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DESTINATION 2050 - ROADMAP

CUSTOMER: A4E, ACI-EUROPE, ASD, CANSO, ERA

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Contents

1 Introduction

In February 2021, European aviation industry trade organisations ACI EUROPE, Airlines for Europe (A4E), ASD Europe, European Regions Airline Association (ERA) and CANSO Europe launched the DESTINATION 2050 alliance and published their first landmark roadmap report on decarbonising European aviation, prepared by Royal Netherlands Aerospace Centre (NLR) and SEO Amsterdam Economics (van der Sman, Peerlings, Kos, Lieshout, & Boonekamp, 2021). The study noted that sustainability forms the aviation sector's licence to operate and showed that net zero CO_2 emissions can be achieved from all flights within and departing the EU+ region[1].

> *As the first edition of the DESTINATION 2050 roadmap report, this revised and updated edition identifies a pathway to decarbonise European aviation. Based on a bottom-up assessment of measures that reduce energy consumption and net CO_2 emissions, it outlines an ambitious but feasible path towards net zero CO_2 emissions in 2050. By doing so, this report aims to continue to inform and guide the joint, coordinated and decisive actions industry and governments need to take to realise this goal.*

The report also noted the need for updating the work as time progresses and history unfolds itself, for the DESTINATION 2050 roadmap report to continue to guide the aviation sector towards its sustainability ambitions. Indeed, between the development of that initial report and today, a lot has happened – ranging from the adoption of a long-term aspirational goal for net zero CO_2 emissions from international aviation (ICAO, 2022a; ICAO, 2022f) to the introduction of the world's first sustainable aviation fuel blending mandate in Europe (EC, 2023a), and from growing knowledge about the relevance of non-CO_2 climate effects of aviation[2] (e.g. EASA, 2020; Lee, et al., 2021) to increasing efforts towards making hydrogen-powered aviation a reality (e.g. Airbus, 2020).

As such, this present document is a revised and updated second edition of the DESTINATION 2050 roadmap report – the results of which are presented in Chapter 2. The revision means that the projections and outlooks on which the roadmap is based – dealing with improvements in aircraft and engine technology (Chapter 3), air traffic management and aircraft operations (Chapter 4), sustainable aviation fuels (Chapter 5) and economic measures (Chapter 6) – have been re-evaluated and updated to reflect the latest insights. More visibly, the effect of decarbonisation on in-sector expenditures, previously studied separately in The Price of Net Zero (Adler, et al., 2023), has been integrated into the chapters dealing with the four decarbonisation pillars, the discussion of sustainable aviation fuels has been expanded to cover energy demand in general, and cumulative emissions between 2020 and 2050 are reported on, and compared to carbon budgets in line with limiting warming to well below 2°C and 1.5°C, as targeted in the Paris Agreement. Lastly, Chapter 7 discusses non-CO_2 climate effects of aviation, summarising the state of science and mitigation measures that are considered. Further details are included in the various appendices to this report. Appendix B specifically provides background and context.

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[1] Defined as the European Union (EU27), the United Kingdom (UK) and the European Free Trade Association (EFTA).

[2] The term 'non-CO_2 climate effects of aviation' is used to collectively refer to various other climate effects, such as contrail-induced cloudiness, that are caused by aircraft emissions. These effects are more extensively discussed in Chapter 7.

Similar to the first edition of the DESTINATION 2050 roadmap report, this work embraces an ambitious but feasible level of technological innovation on various fronts as the primary and preferred means to reduce aviation CO_2 emissions. Similarly, cost-effective solutions sustaining economic growth are strived for. This conceptually puts the current work in line with publications from the International Energy Agency (IEA, 2021; IEA, 2023c).

Notwithstanding this chosen focus, it is stressed that the decarbonisation pathway outlined in this report is not the only one, or one that is (or should be) set in stone. Uncertainties exist: some developments might not live up to expectations, whereas others might surpass these. Future updates of this work are hence recommended, but until that time, the present work should be used as a well-supported foundation for further reducing the carbon footprint of European aviation by industry and policy makers alike. Inaction cannot be afforded.

2 Roadmap

2.1 Introduction

This chapter presents the updated DESTINATION 2050 decarbonisation roadmap from all flights within and departing from the EU+ region by 2050. It confirms that net zero CO_2 emissions can be achieved by a combination of measures and a limited – although increased – (10% in 2050) reliance on out-of-sector carbon removals, compared to the reference scenario.

The subsequent sections explicate scope (Section 2.2), list developments since the launch of the first edition of the DESTINATION 2050 roadmap report (Section 2.3), describe approach (Section 2.4), summarise modelling inputs (Section 2.5) and present results (Section 2.6), before providing a high-level progress report (Section 2.6.6) and drawing conclusions and listing implications for both public and private parties (Section2.7).

2.2 Scope and definitions

This updated roadmap considers CO_2 emissions from fuel combustion (Tank-to-Wake emissions) of scheduled passenger and cargo flights departing from any airport in the EU, UK and EFTA – collectively referred to as EU+ – consistent with the previous roadmap report. Table 1 provides defines the study scope in more detail.

Table 1: Study scope, defining the region, emissions and flights considered

Region	Flights departing from airports within the European Union (EU), the United Kingdom (UK), and the European Free Trade Association (EFTA), consisting of Iceland, Liechtenstein, Norway and Switzerland. This region is designated as the **EU+ region**.
Emissions	The quantitative parts of this study are limited to CO_2 emissions from in-flight fuel combustion or usage, more commonly referred to as **Tank-to-Wake (TtW) emissions**. In line with the UNFCCC reporting framework and the IPCC Guidelines for National Greenhouse Gas Inventories (IPCC, 2006), this study covers the entirety of CO_2 emissions from flights within and departing from the EU+ region.
Flights	For practical reasons, this study is limited to **scheduled passenger and cargo flights**. Non-scheduled passenger and cargo operations, spanning charter flights, general and business aviation, cargo flights carried out by integrators (such as UPS, DHL and FedEx), and all other forms of air traffic not included in OAG Schedules Analyser (Official Airline Guide, 2019) [3], are hence out of scope.

The decarbonisation pathway presented in this report targets net zero CO_2 emissions from all flights within and departing from the EU+ region by 2050. For this target, the report follows the definition of 'net zero' carbon by the IPCC (2018), meaning that any remaining carbon emissions will have to be removed from the atmosphere through negative emissions, achieved through natural carbon sinks (e.g., forests) or dedicated technologies (carbon capture and storage).

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[3] General and business aviation is estimated to account for about 2% of total aviation CO_2 worldwide (ICCT, 2019a). Integrator and charter flights are likely to account only for a small share of aviation emissions.

