary layer Ingestion	Placing the engine air intakes so that they take in the air in the boundary layers that have developed on the aircraft fuselage (or wing) surfaces. Reduces the drag associated with the engine frontal area. (Clean Sky, 2021), (IATA, 2019)	Long-range, wide-body	TRL 3-4	8.5%

Technology	**Description / Reference(s)**	**Market segment**	**Technology Readiness Level**	**Reduction in energy consumption**
Truss-braced wing / Strut-braced wing	Use of trusses or structs to support the wing and take the flight loads, Reduces the loads on the wing structure and hence allows the wing structure design to be tailored just to the aerodynamic requirements, allowing reduced weight and drag. (IATA, 2019)	Short/Medium-range, narrow-body	TRL 4	10% to 15%
Windowless fuselage	Fuselage construction without cabin windows to provide a smoother outer surface (lower drag) and simpler construction (reduced airframe weight) (IATA, 2019)	All ranges, all aircraft configurations	TRL 7	5% to 7%

Table 12-3: Aircraft aerodynamics and structures technologies identified

Technology	**Description / Reference(s)**	**Market segment**	**Technology Readiness Level**	**Reduction in energy consumption**
Composite structures	Construction of the aircraft structure using carbon composite materials in place of metal. Reduces aircraft mass and, hence, drag, leading to reduced fuel consumption. Recent aircraft (Boeing 787, Airbus A350) have begun to use this material, wider use in the aircraft structure is expected to give further improvements. (Tecolote Research, 2015)	All ranges, all aircraft configurations	TRL 9	7% to 11%

Technology	**Description / Reference(s)**	**Market segment**	**Technology Readiness Level**	**Reduction in energy consumption**
Hybrid laminar flow	Use of suction on aircraft surfaces (particularly wings and tail surfaces) to maintain laminar flow in the boundary layers on those surfaces. Laminar flow boundary layers create less drag than turbulent flow, allowing the aircraft to use less engine thrust to fly and hence lower fuel consumption. However, laminar boundary layers are prone to natural transition to turbulent flow and also prone to separation, hence a hybrid approach has been developed. (IATA, 2019), (Air Transport Analytics, 2018), (Clean Sky, 2021)	All ranges, all aircraft configurations	TRL 9 for vertical and horizontal tails; TRL 6 for application to wings.	10% to 15%
Morphing airframes	Changes in shape of aircraft (particularly wing aerofoil section) between low-speed environment (in vicinity of airports) and high-speed environment (during cruise). Allows the shape of the aircraft to be optimised for all flight phases, reducing the need for compromise and reducing drag. (IATA, 2019)	In principle, can be applied to all ranges and all configurations, but likely to have greatest impacts on long-range wide-body aircraft.	TRL 3	2% to 8%
Natural laminar flow	Design of aircraft surface shape to maximise the extent of laminar flow in boundary layers on the surface. (IATA, 2019), (ICCAIA, 2019)	All ranges, all aircraft configurations	TRL 4-5	5% to 10%

Technology	**Description / Reference(s)**	**Market segment**	**Technology Readiness Level**	**Reduction in energy consumption**
Reduced cruise Mach number	Designing the aircraft for a lower cruise speed to reduce drag (at the expense of taking longer to fly to the destination). (Air Transport Analytics, 2018)	Long-range	TRL 7	5%
Riblets	Surface treatment (applied by film coating) with small scale 'riblets' aligned with the main flow direction, to reduce cross-flows and drag. (Air Transport Analytics, 2018)	All ranges, all aircraft configurations	TRL 6	1% to 2%
Ultra-high aspect ratio wings	Longer, narrower-chord wings to deliver the same lift but at lower drag. Has implications for structure (requiring truss or strut bracing, for example, as in technology above) and for airport gate design. May introduce challenges in incorporating aircraft systems in smaller wing box. (Air Transport Analytics, 2018)	Short/Medium-range, narrow-body	TRL 4	11% to 12%
Variable camber with new control surfaces	Wing aerofoil section able to be adjusted during flight to match the flight phase better to provide reduced drag. May incorporate control functions in the varying wing shape rather than separate control surfaces, further reducing drag. (IATA, 2019)	All ranges, all aircraft configurations	TRL 4-5.	5% to 10%

Table 12-4: Aircraft engine and propulsion technologies identified

Technology	Description / Reference(s)	Market segment	Technology Readiness Level	Reduction in energy consumption
Composite fan	Engine fan blade construction using combination of titanium and carbon-fibre composite. Provides reduced weight (compared to an all-titanium blade) and improved ability to tailor the construction to match the loads on the blade. Is particularly appropriate as bypass ratio and fan diameter increase. (General Electric, 2015), (Rolls-Royce, 2020)	All ranges, all aircraft configurations	TRL 9	N/A Primarily an enabler for other technologies to reduce emissions rather than a direct impact on emissions.
Contra-rotating open rotor (CROR)	Engine design in which the fan design is unshrouded (similar to a propeller) and two blade rows are used, rotating in opposite directions. Provides improved efficiency compared to a conventional turbofan engine and higher speed capability than a conventional turboprop. (Clean Sky, 2021)	Short/Medium-range, narrow-body	TRL 5	14%
Full-electric turboprop	Use of battery electric systems (recharged while on the ground) to drive propellers for short-range aircraft. (Schäfer, et al., 2018)	Short-range, narrow-body	TRL 5-6	About 50%, subject to the impacts of the increased mass of energy storage (batteries vs. fuel in fuel tanks).
Geared fan	Use of a high-power gearbox between the low-pressure turbine and the fan (which is driven by the turbine) to allow higher rotation speeds for the turbine (reducing size and weight) and lower rotation speed for the fan, improving the efficiency. Currently implemented in the Pratt & Whitney PW1000 series engines.	All ranges, all aircraft configurations	TRL 7-9	5%