> **NET ZERO DEFINITION IN RELATION TO THE DESTINATION 2050 ROADMAP**
> The authors acknowledge that there are variations in definitions of net zero that can inform different trajectories toward this goal (e.g. ISO IWA 42:2022 ; the Corporate Sustainability Reporting Directive of the EU (CSRD)) and the standards set in the European Commission Delegated Regulation (EU) 2023/2772) (EC, 2023c). For the sake of consistency and comparability, this report is based on the same net zero definition used in the first edition of the roadmap. This approach ensures a coherent framework for evaluating progress in achieving European aviation's ambitious emissions reduction target in the EU+ region.
>
> This Roadmap outlines a decarbonisation pathway for flights within and departing from the EU+ region. It addresses the decarbonisation challenge from the overall aviation sectoral perspective. Although DESTINATION 2050 is out of the scope of the CSRD, individual companies may leverage the information provided in this roadmap for their own decarbonisation strategy and objectives and their corporate sustainability responsibility. Furthermore, companies may use sector specific roadmaps to prepare for the expected future sector specific standards within the CSRD. Although not directly applicable, the Roadmap report includes:
>
> - A separate analysis on cumulative emissions and carbon budgets using the International Energy Agency Net Zero Roadmap for both a 1.5°C and 1.7°C sector specific carbon budgets, see Section 2.6.2;
> - The results Section 2.6 includes the amount of CO_2 removals in 2050 compared to the baseline year of this analysis, namely 2019.

For the expenditure analysis, the scope includes any expenditures required to achieve net zero CO_2, consistent with the previously published Price of Net Zero, prepared by Roadmap research consortium of NLR and SEO (Adler, et al., 2023). Insofar possible, the study distinguishes between costs (typically: short-term, recurring, operational expenditures) and investments (typically: long-term, one time, capital expenditures). Investments are only considered if they occur within the aviation sector and, hence, are related to the key activities of airports, airlines, aircraft manufacturers and ANSPs. Investments made by parties in other sectors (e.g., producers of SAF and other alternative energy carrier producers) are not explicitly considered, but are assumed to be passed on to sector parties in the selling price of the final product (e.g., SAF or hydrogen).

2.3 Developments since the initial roadmap

This timeline distinguishes between **developments in government and policy**, **industry progress** and **joint actions**.

02/2021: Launch of DESTINATION 2050 and the first European Aviation Net-Zero roadmap

07/2021: Fit for 55 package

The Fit for 55 package is a set of proposals by the European Commission aimed at reducing greenhouse gas emissions by at least 55% by 2030, as part of the European Union's efforts to become climate neutral by 2050.

07/2021: Revision of the EU ETS

The revision of the EU ETS (Emissions Trading System) trading scheme by the European Commission strengthens the EU's carbon pricing mechanism, which aims to reduce greenhouse gas emissions from certain industries, including aviation. The revision includes changes such as expanding the scope of the scheme to include more sectors, increasing the ambition of emission reduction targets, and introducing new rules to prevent carbon leakage and ensure a level playing field.

11/2021: Launch of Clean Hydrogen Partnership

The Clean Hydrogen Partnership aims to “strengthen and integrate EU scientific capacity” with respect to the development of clean hydrogen applications (Clean Hydrogen JU, n.d.). Aviation is also in focus, as evidenced by the funding of projects relating to on-board hydrogen storage and aircraft fuel cell power generation systems.

11/2021: Launch of SESAR 3 Joint Undertaking

The European institutional public-private partnership Single European Sky ATM Research 3 Joint Undertaking (SESAR 3 JU) was launched as a successor to the earlier SESAR programmes. Its goal is the acceleration of research and innovation in ATM and the introduction of the “Digital European Sky” to further increase the efficiency and environmentally-friendliness of the air traffic in Europe (SESAR, n.d.).

12/2021: Launch of Clean Aviation Joint Undertaking

Building on the Clean Sky and Clean Sky 2 programmes, the Clean Aviation Joint Undertaking was launched (Clean Aviation, 2022a). Through a combination of €1.7 bn of public funding and a €2.4 bn in-kind contribution from industry, it supports technology development for a next generation of regional and single-aisle aircraft.

04/2022: ICAO LTAG report

CAEP formed the Long-Term global Aspirational Goal Task Group (LTAG-TG) to provide technical analyses of future international aviation CO_2 emission trajectories up to 2070 with the aircraft technologies, operations and alternative fuels associated with varying future scenarios. (ICAO, 2022e). In October 2022 the 41st ICAO Assembly adopts LTAG for international aviation of net zero carbon emissions by 2050 (ICAO, 2022a).

10/2023: Final ReFuelEU Aviation Regulation (EC, 2023h)

ReFuelEU Aviation is a European Union regulation aimed at increasing the use of sustainable aviation fuels (SAF) in the aviation sector, with the goal of reducing greenhouse gas emissions from aviation. The mandate requires fuel suppliers to blend an increasing percentage of SAF with conventional aviation fuels, starting from 2% in 2025 and rising to 70% by 2050, to help decarbonise the aviation industry.

11/2023: ICAO CAAF/3

Global Framework for SAF, LCAF and other Aviation Cleaner Energies. The framework includes a 5% emission reduction target by 2030 through the use of cleaner energy sources. It also contains provisions to avoid double counting of the emission reductions derived from the use of cleaner energies.

2.4 Approach

This report was developed following the same approach used for the previous DESTINATION 2050 roadmap report, schematically illustrated in Figure 1. This means that the effect of decarbonisation measures is evaluated for a single traffic scenario (described in Section 2.4.1). The modelling (outlined in Section 2.4.2) takes into account the effects of decarbonisation measures on the development of the traffic and estimates CO_2 emissions. It does so for a 'hypothetical no-action growth' reference scenario (also outlined in 2.4.1) without further decarbonisation measures, as well as for the DESTINATION 2050 scenario, which does include these efforts. Results are evaluated for horizon years 2030, 2040 and 2050 and linearly interpolated in between.

The decarbonisation pathway itself is developed using a combined top-down and bottom-up methodology. Although the ambition level (net zero CO_2 emissions) was already defined by the previous DESTINATION 2050 roadmap report, the contributions by different measures were modelled based on ambitious but feasible expectations of future developments, based on an updated literature review and various workshops and interviews with (industry) experts and researchers (Appendix A).

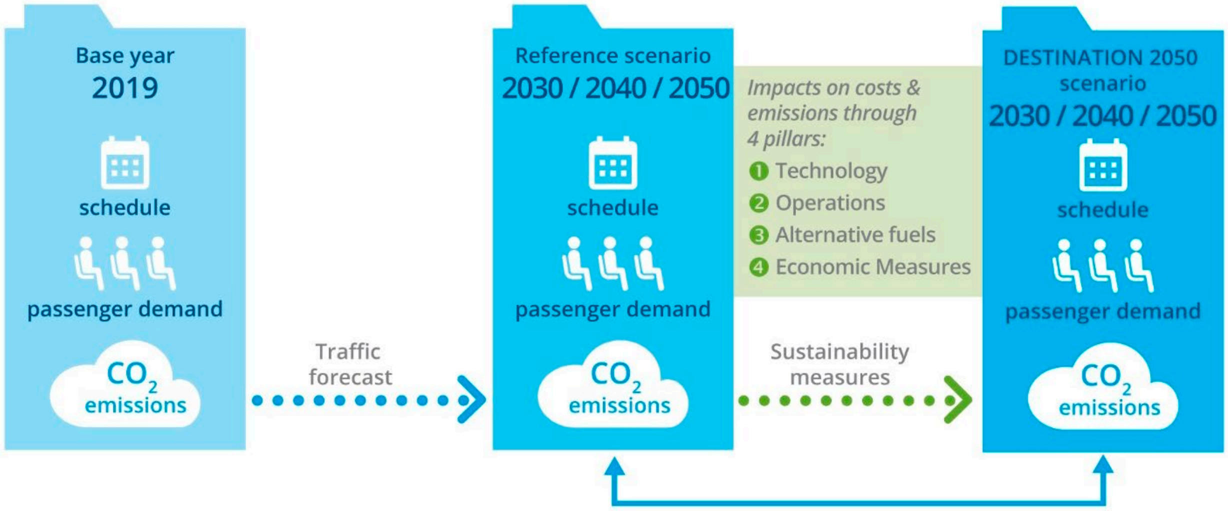

Figure 1: Schematic overview of the research approach

2.4.1 Traffic scenario

To assess the impact of various sustainability measures, a detailed route-level forecast for 2030 and 2050 is created[4]. This forecast is based on 2019 reference data (sourced from OAG) to exclude temporary COVID-19 effects on demand and supply. Excluding temporary effects from long-term forecasts is advisable in balance with the alternative of using newer forecasts that are biased.

Growth forecasts

The number of passengers and aircraft movements in the reference scenario are estimated on the basis of external, unconstrained industry forecasts. A forecast by EUROCONTROL (2018, Regulation & Growth scenario), estimating flight movements until 2040 per country, is used as basis. Aggregate growth rates based on EUROCONTROL are adjusted based on the regional breakdown by Airbus. For the period beyond the horizon of each growth forecast, the growth rate reported for the period 2035-2040 is applied. Cargo growth rates are based on the Airbus-data, found consistent with an overall EUROCONTROL cargo growth rate and forecasts from Boeing (2019b).

Load factor and aircraft size

Load factor and aircraft size have increased over time, and these trends are expected to continue, particularly considering airport and airspace capacity constraints (EUROCONTROL, 2023a). Airline operations become more (fuel) efficient by deploying aircraft with a larger seat capacity – up to a certain extent – and achieving a higher load factor. Based on analysis in the first edition of the DESTINATION 2050 roadmap report (van der Sman, Peerlings, Kos, Lieshout, & Boonekamp, 2021, pp. 21-22), load factor and aircraft size growth are assumed to be 0.3% each year over the time period 2018-2050 [5].

COVID-19 and geopolitical events

The impact of COVID-19 on air traffic is taken into account for the reported annual growth rates and cumulative emission figures, by modelling a CO_2 emissions level (with respect to 2019) of 43.5% in 2020, 44.2% in 2021, 78.3% in 2022 and 88.5% in 2023 (EASA; EEA; EUROCONTROL, 2022). Traffic for 2024 is assumed to be in line with 2019, and any distributional effects on the share of business and leisure travel are expected to be non-structural and therefore not carry over to 2030 and later[6]. Other geopolitical and regulatory disturbances of air traffic (e.g. Ukraine-Russia conflict, Israel-Hamas conflict, etc.) are all assumed to be temporary in nature.

Reference scenario

The reference scenario assumes that no additional measures are taken in response to the Paris Agreement. With regard to technology, operations and SAFs, the reference scenario is a hypothetical no-action scenario, meaning that fuel consumption in the reference scenario does not improve with time, and that SAFs uptake remains negligible. Lastly, trends about the increasing societal awareness of climate change are not included in the reference scenario.

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[4] The intermediate horizon year 2040 is not explicitly modelled, but interpolated.

[5] This means that these are also reflected in the reference scenario. As such, associated reductions in CO_2 emissions are not considered pillars of the decarbonisation pathway. From an industry-average load factor of approximately 83% in 2019, this implies an increase to an industry average load factor of 91% by 2050.

[6] No structural changes to the long-term trend are assumed to ensure that future traffic and CO_2 emissions are not underestimated

2.4.2 Modelling

The changes in passengers, operations and emissions are forecasted according the NetCost passenger choice model on the route level. The same model has also been used in the first edition of the DESTINATION 2050 roadmap report, the related work The Price of Net Zero and various other works and scientific publications[7].

The model calculates the expected impact of this DESTINATION 2050 roadmap measures on operations as well as ticket prices, the resulting change in passenger volumes and emission. Figure 2 and Appendix 4.1 provide more information, with some key aspects being outlined in the remainder of this section.

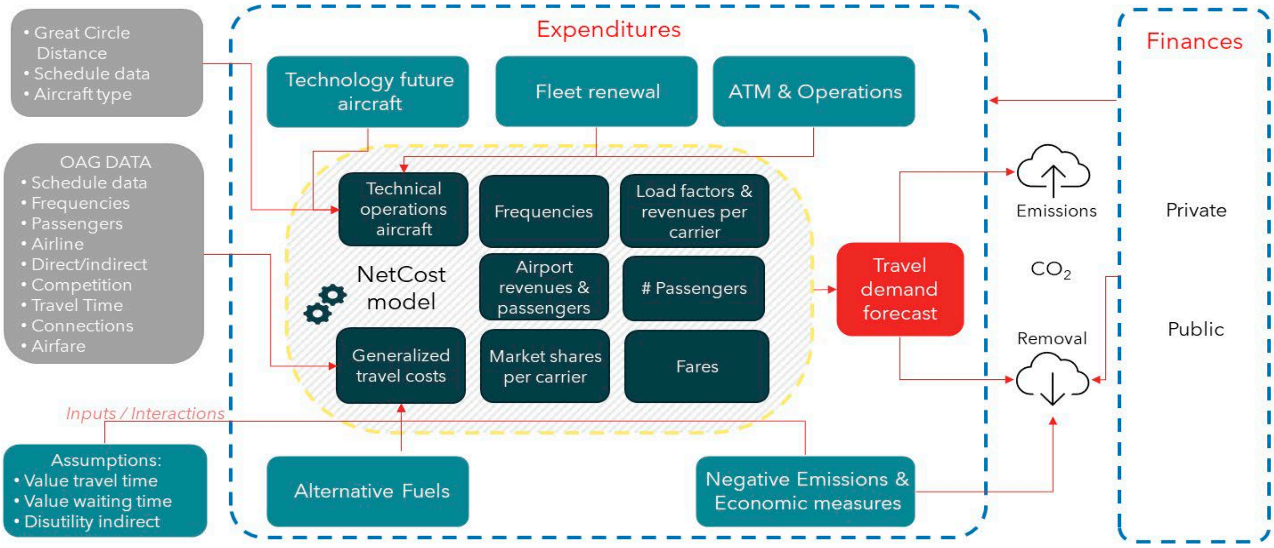

Figure 2: Passenger behaviour model schematics

Cost pass-through

The sustainability measures modelled in this report result in cost increases. Table 2 shows these cost components and if, and to what extent, these cost increases have been modelled to be passed on to consumers through an increase in ticket prices. For the most prominent cost increases, full pass-through is assumed – either as suggested by literature for markets were cost increases are sector-wide (Koopmans & Lieshout, 2016), or as simplifying assumption[8,9,10].