Technology	Description / Reference(s)	Market segment	Technology Readiness Level	Reduction in energy consumption
Hybrid-Electric powertrain	Propulsion system combining conventional gas turbine engines with battery electric systems. Electric power is used when high thrust is required, while cruise uses gas turbine only. Batteries can be recharged while on ground and/or from the main engines during cruise. (ICCAIA, 2019)	Short/Medium-range, narrow-body	TRL 3	Up to 40% for short/medium range aircraft
Hydrogen fuel cell plus electric power for turboprop	Use of hydrogen-fuelled fuel cells to produce electricity to drive propellers via electric motors. (Clean Sky, 2020)	Short/Medium-range, narrow-body	TRL 3	8% to 10% for regional segment
Hydrogen fuel cell plus electric powered fans for jet propulsion	Hydrogen fuel cells to provide electric energy to drive shrouded fan (similar to the fan in a conventional jet engine). May be hybridised with a hydrogen-fuelled gas turbine to provide the additional thrust required for take-off and climb, with the fuel cell system used for cruise. (Clean Sky, 2020)	All ranges, all aircraft configurations	TRL 3	4% for short-range aircraft (up to 2,000 km range)
Hydrogen-fuelled gas turbine jet engine	Aircraft jet engine with conventional configuration, fuelled by liquid hydrogen. (Mukhopadhaya & Rutherford, 2022)	All ranges, all aircraft configurations	TRL 3	5% to 26% increase in energy consumption, depending on the fuel system mass

Technology	Description / Reference(s)	Market segment	Technology Readiness Level	Reduction in energy consumption
Very high bypass ratio large turbofan	Gas turbine jet engine with bypass ratio (ratio of the mass of air that, after passing through the fan, goes through the bypass duct to the mass that enters the engine core) of over 10:1. Delivers increased cycle efficiency. (Clean Sky, 2021), (ICCAIA, 2019)	All ranges, all aircraft configurations	TRL 7	Up to 20%
Very high overall pressure ratio	Use of very high pressure ratios (pressure at exit of the compressor divided by that at the engine inlet) of over 50:1. Delivers increased engine thermal efficiency. (ICCAIA, 2019)	All ranges, all aircraft configurations	TRL 7	15% to 20%

Table 12-5: Operational measures identified

Technology	Description / Reference(s)	Market segment	Technology Readiness Level	Reduction in energy consumption
Cruising at optimum speed and altitude	Improved use of European ATM systems to enable aircraft to optimise their flight trajectories to reduce emissions. (EUROCONTROL, 2021)	All ranges, all aircraft configurations	TRL 8	9% to 11%
E-tug for Narrow body aircraft	Use of external electrically-powered tug to move aircraft to the vicinity of the runway before starting the aircraft main engines. These need 3 to 5 minutes running to warm up prior to take-off, so the tug would not tow the aircraft all the way to the take-off point. (Mototok, n.d.), (Air Transport Analytics, 2018)	Short/Medium-range, narrow-body	TRL 9	3.6% to 4.5% (depending on the flight distance as reduction occurs only in the taxi phase)

Technology	Description / Reference(s)	Market segment	Technology Readiness Level	Reduction in energy consumption
E-taxi for Wide body aircraft	Aircraft main wheels driven by electric motors for taxiing the aircraft to the vicinity of the runway before starting the aircraft main engines. (Mototok, n.d.), (Air Transport Analytics, 2018)	Long-range, wide-body	TRL 7	1.3% (depending on the flight distance as reduction occurs only in the taxi phase)
Reduced take- off thrust	Selection of engine thrust for take-off appropriate to the combination of actual aircraft take-off weight and runway length. Reduces fuel consumption during the take-off. (Koudis, Hu, Majumdar, Jones, & Stettler, 2017)	All ranges, all aircraft configurations	TRL 9	Up to 23% reduction in emissions during the take-off phase. Overall reduction depends on flight distance.
Single-engine taxiing	Use of less than all aircraft main engines when taxiing. Can be used on taxi out from the stand to the runway (all engines need to be operative for the final 3 to 5 minutes to allow for warm-up prior to take-off) and for taxi in from the runway to the stand (engines to be shut down need to run for about 2 minutes after landing to allow to cool prior to shut down). (Sustainable Aviation, 2018)	All ranges, all aircraft configurations	TRL 9	20% to 40% of emissions during taxiing. Equates to up to 2% of full flight emissions, depending on the flight distance.

Technology	**Description / Reference(s)**	**Market segment**	**Technology Readiness Level**	**Reduction in energy consumption**
Substituting APU use with fixed electric ground power (FEGP) and preconditioned air (PCA)	Aircraft use on-board auxiliary power units (APU) to power their systems, including air conditioning for the passenger cabin, while parked at a gate or stand. The provision of electric power and pre-conditioned air from the airport infrastructure allows the APU to be switched off for much of the time at the gate/stand. (Sustainable Aviation, 2018)	All ranges, all aircraft configurations	TRL 9	40% to 75% of emissions while the aircraft is at the gate/stand. Impact on full flight emissions depends on a wide range of factors, including taxi times and flight times.

Table 12-6: Alternative fuels options identified

Technology	**Description / Reference(s)**	**Market segment**	**Technology Readiness Level**	**Reduction in emissions**
Sustainable Aviation Fuel – HEFA-SPK	Hydroprocessed Esters and Fatty Acids Synthetic Paraffinic Kerosene fuel, usually based on vegetable oils (e.g. used cooking oil). Currently certified by ASTM for use at up to 50% blend with conventional fuel.	All ranges, all aircraft configurations	TRL 7-8	No change in TTW emissions. 63% to 90% reduction in WTW emissions (when used as 100% SAF), depending on the feedstock (Nordic Energy, 2016)