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[7] The Price of Fit for 55 (Konijn, Adler, Boonekamp, & Peerlings, 2022); Up in the air (Adler & Petrat, 2022); as well as Aviation Fit for 55 (SEO & NLR, 2022). The NetCost model has been used in many different studies for IATA, ACI EUROPE, the Civil Aviation Authority of Singapore (CAAS) and the Dutch government. See for academic examples of the model use in: Burghouwt, G. (2019). Assessing consumer welfare impacts of aviation policy measures. International Transport Forum Discussion Paper; Lieshout, R., & Matsumoto, H. (2012). New international services and the competitiveness of Tokyo International Airport. *Journal of Transport Geography*, *22*, 53-64; and Veldhuis, J. (2010). The impact of airline network strategies for service quality of airports. *Critical Issues in Air Transport Economics and Business*.

[8] In some cases, cost increases might not apply to all competitors in a market. This could for example be the case for competition in international hub markets, in which some airlines are not subject to local or European measures. In such cases, airlines might choose to absorb (part of) the cost increase to avoid losing market share. Such choices are difficult to model, as they are highly dependent on the market and the financial situation of airlines.

[9] There is an academic discussion to what extent cost of sustainability measures can be passed-through given slot restrictions and market power on the route level (Koopmans & Lieshout, 2016; Starkie & Yarrow, 2013) As such, demand impacts – and associated CO_2 reductions – might be (slightly) overstated. However, considering the relatively low profit margins in the sector, the extent to which airlines can absorb costs is limited.

[10] The notion that airlines are not able to internalise cost increases related to sustainability is exemplified by various European carriers that have announced or already implemented increases in ticket prices (Petersen, 2024).

Table 2: Cost pass-through assumptions for each of the cost components per pillar

Pillar	Cost component	Cost pass-through	Rationale / remarks
Improvements in aircraft and engine technology	Future aircraft research and development	None	Funded from aircraft and engine sales revenue, partly publicly funded
	Fleet renewal	None	Funded from fuel (and related) savings
	Infrastructure for future aircraft	Part of fuel premium	Included in fuel cost, and thereby fully passed through
Improvements in ATM and operations	Airline operations	None	Funded from fuel (and related) savings
	Airspace and air traffic management	None	Funded from fuel (and related) savings, partly publicly funded
	Ground operations at airports	None	Funded from fuel (and related) savings
Alternative fuels and sustainable energy	Drop-in sustainable aviation fuels	Full price premium	
	Hydrogen	Full price premium	
	Renewable electricity	None	Negligible amount (Adler, et al., 2023; Section 5.5.5)
Carbon pricing / negative emissions		Full	

Elasticities

Using price elasticities for business and leisure from the scientific literature[11] and own estimations, the NetCost model computes the change in demand due to changes in generalized travel costs between the reference and DESTINATION 2050 scenario.

Emissions modelling

Tank-to-wake emissions in the scope of this work (as defined in Section 2.2) are modelled from estimates of fuel consumption for each individual aircraft operation during each flight phase. For the climb, cruise and descent phases the fuel consumption data is based on EUROCONTROLs Base of Aircraft Data (BADA), which is extensively used in the (scientific) literature. For the LTO phase, fuel consumption is taken from ICAOs Engine Emissions Databank. CO_2 emissions are directly related to fuel consumption and hence follow directly from the model.

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[11] Initial price elasticities of demand of -1 and -1.5 are assumed for business and leisure passengers respectively, see further support in, for example: Perera & Tan (2019).

2.5 Measures and impact modelling

With further detail in their respective chapters, the next sections provide an overview of the most important assumptions and modelling choices with respect to improvements in aircraft and engine technology (Section 2.5.1), ATM and aircraft operations (Section 2.5.2), alternative fuels and renewable energy (Section 2.5.3) and economic measures (Section 2.5.4). Changes compared to the first edition of the DESTINATION 2050 roadmap are outlined.

2.5.1 Improvements in aircraft and engine technology

Improvements in aircraft and engine technology are ultimately delivered through fleet renewal: first by ‘recent and imminent’ aircraft (recently introduced or shortly available), later by ‘future’ aircraft. Table 3 shows the average fuel efficiency (and corresponding reduction in CO_2 emissions) per flight compared to previous generation aircraft, as well as the fleet level CO_2 emissions reductions that these aircraft realise by 2030, 2040 and 2050, taking into account a fleet replacement period of 22.5 years.

> MAIN CHANGES FROM THE FIRST EDITION OF THE DESTINATION 2050 ROADMAP REPORT
> For the first period of the roadmap, delays in the entry into service of recent and imminent aircraft (2 years on average) reduce their contribution to decarbonisation. For the period from 2030, in which ‘future’ aircraft are introduced, regional hydrogen-powered aircraft have been added to the modelling, whereas the overall market uptake of hydrogen-powered aviation in general is reduced due to lower market shares modelled (up to 50%) and a later (2040 versus 2035) entry into service for the hydrogen-powered single-aisle.

Table 3: Class-averaged fuel efficiency improvement (and CO_2 emissions reduction) of recent and imminent aircraft, per flight with respect to previous generation aircraft, and fleet level CO_2 emissions reductions delivered by these recent and imminent aircraft, taking into account the time required for fleet replacement (22.5 years). The fuel efficiency improvement figure for the regional class is notably larger due to an increasing share of turboprop aircraft, which are inherently more efficient than regional jets

Class	Seating capacity	Fuel efficiency improvement (and CO_2 emissions reduction) per flight	Fleet level CO_2 emissions reduction		
			2030	2040	2050
Larger Regional (R)	20 – 100	29% (excl. effect of SAF)	12.6%	15.5%	18.4%
Single aisle (SA)	101 – 240	17% (excl. effect of SAF)	8.7%	10.2%	11.6%
Small/medium twin aisle (SMTA)	241 – 350	18% (excl. effect of SAF)	9.2%	13.0%	16.7%
Large twin aisle (LTA)	351 +	19% (excl. effect of SAF)	7.5%	13.1%	18.7%

From 2030, future aircraft will enter into the fleet, including one hybrid-electric and three hydrogen-powered types. Similar to Table 3, Table 4 shows the effect of these future aircraft on CO_2 emissions. The hydrogen-powered aircraft are only operated on a share (regional: 50%; single-aisle: 60%) of applicable (regional: up to 775km; single-aisle: up to 2000km) intra-EU+ routes and for such aircraft, increase in cost per ASK (regional: +28%; single-aisle: +21%; both excluding change in energy carrier) are modelled to be passed through to consumers, thereby affecting demand.

Table 4: Class-averaged fuel efficiency improvement and CO_2 emissions reduction of future aircraft, per flight with respect to recent and imminent aircraft, and fleet level CO_2 emissions reductions delivered by these future aircraft, taking into account the time required for fleet replacement (22.5 years). Entry into service (EIS) years are rounded to a 5-year resolution

Class, aircraft type, technologies and applicability	EIS	Energy efficiency improvement per flight	CO_2 reduction per flight	Fleet level CO_2 emissions reduction (excl. SAF)	
				2040	2050
Small (S), *with various technologies*	2030	not assessed	100%	44.0%	88.0%
H_2 fuel cell regional propeller aircraft (R), *retrofit, <700 km, 55 pax., intra-EU+*	2030	30%	100%	45.0%	90.0%
Hybrid-electric regional (R), *80 pax.*	2035	45%	50% (excl. SAF)	11.1 %	33.3 %
H_2 fuel cell regional propeller aircraft (R), *clean sheet, <1000 km, 100 pax., intra-EU+*	2035	40%	100%	22.2 %	66.7%
Single-aisle (SA)*, conventionally or SAF-powered*	2035	30%	30% (excl. SAF)	6.7 %	20.0%
H_2 fuel cell / combustion hybrid single-aisle (H_2-SA)	2040	20%	100%	0.0%	20.0%
Small/medium twin aisle (SMTA), *conventionally or SAF-powered*	2035	30%	30% (excl. SAF)	6.7%	20.0%
Large twin aisle (LTA), *conventionally or SAF-powered*	2040	30%	30% (excl. SAF)	0.0 %	20.0%

2.5.2 Improvements in Air Traffic Management (ATM) and aircraft operations

The improvements in air traffic management (ATM) and aircraft operations generally lead to a reduction of fuel burn and thus CO_2 emissions. The potential CO_2 emission reduction per individual measure is estimated in Section 3.4 and modelled for the years 2030 and 2050 [12].

> MAIN DIFFERENCES COMPARED TO THE FIRST EDITION OF THE DESTINATION 2050 ROADMAP REPORT
> Compared to the assumptions for the ATM and aircraft operations pillar of the first edition of the DESTINATION 2050 roadmap, a few changes and updates have been made. The Single European Sky and SESAR improvement numbers are reduced compared to the first edition. Now, the numbers from the European ATM Master Plan 2020 Edition (SESAR JU, 2019b) with additional information from the EASA Environmental Report 2022 (EASA; EEA; EUROCONTROL, 2022) have been directly taken into account with a split in additional ATM related improvements and unimpeded improvements. The numbers from the European ATM Master Plan 2025 Edition are not directly taken for the modelling, but a comparison is made. The “further CO_2 emissions reduction potential” from the first edition of DESTINATION 2050 is not used anymore and the “Non-European ATM efficiency improvements” are put in one category with the SES(AR) improvements for departure flights to outside of the EU+. Based on more recent estimations from the ICAO LTAG report (ICAO, 2022e) the airframe condition and maintenance CO_2 emission savings increased compared to the last edition and the weight reductions are assumed to take place until 2050. Reduced tankering is added as an additional measure reducing the average fuel burn per flight for intra-EU+ flights. The timelines of the introduction of wake energy retrieval are postponed, assuming that it will be slowly upscaled from 2030 and assuming that except for flights over the North Atlantic, this concept will be only introduced on few flights until 2050. Based on an updated calculation of the taxi fuel consumption compared to the total fuel consumption, the reduction potential of reduced engine taxiing and operational towing for long-haul flights and the associated weight savings for all flights are corrected downwards.

Table 5 gives an overview of the modelled assumptions of the measures grouped under airline operations, Table 6 presents the modelled assumptions of the measures falling under airspace and air traffic management (ATM) and Table 7 gives an overview of the modelled assumptions of the measures related to ground operations at airports.

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[12] The numbers for 2040 are estimated in section 4.4 but not explicitly modelled as there is no big deviation from a linear interpolation of the 2030 and 2050 numbers.

Table 5: Potential CO_2 emission reductions per flight to be delivered by airline operations

Measure	2030	2050	Remarks
Improved flight planning	1.2%/flight	1.2%/flight	
Reduced cruise speeds	0.3%/flight	0.3%/flight	
Flight management system updates	0.5%/flight	1%/flight	
Weight reduction	0.56%/flight	0.71%/flight	
Reduced tankering	0.41%/flight	0.41%/flight	Intra-EU+ flights
Airframe condition and maintenance	0.53%/flight	1.05%/flight	

Table 6: Potential CO_2 emission reductions per flight to be delivered by airspace and air traffic management (ATM)

Measure	2030	2050	Remarks
Single European Sky / SESAR – intra-EU+	3.9%/flight	5.7%/flight	Intra EU+ flights
Single European Sky / SESAR – extra-EU+ including non-European ATM efficiency improvements	2.7%/flight	3.9%/flight	Departure flights to outside EU+
Improved North Atlantic flight-efficiency	1.3%/flight	1.3%/flight	Flights from Europe to North-America
Wake energy retrieval	0%/flight	2%/flight	Flights from Europe to North-America
	0%/flight	0.38%/flight	Other flights

Table 7: Potential CO_2 emission reductions (unless otherwise specified: per flight) to be delivered by ground operations at airports

Measure	2030	2050	Remarks
Reduced engine taxi – SH	0.42%/flight	0.42%/flight	From taxi-out
Reduced engine taxi – LH	0.14%/flight	0.14%/flight	From taxi-out
Reduced engine taxi – SH	0.24%/flight	0.24%/flight	Intra-EU+ arrivals only
Reduced engine taxi – LH	0.03%/flight	0.03%/flight	Intra-EU+ arrivals only
Electric taxi / operational towing – SH	0.48%/flight	0.96%/flight	From taxi-out
Electric taxi / operational towing – LH	0.16%/flight	0.32%/flight	From taxi-out
Electric taxi / operational towing – SH	0.36%/flight + 14.5 kg weight reduction	0.72%/flight + 29 kg weight reduction	Intra-EU+ arrivals only, weight saving modelled using 3.5% cost of weight per block hour
Electric taxi / operational towing – LH	0.05%/flight + 26 kg weight reduction	0.1%/flight + 52 kg weight reduction	Intra-EU+ arrivals only, weight saving modelled using 3.5% cost of weight per block hour
Reduced APU usage	0.3%/flight	0.3%/flight	

2.5.3 Alternative fuels and sustainable energy

The use of alternative fuels made from sustainable energy/feedstocks, rather than fuels from fossil resources, helps reduce the carbon footprint of aviation. Using fossil resources-based fuels in aviation, adds new carbon to the atmosphere when combusted, which increases the climate change impact of aviation. Using alternative fuels from sustainable resources reduces the amount of carbon aviation adds to the atmosphere, thus reducing its climate change impact[13]. This is the biggest lever to reduce the carbon footprint of the aviation sector.