Technology	**Description / Reference(s)**	**Market segment**	**Technology Readiness Level**	**Reduction in emissions**
Sustainable Aviation Fuel – AtJ	Alcohol to Jet fuel, based on isobutanol and ethanol produced from sugar cane, sugar beet and other ligno-cellulosic sources. Currently certified by ASTM International for use at up to 50% blend with conventional fuel.	All ranges, all aircraft configurations	TRL 6-7	No change in TTW emissions. 45% to 66% reduction in WTW emissions (when used as 100% SAF), depending on the feedstock and treatment of co-products (Nordic Energy, 2016)
Sustainable Aviation Fuel – Biomass Gasification + FT	Gasification of biomass with Fischer-Tropsch processing to produce liquid fuel, based on biomass sources (municipal wastes, wood). Currently certified by ASTM for use at up to 50% blend with conventional fuel.	All ranges, all aircraft configurations	TRL 6-7	No change in TTW emissions. Up to 90% reduction in WTW emissions (when used as 100% SAF), depending on the feedstock (Nordic Energy, 2016)

Technology	Description / Reference(s)	Market segment	Technology Readiness Level	Reduction in emissions
Sustainable Aviation Fuel – Electrofuel (synthetic kerosene)	Synthetic jet fuel using sustainable hydrogen (produced by electrolysis of water using sustainable electricity) and CO_2 captured from the atmosphere or exhausted from other industrial processes.	All ranges, all aircraft configurations	To be completed for final report.	No change in TTW emissions. Up to 97% reduction in WTW emissions (when used as 100% SAF), depending on the emissions from electricity production and the source of the captured CO_2.
Hydrogen fuel (sustainable)	Hydrogen fuel produced electrolysis of water using sustainable electricity. Unlike the other fuels above, which are drop-in replacements for conventional fuels, hydrogen will require new engines and/or propulsion systems.	All ranges, all aircraft configurations	TRL 3	100% reduction in TTW emissions. Up to 100% reduction in WTW emissions (depends on the emissions associated with electricity generation for electrolysis)

13. A3 – COST CALCULATION METHODOLOGY

Section 4 of the main report provided the results of analyses of the costs associated with the development and implementation of the technologies and operational measures described in Section 3. This annex provides additional details of the methodology used to develop these costs.

The cost calculations include three cost elements:

- Technology development costs.
- Additional purchase costs.
- Fuel costs.

The approaches used to derive these cost elements are described in the sections below.

13.1. A3.1 - Technology development costs

These costs relate to the cost to develop the technology to the point that the manufacturer is able to implement them in a new product. As described in the main report, they do not include the costs internal to the manufacturers for the final development and certification of the product (aircraft, engine, etc.) incorporating the technology.

The desk research identified limited information for the estimated costs for developing the different technologies. For those technologies where development cost data were identified, those costs were used in the calculation. For the other technologies, data from the major European research programmes on aviation technology development were used, together with the total percentage emissions reduction associated with the technologies identified as being researched by those programmes to derive a 'cost per percentage reduction in fuel consumption' value.

The major European programmes considered were:

Table 13-1: Major European aviation research programmes and associated values

Programme	Years	Total value
Clean Sky	2007 - 2014	€ 1.6 billion
Clean Sky 2	2014 - 2021	€ 4.0 billion
Clean Aviation	2021 - 2028	€ 4.1 billion

Source: (European Council, 2007); (European Council, 2014); (European Council, 2021).

The technologies that were identified as being developed by these programmes, together with their energy consumption reductions as given in Section 3, are shown in Table 13-2.

Table 13-2: Technologies identified as being developed by the major European programmes

Technology	Energy reduction
Blended Wing Body (BWB)	30%
Boundary Layer Ingestion	8.50%
Hybrid laminar flow control on wing and tail	10% to 15%
Morphing airframes	2% to 8%
Natural laminar flow	5% to 10%

Technology	Energy reduction
Truss-braced/strut-braced wing	8% to 15%
Contra-rotating open rotor (CROR)	14%
Hybrid-Electric powertrain	40%
Very high bypass ratio large turbofan	20%
E-taxi for Wide body	Up to 100% during taxiing (equivalent to about 1.30% of full-flight energy consumption)

Source: Authors' review of technologies developed under Clean Sky programmes and energy reduction values from Annex A2.

The overall energy reduction achieve by combining the reductions in Table 13-2 is approximately 83%[97]. Dividing the total costs by this value gives a cost per percentage reduction of approximately € 117.3 million.

For technologies for which data on the development costs were not identified from the literature review, the development cost was estimated by multiplying the EUR 117.3 million figure by the percentage reduction in energy consumption associated with the technology. The resulting technology development costs are shown in Table 13-3.

Table 13-3: Development costs for technologies derived from literature sources or using method described above

Technology	Development cost from literature	Development cost estimated using approach described above[98]
Blended wing body		€ 3,250.25 million
Boundary layer ingestion		€ 920.90 million
Windowless fuselage		€ 0.00 million
Truss-braced/strut-braced wing		€ 1,354.27 million
Natural laminar flow		€ 812.56 million
Hybrid laminar flow		€ 1,354.27 million
Riblets		€ 162.51 million
Composite materials for aircraft structures		€ 975.07 million

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[97] Note that, when combining multiple technologies, the approach adopted is to derive a factor on energy consumption for each (by subtracting the percentage reduction from 100%). The factors for all technologies are then multiplied to give an overall factor, which is then subtracted from 100% to give an overall percentage reduction. A simple summation of the reductions for all the technologies would lead to a reduction of over 100%.

[98] Total cost to develop the technology to be ready for inclusion in new aircraft designs. For modelling purposes, these costs are spread evenly over the period from 2020 to the assumed entry-into-service date of aircraft including the technology.

Technology	Development cost from literature	Development cost estimated using approach described above[98]
Morphing airframes		€ 812.56 million
Reduced design cruise Mach number		€ 541.71 million
Very high bypass ratio large turbofan		€ 2,166.83 million
Very high overall pressure ratio		€ 1,895.98 million
Geared fan	€ 923.80 million[99]	
Composite fan		€ 920.90 million
Contra-rotating open rotor		€ 1,516.78 million
Full electric propeller-driven aircraft	€ 705.78 million[100]	
Hybrid electric powertrain		€ 4,333.66 million
Hydrogen-fuelled gas turbine engine	€ 1,403.25 million[101]	
Hydrogen fuel cell plus electric power for turboprop	€ 316.83 million[102]	
Hydrogen fuel cell plus electric powered fans for jet propulsion		€ 469.11 million
Cruise at optimum speed and altitude		€ 1,083.41 million
Reduced take-off thrust		€ 0.00 million
Single-engine taxiing		€ 0.00 million
E-tug for narrow-body aircraft		€ 438.78 million
E-taxi for wide-body aircraft		€ 140.83 million
Substituting APU use by FEGP and PCA		€ 0.00 million

Annual costs for technology development, applied to each year between 2020 and the entry-into-service date of the technology, were derived by dividing the values in Table 13-3 by the number of years between 2020 and the relevant entry-into-service year.

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[99] (Leeham News and Analysis, 2016) – reference quotes '$1 billion negative cost margin' by 2018. Interpreted as overhead cost for engine technology development and converted to €923.8 million at an exchange rate of €1 = $1.0825 (https://www.xe.com/currencyconverter/convert/?Amount=1&From=USD&To=EUR, 13/04/2022)

[100] (Schäfer, et al., 2018) provides information on potential additional purchase costs of an electric aircraft (pages 24 to 25 of the reference), using a total battery capacity of 28 MWh, battery costs of up to $200/kWh, plus about $ 2 million for propulsion system. These values have been used, together with an assumption of 100 aircraft to offset development costs and an exchange rate of €1 = $1.0825 (https://www.xe.com/currencyconverter/convert/?Amount=1&From=USD&To=EUR, 13/04/2022)

[101] The Clean Sky JU/FCH JU Hydrogen-powered aviation report (Clean Sky, 2020) indicates a 31% increase in capital cost (CAPEX) for a hydrogen-fuelled short-range aircraft. This percentage increase was applied to the assumed price of a representative narrow-body aircraft (see Table 13-8 in Annex A3.2 and then multiplied by 100 to estimate the development cost.

[102] (GKN Aerospace, 2021)

The development costs for the different alternative fuels that, collectively, are considered under the heading of 'sustainable aviation fuel' (SAF) are treated differently to the other technologies. The development costs are derived as the investments needed in production facilities to be able to deliver the required quantities of SAF. These investments are extracted from the impact assessment for the ReFuelEU Aviation study (European Commission, 2021p) (see Figure 4 in Section 6.2.5 of the impact assessment). That study provides average annual investments for different fuel types for the periods 2020 to 2030, 2031 to 2040 and 2041 to 2050. Table 13-4 shows the total investment costs for the different fuels from 2020 to 2050. The development of hydrogen and electricity as energy sources for aviation is assumed to require little direct investment beyond that which will be incurred as part of the aircraft technology development.

Table 13-4: Development costs for alternative fuels

Technology	Development cost from literature	Development cost estimated using approach described above
Hydroprocessed esters and fatty acids	€ 230.00 million	N/A
Alcohol-to-jet	€ 2,468.00 million	N/A
Biomass gasification + Fischer-Tropsch	€ 3,733.50 million	N/A
Electrofuel	€ 9,842.00 million	N/A
Hydrogen	€ 0.00 million	N/A
Electricity	€ 0.00 million	N/A

Source: Authors' analyses of investment data from ReFuelEU Aviation impact assessment study (European Commission, 2021p)

13.2. A3.2 - Additional purchase costs

The additional aircraft purchase costs, associated with the inclusion of the technologies discussed in Section 3, were calculated by calculating the number of aircraft to be delivered each year that include the technology by the price increase per aircraft.

The initial step in calculating the numbers of deliveries was to identify the number of aircraft in the European fleet in a base year and then to project the numbers to future years. Eurostat (table avia_eq_arc_typ) provides numbers of aircraft in the European fleet by seat size category. Collating these data for the years 2015 and 2020 gave:

Table 13-5: Numbers of aircraft in European fleet by seat class

Year	Up to 50 seats	51 to 150 seats	151 to 250 seats	Over 250 seats	Other categories
2015	275	1,054	1,502	496	1,951
2020	84	479	913	229	1,767

Source: Eurostat (table avia_eq_arc_typ).

These numbers by seat categories were mapped to aircraft market categories (turboprops (TP), regional jets (RJ), narrow-body jets (NB) and wide-body jets (WB)) using the mapping in Table 13-6, based on expert judgement of the authors.

Table 13-6: Mapping from seat classes to aircraft market categories

	TP	RJ	NB	WB
Up to 50 seats	75%	25%		
51 to 150 seats		50%	50%	
151 to 250 seats			50%	50%
Over 250 seats				100%
Other categories				

Source: Authors' judgement.

Although the Eurostat data for the European aircraft fleet in 2020 are more recent than those for 2015, they also show the strong impacts of the COVID-19 pandemic on demand and hence in-service aircraft. Recognising that, in most cases, the reduction in fleet numbers in 2020 is not due to aircraft being scrapped, but to them being taken out of service temporarily, it was decided to project the future fleet starting from 2015.

The fleet numbers for 2015 (after mapping to market category based on Table 13-6) were then projected to 2050 in line with the growth in demand in the European Commission's MIX scenario. This resulted in the following fleet sizes by aircraft market category.