> MAIN CHANGES FROM THE FIRST EDITION OF THE **DESTINATION 2050** ROADMAP REPORT
> Since the first edition of DESTINATION 2050 was published the landscape for alternative fuels and sustainable energy has changed. Below the most significant changes are described:
>
> - The uptake of SAF in 2050, i.e., the share of SAF in the energy mix, is now based on the ReFuelEU Aviation regulation plus an additional 10% to decrease the dependence on carbon removal technologies. Previously it was modelled using potential availability and pricing based on global and European scenarios from literature.

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[13] Alternative fuels made from sustainable resources reuse currently present carbon in the atmosphere, either via the use of biomass which has taken up carbon from the atmosphere during photosynthesis, or via direct air capture of carbon from the atmosphere. Additionally, some alternative fuels, like hydrogen, do not contain carbon.

> - The SAF pricing estimates have been improved using market factors to convert minimal fuel selling prices (MSFPs) to actual prices, and extrapolating this to 2050. Previously only MSFPs were used in the modelling. In the first edition theoretical prices (minimal fuel selling prices (MFSPs)) were used for SAF prices in the modelling. MFSPs do not represent the actual price of SAF, given that market dynamics also influence the pricing, therefore they were adjusted.
> - The emission reduction of SAF is now based on the Tank-to-Wake (TtW) emission reduction, in alignment with the scope of this study (Section 2.2). This is done following the developments in the emission accounting landscape that have taken place since the first edition of DESTINATION 2050. Previously the complete life-cycle, i.e., Well-to-Wake, emission reduction was compared to the TtW emissions of aviation, which leads to a scope misalignment. A more detailed explanation of the difference in approach is given in the box in Section 5.4.1.

Improvements in aircraft and engine technology, and in ATM and aircraft operations reduce the demand for energy, thereby reducing CO_2 emissions. The remaining energy demand can be fulfilled by alternative fuels and sustainable energy, to further reduce the carbon footprint of aviation. Hereto, SAF and hydrogen are considered in this study. In Table 8 the modelling assumptions regarding alternative fuels are given for 2030, with Table 9 showing the modelling assumptions for 2050.

Table 8: Overview of alternative fuels modelling assumptions for 2030
Total fuel demand is an output of the model; therefore, data is presented as percentual shares. HEFA-based SAF is constrained by feedstock availability, and H_2 (as a direct fuel) is constrained by the number of hydrogen-powered aircraft in operation, therefore these numbers are given in absolute terms

Fuels	**Composition of fuel mix**		**Market price**
	[%]	**[Mt]**	**[€/t]**
SAF (non-synthetic)	5.8%		
HEFA		2.7	2.400
FT	50% of remainder		3.900
AtJ	50% of remainder		4.000
SAF (synthetic)	1.2%		3.900
PtL	1.2%		3.900
H_2 (in Mt SAF equivalents)		-	2.900
Conventional Aviation Fuel	93%		680
Total	100%		

The share of alternative fuels in 2030 is slightly higher, at 7%, than the ReFuelEU Aviation regulation mandates (at 6%). This is due to the voluntary SAF targets set by several airline operators for 2030, that exceed the 6% SAF share initially set by the ReFuelEU Aviation regulation.

The share of alternative fuels in 2050 is higher than what the ReFuelEU Aviation regulation proposes, to decrease the dependence on carbon removal technologies. The additional uptake of alternative fuels, approximately 10% higher than the mandate, can be attained by a combination of options, explained in section 5.5.2.

Table 9: Overview of alternative fuels modelling assumptions for 2050
Total fuel demand is an output of the model; therefore, data is presented as percentual shares. HEFA-based SAF is constrained by feedstock availability, and H_2 (as a direct fuel) is constrained by the number of hydrogen-powered aircraft in operation, therefore these numbers are given in absolute terms

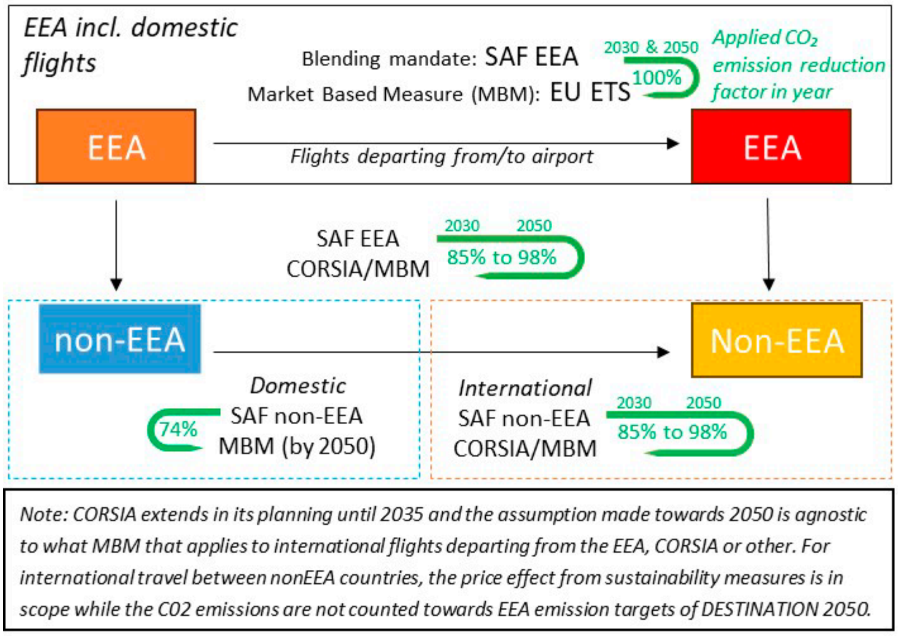
Fuels	**Composition of fuel mix**		**Market price**
	[%]	**[Mt]**	**[€/t]**
SAF (non-synthetic)	45%		
HEFA		4.6	1.800
FT	50% of remainder		2.400
AtJ	50% of remainder		2.600
SAF (synthetic)	35%		
PtL	Remainder of demand after H_2		2.300
H_2 (in Mt SAF equivalents)		Dependent on H_2 aircraft	1.600
Conventional Aviation Fuel	20%		840
Total	100%		

2.5.4 Economic measures

Market-based measures (MBM) in scope are EU ETS as a Regulated Carbon Market (with mandatory participation) and CORSIA as a Voluntary Carbon Market (with voluntary participation).