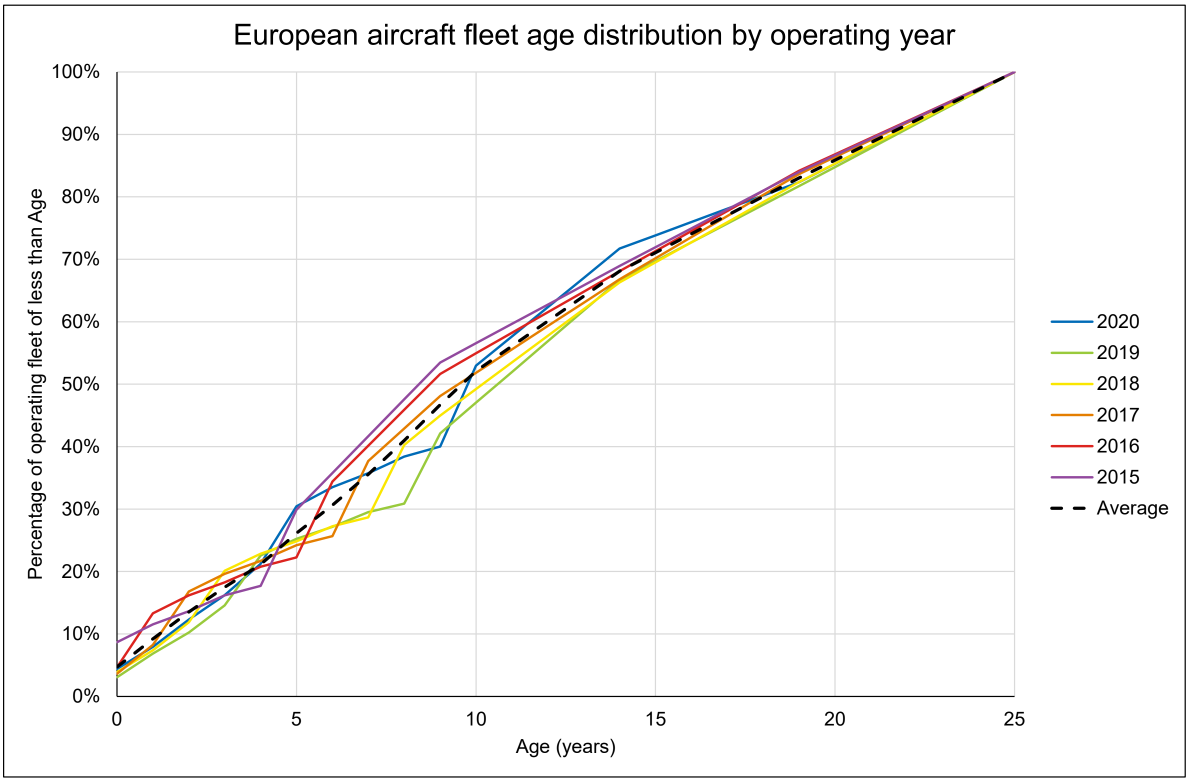
Table 13-7: EU-27 fleet size projections by aircraft market category

	TP	RJ	NB	WB
2015	206	596	1,278	1,247
2020	213	635	1,439	1,409
2025	232	687	1,620	1,593
2030	244	736	1,785	1,793
2035	258	780	1,917	1,930
2040	276	833	2,056	2,077
2045	289	877	2,176	2,206
2050	311	944	2,343	2,393

Source: Authors' calculations based on 2015 fleet from Eurostat and demand projections from the MIX scenario.

Data from Eurostat (table Commercial aircraft fleet by age of aircraft and country of operator) were also used to derive the age profile of the European aircraft fleet. The data provide the number of aircraft in the fleet by five-year age band. The data are provided for each year from 2001 to 2020. By calculating the percentage of the fleet in each age band (and assuming that the numbers were uniformly distributed across all ages within a band), an estimate of the age profile was derived for the fleet in each year from 2015 to 2020. Averaging across all these years (to remove the variations caused by the 'uniform age distribution within an age band' assumption referred to above) gives the average age profile shown in Figure 13-1.

Figure 13-1: Fleet age profiles derived for each year 2015 to 2020 and average



Source: Authors' analysis based on Eurostat fleet data.

By assuming that the average age profile shown in Figure 13-1 remained valid for future years, and applying it to the fleet size projections shown in Table 13-7, the percentage of the fleet delivered in a given analysis year (e.g. 2040), delivered after the entry into service of a technology (e.g. 2030; thus aircraft that are 10 years of age or less) can be derived to input to the calculation of the impact of the technology on the fleet fuel (energy) consumption. Similarly, the age profile can be used to define the number of deliveries in a given year to input to the calculation of the additional purchase costs.

Similarly to the technology development costs described in Annex A3.1 (section 13.1), the literature were reviewed to identify available information on the impacts of a technology on the aircraft purchase price.

Again, a limited number of data points were identified. In a small number of cases, the increase was given as a percentage increase in the aircraft price, rather than in dollars or euros. To use such data, estimated purchase prices of representative aircraft types in each market category were identified, as shown in Table 13-8.

Table 13-8: Estimated purchase prices for representative aircraft types

Category	Representative Aircraft	Price	Source
TP	ATR 72-600	€ 26,000,000	https://simpleflying.com/atr-72-vs-dash-8/
RJ	Airbus A220-100	€ 33,000,000	https://www.statista.com/statistics/273962/prices-of-airbus-aircraft-by-type/
NB	Airbus A320neo	€ 49,000,000	https://www.statista.com/statistics/273962/prices-of-airbus-aircraft-by-type/

Category	Representative Aircraft	Price	Source
WB	Airbus A350-900	€ 146,000,000	https://www.statista.com/statistics/273962/prices-of-airbus-aircraft-by-type/

Source: As shown in table.

For technologies for which it was not possible to identify relevant information, the additional purchase price was estimated by assuming that the development costs would be recovered through the sale of 100 aircraft (thus the additional purchase price was set at 1% of the development cost). The additional purchase prices identified from the literature, or calculated in this manner, are shown in Table 13-9.

Table 13-9: Additional purchase prices for aircraft with technologies, derived from literature or calculated as described

Technology	Additional purchase price from literature	Additional purchase price estimated using approach described above
Blended wing body	€ 2.0 million [103]	
Boundary layer ingestion		€ 9.21 million
Windowless fuselage		€ 7.04 million
Truss-braced/strut-braced wing		€ 13.54 million
Natural laminar flow	+5-10% of the conventional aircraft list price [104]	
Hybrid laminar flow	+5-10% of the conventional aircraft list price[87]	
Riblets		€ 1.63 million
Composite materials for aircraft structures		€ 9.75 million
Morphing airframes		€ 8.13 million
Reduced design cruise Mach number		€ 5.42 million
Very high bypass ratio large turbofan		€ 21.67 million
Very high overall pressure ratio		€ 20.52 million
Geared fan	$2 million to $10 million [105]	
Composite fan		€ 9.97 million

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[103] (Goldberg, 2017)

[104] (IATA, 2019)

[105] (Leeham News and Analysis, 2016)

Technology	Additional purchase price from literature	Additional purchase price estimated using approach described above
Contra-rotating open rotor	\$8.5 million to \$9.3 million [106]	
Full electric propeller-driven aircraft	€ 7.0 million [107]	
Hybrid electric powertrain		€ 43.3 million
Hydrogen-fuelled gas turbine engine	€ 14.0 million [108]	
Hydrogen fuel cell plus electric power for turboprop		€ 10.56 million
Hydrogen fuel cell plus electric powered fans for jet propulsion		€ 4.69 million
E-tug for narrow-body aircraft	€ 61,000 - € 79,000 [109]	
E-taxi for wide-body aircraft		€ 1.41 million

Sources: From literature – as in footnotes – or evaluated by authors as described.

As described above, these additional purchase prices were multiplied by the number of relevant aircraft calculated to be delivered in each year to derive the overall additional purchase costs. As described in Section 4.3, where multiple technologies were not compatible on the same aircraft, they were assigned to equal percentages of the deliveries to calculate the costs.

13.3. A3.3 - Fuel costs

The final step in the cost calculation was the calculation of the fuel costs. This calculation started from the energy consumption data for 2020 from the European Commission's MIX scenario. These data were presented for intra-EU and extra-EU flights, and for different distance bands, separately. Similarly to the approach described above for mapping from aircraft seat categories to market categories, the energy consumption data were mapped to the aircraft market categories using the percentages in Table 13-10.

Table 13-10: Mapping from flight distance bands to aircraft market categories

Domestic and International intra-EU				
Distance band	**TP**	**RJ**	**NB**	**WB**
<500km	50%	50%		
500-1000km	25%	25%	50%	

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[106] (Clean Sky, 2021)

[107] (Schäfer, et al., 2018) provides information on potential additional purchase costs of an electric aircraft (pages 24 to 25 of the reference), using a total battery capacity of 28 MWh, battery costs of up to \$200/kWh, plus about \$ 2 million for propulsion system. These values have been used, with an exchange rate of €1 = \$1.0825 (https://www.xe.com/currencyconverter/convert/?Amount=1&From=USD&To=EUR, 13/04/2022)

[108] The Clean Sky JU/FCH JU Hydrogen-powered aviation report (Clean Sky, 2020) indicates a 31% increase in capital cost (CAPEX) for a hydrogen-fuelled short-range aircraft. This percentage increase was applied to the assumed price of a representative narrow-body aircraft (see Table 13-8 in Annex A3.2) to derive the additional purchase price for an aircraft fitted with the technology.

[109] (Air Transport Analytics, 2018)

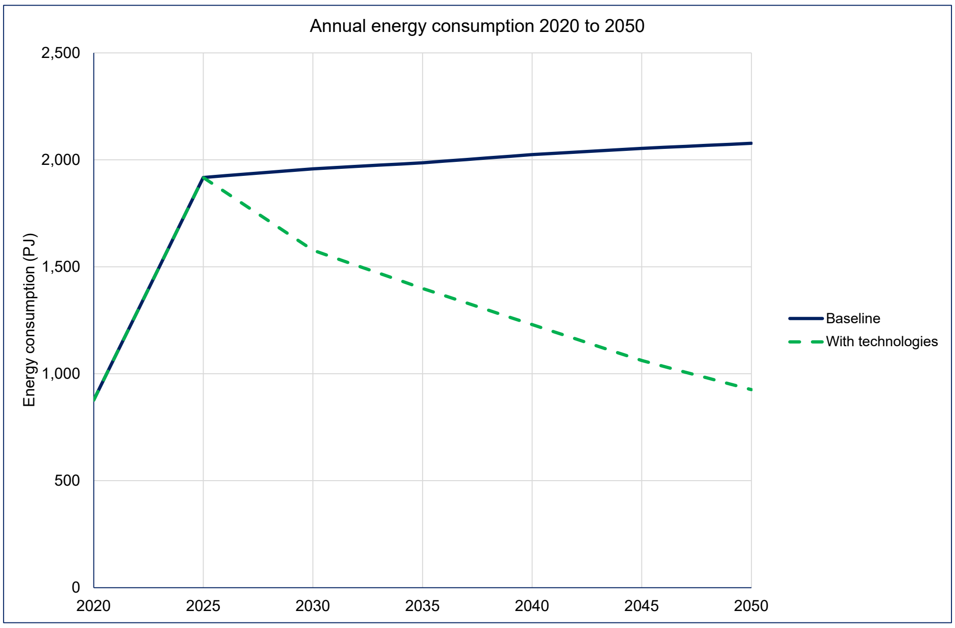
1000-1500km		25%	75%	
1500-2000km			100%	
>2000km			75%	25%
International extra-EU				
Distance band	**TP**	**RJ**	**NB**	**WB**
<500km	50%	50%		
500-1000km		50%	50%	
1000-1500km		25%	75%	
1500-2000km			80%	20%
>2000km			10%	90%

Source: Authors' judgement.

This mapping allowed the energy consumption data from the MIX scenario to be assigned to the different aircraft market categories. The energy consumptions were then projected to future years using the demand (passenger-km) data projections from the 2020 Reference scenario. For the baseline case (assuming no new technology insertion), the fleet fuel efficiency (energy consumption per passenger-km) was held constant.

To develop the energy consumption results for the case including the insertion of the new technologies, the identification of the percentage of the fleet including the different technologies, as described in Annex A3.2 (Section 13.2) was used, together with the identified energy consumption reductions for each technology (as presented in Annex A2 (Section 12)) to identify the total reduction in energy consumption by the fleet. The results, as shown in Figure 4-3, are repeated in Figure 13-2, below.