> **MAIN CHANGES FROM THE FIRST EDITION OF THE DESTINATION 2050 ROADMAP REPORT**
> - The price for a CORSIA carbon off-set is lowered from €60 to €25 in 2030
> - The adoption of the Efficient Market Hypothesis (EMH) to assess the CO_2 emission reduction quality of EU ETS and CORSIA using the current price and the long-term price expectation. As a result, in 2030, EU ETS and CORSIA have reduced CO_2 emission reduction effectiveness by 10% and 85% respectively. The 100% effectiveness in 2050 remains unaffected for both.
> - Earlier phase out of aviation EU ETS free allowances by 2026 instead of 2027
> - CORSIA carbon off-sets for emissions above 85% of 2019 emissions instead of 100% previously
> - Assumption of Market Based Measures on all domestic, international aviation markets in 2050

The model assumptions regarding geographical scope and SAF applicability to each MBM are summarized in Figure 3. It is assumed that EU ETS applies on flights within the EEA and CORSIA to all flights leaving the EEA and international flights outside the EEA.



Note: CORSIA extends in its planning until 2035 and the assumption made towards 2050 is agnostic to what MBM that applies to international flights departing from the EEA, CORSIA or other. For international travel between nonEEA countries, the price effect from sustainability measures is in scope while the C02 emissions are not counted towards EEA emission targets of DESTINATION 2050.

Figure 3: Market Based Measures: EU ETS and CORSIA

For all intra EEA flight emissions, EU ETS are necessary. These allowances can only be either bought in an auction or from other sectors after the end of free allowances in 2026. EU ETS allowances are expected to cost €130 per tonne CO_2 by 2030 and €315 per tonne CO_2 in 2050.

CORSIA carbon credits are necessary for emissions above 85% of 2019 emissions levels by 2030, which will extent to all emissions by 2050 through CORISA or another market-based measure in its place. CORSIA is assumed to apply to all (relevant) international flights leaving and entering the EEA, and outside the EEA by 2030. CORSIA carbon credits are assumed to be €25 per tonne CO_2. The low price of CORSIA is because of the voluntary nature of the market, its lower size at the moment and considered to be indicative of the lower CO_2 emission reduction effectiveness.

Residual CO_2 emissions from SAF blending are zero rated, i.e. the assumed emission reduction factor from blending with SAF are not demanding EU ETS allowances since these are considered to be 100% CO_2 reducing. However, residual emissions from SAF blending do require CORSIA carbon credits since SAF is only assumed to reduce between 85% and 89% of emissions in 2030 and 2050 respectively.

Effective CO_2 emission reduction of MBMs is based on the EMH and is expected to be 15% for CORISA in the year 2030. For EU ETS the effective CO_2 emission reduction is 40% for auctioned allowances and 100% for out of sector purchased allowances. By 2050, the effective CO_2 emission reduction needs to be 100% for all MBMs and is assumed to be equivalent to the market price of CO_2 removal via Direct Air Carbon Capture and Storage (DACCS). All residual CO_2 emissions by 2050 will need to be removed through DACCs at a cost of €160 per tonne CO_2 for CORSIA flights and €315 per tonne CO_2 for flights within the EEA. These prices for EU ETS and CORSIA in 2050 are based on assumed technology costs, see the first version of DESTINATION 2050 and The Price of Net Zero (Adler, et al., 2023) which also explain why DACCS is the preferred technology over other carbon removal technologies.

Consistent with net zero ambitions and the well below 2C degrees Paris climate goal, it is assumed that domestic non-EEA markets have carbon removal projects at €160 per tonne CO_2, which is relevant for sectoral growth forecasts but does not directly enter the CO_2 accounting of DESTINATION 2050.

The DESTINATION 2050 roadmap report makes the strong assumption that there is no effect of SAF free allowances on prices (i.e. SAF and EU ETS) or volumes (i.e. SAF and EU ETS) in 2030. This is equivalent to no available SAF allowances beyond end of 2028, i.e. claimable as EU ETS credits in 2029.

Table 10: EU ETS and CORISA amounts, prices and CO_2 emission reductions

Year	Type of measure	Amount (Mt CO_2)	Price (2019 €)	CO_2 reduction	Note
2030	EU-ETS; auctioned allowances	19.5	€130	40%	Predictions by Morgan Stanley (2022), BofA (2021), and Pietzcker et al. (2021)
	EU-ETS allowances bought from other sectors	31.8	€130	100%	Market price equivalence with auctioned allowances due to trading
	CORSIA eligible carbon credits	8.7	€25	15%	Price based on ICAO (n.d. - a) and Trove Research (2021)
2050	EU-ETS allowances bought from other sectors	11.8	€315	100%	Price based on cost of carbon removal projects DACCS within the EEA, see (Adler, et al., 2023)
	Market Based Measure	21.2	€160	100%	Price based on cost of carbon removal projects DACCS globally, see (Adler, et al., 2023)

2.6 Results

Results of this updated DESTINATION 2050 roadmap report show that net zero CO_2 emissions from all flights within and departing from the EU+ region can be achieved, provided that public as well as private actors realise the decarbonisation measures modelled in this work. By 2050, net in-sector emissions reduce by 90% for all flights, and by 91% for intra-EU+ flights. In order to get to net zero CO_2, the remaining 29 Mt (10 Mt for intra-EU+ flights) is to be removed from the atmosphere through negative emissions technologies such as direct air carbon capture and storage (DACCS).

Between 2020 and 2050, net-in sector cumulative emissions amount to approximately 3.3 Gt, a reduction of 52% compared to the cumulative emissions in the reference scenario (6.9 Gt). For the production of alternative fuels and energy carriers (renewable electricity, green hydrogen and drop-in and non-drop-in SAF) as well as for direct air capture, 762 TWh of renewable electricity is required by 2050. Decarbonising European aviation along the DESTINATION 2050 roadmap pathway comes at an expenditures premium of €1,300 bn, cumulative over the period from 2019 to 2050.

2.6.1 Decarbonisation pathway

Figure 4 shows the overall decarbonisation pathway for flights within and departing from the EU+ region. Net emissions are anticipated decline continuously after their peak in 2019 (except of the COVID-impact), most notably from 2030. The main contributions to achieving net zero CO_2 by 2050 are delivered by sustainable aviation fuels (SAF; 35%), improvements in conventionally fuelled aircraft and engine technology (24%) and improvements in ATM and operations (6%). Demand impacts from increased ticket prices, due to increased cost of technology (hydrogen), fuel (hydrogen or SAF) or due to economic measures in total avoids 55 Mt of CO_2 emissions and thereby contribute 19% to decarbonisation, compared to the no-action reference scenario in 2050. In 2050, residual emissions amount to 29 Mt, which is 16% of CO_2 emissions in 2019.