Figure 13-2: Evolution of annual energy consumption under 'baseline' and 'with technologies' scenarios



Source: compiled by authors using demand data from the 2020 Reference Scenario (see Section 2) energy consumption data from the MIX scenario and energy efficiency reductions from technologies as described in Section 3.

The energy consumption under the 'With technologies' scenario was then distributed across the different fuel types in multiple steps, as described below:

- The percentage of the energy consumption as electricity or hydrogen was assumed to be the same as the percentage of the fleet assigned to technologies associated with those fuels.
- The remaining energy was assumed to be consumed as drop-in liquid fuels.
- The percentage of the drop-in fuel in the form of electrofuel was obtained from the electrofuel element of the ReFuelEU aviation mandate proposal for each year.
- The total percentage of drop-in fuel assigned to the other sustainable aviation fuels (i.e. the biofuel-based SAF) was the difference between the total SAF mandate and that for electrofuel in each year from the ReFuelEU aviation mandate proposal. This total energy consumption was divided among the three biofuel-based SAF being modelled in line with the splits in Policy Option A1 in the ReFuelEU Aviation study (European Commission, 2021i).

The identification of the percentage of the operating fleet in a future year using electricity or hydrogen fuel, as mentioned in the first bullet point above, used the authors' assumptions for the potential percentage of aircraft deliveries using these energy carriers following the first availability, as shown in Table 13-11.

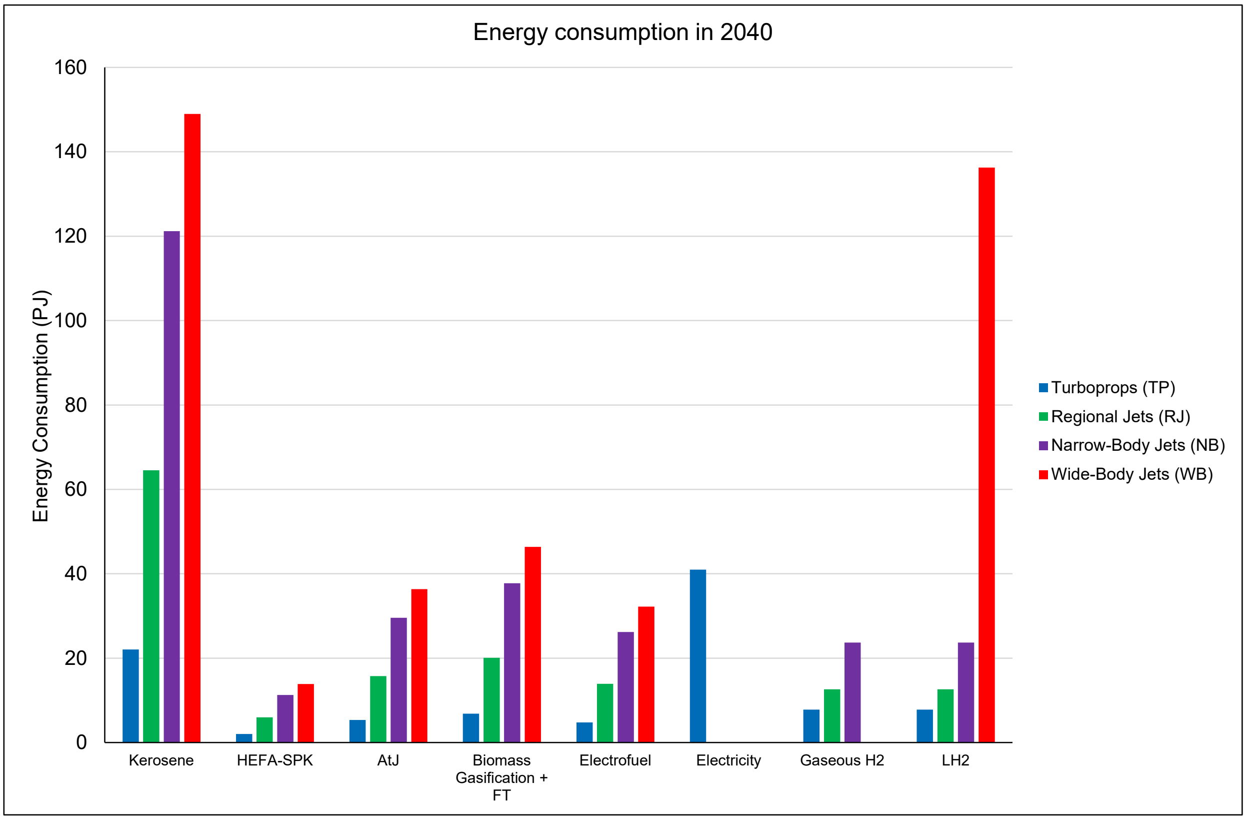
Table 13-11: Assumed applicability of electric and hydrogen fuel technologies to new aircraft deliveries

Energy Carrier	Technology	Aircraft Category	Initial availability	% Deliveries
Electricity	Full electric propeller-driven aircraft	TP	2025	50%
	Hybrid electric powertrain	RJ	2035	50%
		NB	2035	50%
Hydrogen	Hydrogen-fuelled gas turbine engine	RJ	2030	50%
		NB	2030	50%
		WB	2030	100%
	Hydrogen fuel cell plus electric power for turboprop	TP	2026	20%

Source: Authors' judgement.

This approach allowed the energy consumed using each fuel type in each year. The distribution among the different aircraft categories and fuel types for the year 2040 is shown in Figure 13-3 (the similar distribution for the year 2050 was shown in the main report as Figure 4-5).

Figure 13-3: Energy consumption in 2040 by fuel (energy carrier) type and market segment



The costs for the different fuels were then obtained by multiplying the quantity of fuel consumed in each year (after converting the fuel quantities from energy terms to mass terms) by the assumed fuel prices. These prices were mostly obtained from the ReFuelEU aviation proposal.

Table 13-12: Assumed fuel prices to 2050 (all in €/tonne, except for electricity, which is in €/GJ)

Year	Kerosene	HEFA-SPK	AtJ	Biomass Gasification + FT	E-fuel	Gaseous H_2	Liquefied H_2	Electricity (€/GJ)
2020	€550	€1.045	€2,900	€2,075	€2,660	€4,476	€4,476	€13
2030	€1,010	€1,005	€2,086	€2,057	€2,968	€2,743	€2,743	€11
2040	€1,100	€1,042	€2,164	€2,039	€2,310	€2,218	€2,218	€9
2050	€1,250	€1,048	€2,161	€2,088	€1,925	€2,051	€2,051	€8

Sources: Kerosene, HEFA-SPK, AtJ, Electrofuel (European Commission, 2021i); Biomass Gasification + FT (Pavlenko, Searle, & Christensen, 2019), Hydrogen, Electricity (Ricardo, 2022).

The approach described above then allows the total variation in fuel costs to be developed for the 'With technologies' scenario. The increase in fuel costs from the baseline is then derived by using the same approach to calculate the baseline fuel costs (assuming that all energy is consumed as kerosene) and subtracting the 'With technologies' costs from them.

14. A4 – LEGAL CONSIDERATIONS ON STATE AID

Article 107(1) of the TFEU prohibits state aid because it distorts competition in the internal market and affects trade between Member States in a way that is contrary to the common interest.

State aid measure is defined as an intervention by the State or through State resources which may take a variety of forms (e.g., grants, interest and tax reliefs, guarantees, government purchasing of all or part of a company at a price that would differ from a market price, or providing goods and services on preferential terms, etc.) granted to undertakings as an advantage on a selective basis, for example to specific enterprises or industry sectors, or to enterprises located in specific regions and affects trade between Member States in a way that is contrary to the common interest.

A State aid measure involves the allocation of state resources to a private or public company. Therefore, subsidies granted to individuals or general measures open to all enterprises are not covered by this prohibition and do not constitute State aid (examples include general taxation measures or employment legislation).

Under the TFEU rules, State aid in the EU is, in principle, prohibited because it gives a company an advantage over its competitors. While the TFEU prohibits State aid because it distorts the market, it does allow for a few exceptions where state aid may be considered to be compatible with internal market, including (and the most relevant one) 'aid to facilitate the development of certain economic activities or of certain economic areas, where such aid does not adversely affect trading conditions to an extent contrary to the common interest' (Article 107(3)c) TFEU). Other categories of exceptions are laid down in Article 107(2) TFEU or in other provisions under Article 107(3) TFEU. Furthermore, Articles 42 (production of and trade in agricultural products) and 93 (transport public service) and Article 106(2) regarding services of general economic interest also provide for conditions under which state aid may be considered compatible with the internal market. Furthermore, Important Projects of Common European Interest (IPCEI) may be considered subject to state aid under Article 107(3)(b). The Commission has adopted a Communication setting out criteria under which Member States can grant state aid to transnational projects of strategic significance.

Article 108(2) and (4) TFEU establish certain procedural rules for the authorisation of state aid, as an exclusive competence of the Commission. On this basis, Member States should notify the Commission of any plans to grant aid, unless they are exempted from notification under an exemption regulation. Under Article 108 TFEU if the Commission considers that such an aid is incompatible with the internal market, it should initiate a procedure and request the State to abolish or alter the aid within a certain time frame. The Member State cannot put into effect any state aid measures until the procedure has resulted in a final positive decision. The Commission has adopted regulations declaring certain categories of aid as compatible with internal market rules (e.g., state aid to support certain environmental measures or energy measures). Some types of aid are exempt from notification to the Commission if they meet all of the conditions in the General Block Exemption Regulation.

State aid control requires that any new aid measure, including to state-owned operators, that is notified to the Commission, is analysed regarding its compatibility with EU rules and conditions. Those rules define the common assessment principles for the State aid to be granted to limit market distortion. They require State aid measures to have positive effects that outweigh the market distortion caused. They also require the aid to contribute to the Union objectives, including EU environmental protection without adversely affecting trading conditions to an extent contrary to the common interest. The Commission also considers if the aid is needed because it effectively targets a (residual) market failure which is not addressed. The Commission also assesses if the aid has an incentive effect and induces the beneficiary to change its behaviour to reach the EU objective, which it would not have undertaken without the aid. The aid cannot compensate for the normal business risk of an economic activity.

The aviation sector has benefited from State aid measures such as exempting airlines from fuel tax, airline tickets exempted completely from VAT or operating aid to airports to boost their turnover under the Aviation State Aid Guidelines. The current Guidelines on State Aid for climate, environmental protection and energy 2022 establish that for refuelling infrastructure for air transport supplying synthetic fuels, including renewable liquid and gaseous transport fuels of non-biological origin, or biofuels (including sustainable aviation fuels), the Member State must justify the need for new infrastructure, taking into account the technical characteristics of the fuel or fuels to be supplied using that infrastructure. In the case of drop-in synthetic fuels or biofuels, the Member State must consider the extent to which existing infrastructure can be used for the supply of drop-in synthetic fuels or biofuels. The Commission is also facilitating the coordination between Member States towards Important Projects of Common European Interest (IPCEIs) in the area of new hydrogen related technologies and infrastructure.

State aid for aircraft replacement does not seem to be justified and comply with the State aid conditions under EU law, including the incentive effect as, in any case, airlines need to take measures to ensure decarbonisation by law. However, providing State aid for going beyond the law such as ensuring the production of aircraft fuelled by hydrogen within the next decades might be justified and the Commission could consider their inclusion in the revised version of the Guidelines on State Aid for climate, environmental protection and energy or the Aviation Guidelines. The Commission has announced that it will also do its utmost to assess state aid related to renewable hydrogen, while ensuring a level playing field and considering technology neutrality, including in the framework of the IPCEIs (European Commission, 2022g).

This study discusses the technological innovations, operational measures and alternative fuels that are needed for the aviation industry to achieve the objectives of the European Green Deal by 2050. It also presents estimates of the investment needed for the industry to achieve those goals and analyses the EU regulatory framework and funding sources that can support the industry in its decarbonisation pathway.

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