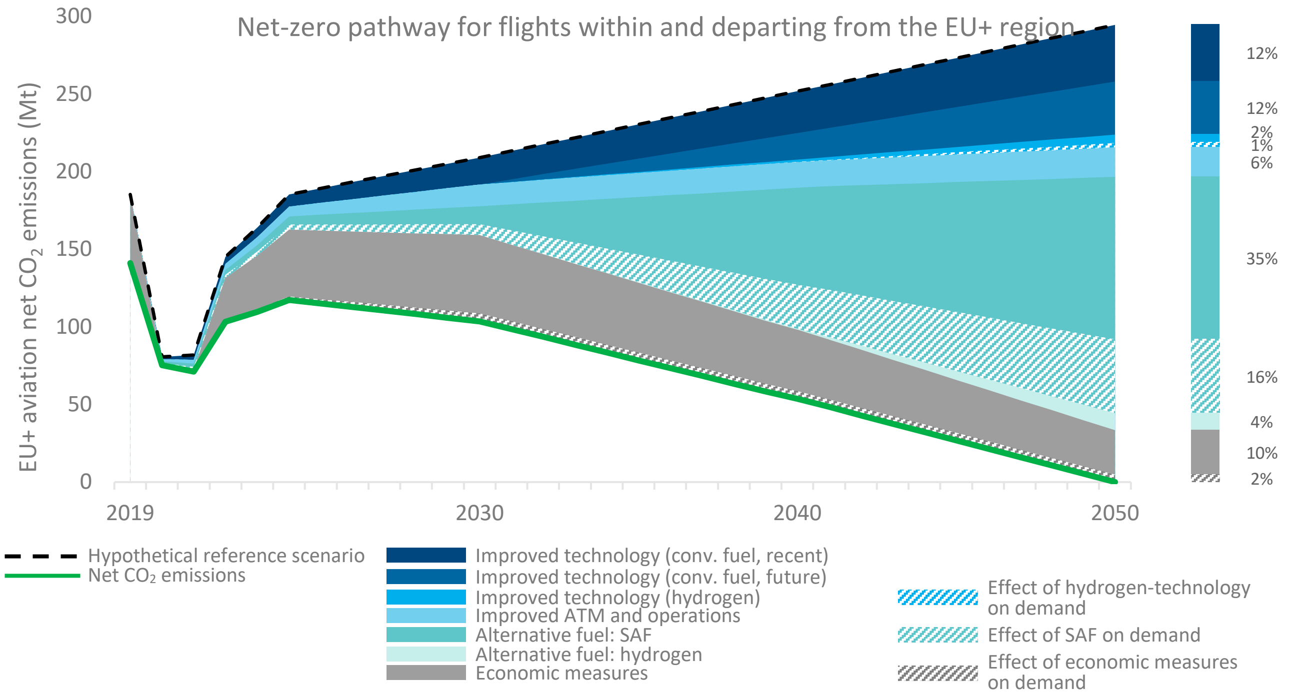


Figure 4: Overall impacts on net CO₂ emissions (TtW) of flights within and departing from the EU+ region, for 2030, 2040 and 2050. Sustainability measures are not assessed year by year, as such pathways and contributions of individual measures may differ from the linear interpolation shown in the graph

The demand impacts affect traffic growth over time. Compared to the reference scenario, the compound annual growth rate in terms of flights movements reduces from 1.4% per year to 0.9% per year [14] in the decarbonisation scenario. Similarly, passenger growth rates reduce from 2.0% per year to 1.4% per year [15]. This is shown in Figure 5 [16].

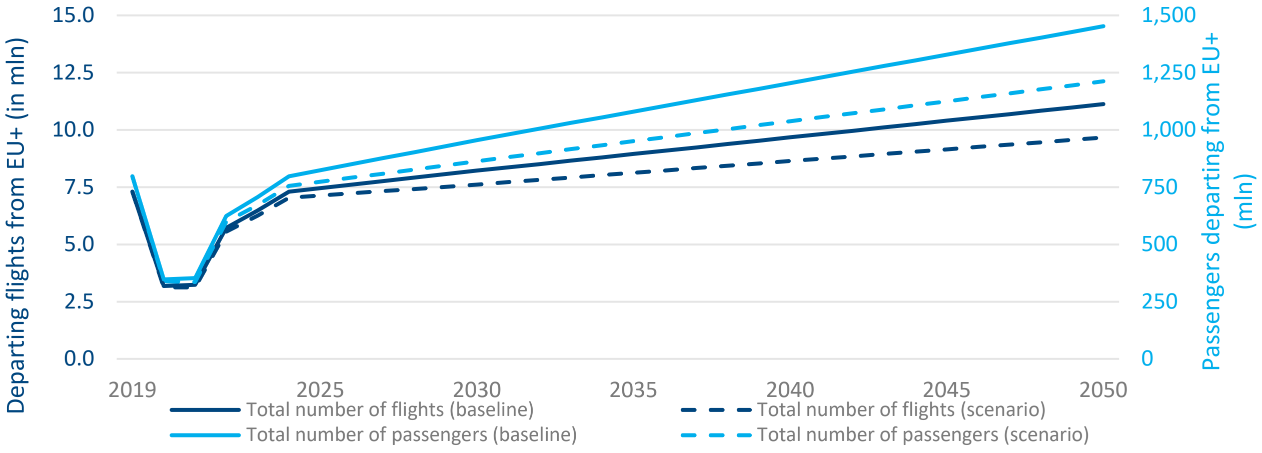


Figure 5: Forecast flights and passenger growth from EU+ airports between 2019 and 2050

Appendix D.2.1 shows how emissions develop over time in the reference scenario and details the relative contributions of passenger and cargo flights.

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[14] From 7.3 million departures in 2019 to 11.1 million in 2050 in the reference scenario, and to 9.7 million in 2050 in the decarbonisation scenario.

[15] From 797 million departing passengers in 2019 to 1.45 billion departing passengers in 2050 in the reference scenario, and to 1.21 billion departing passengers in 2050 in the decarbonisation scenario. Passenger growth is higher than flight growth due to seat densification and increases in load factor.

[16] Scheduled cargo-only operations are excluded from the graph as well as the reported figures, as these account for only a very limited share of the total number of flights and are not specifically addressed in the decarbonisation roadmap.

By 2030, economic measures are by far the biggest driver for net emissions reductions. ETS allowances, 62% bought from other sectors and therefore modelled to have an 100% CO_2 reduction, comprise almost the entirety (49 Mt) of this wedge in this year, with the remaining 1 Mt part of CORSIA. Improvements in conventionally fuelled aircraft and engine technology and improvements in ATM and operations contribute about the same: 8% and 7%, respectively, highlighting the relatively shorter timeframe at which operational improvements can help decarbonise aviation.

In 2040, net emissions are modelled to reduce by 78% compared to the reference scenario, leaving 54 Mt unabated. The contribution by sustainable aviation fuels is largest at 25%, followed by improvements in conventionally fuelled aircraft and engine technology (17%), economic measures (16%) and improvements in ATM and operations (7%), and hydrogen-powered aircraft also start to make their contribution (1%).

Flights within the EU+ region (intra-EU+ flights)

For intra-EU+ flights (detailed in Figure 6), specifically, the role of hydrogen – in terms of technology as well as fuel – is relatively bigger (combined to 15%, excluding a 3% demand impact), due to the fact that hydrogen-powered aircraft are only modelled to operate intra-EU+ routes. The effects of energy efficiency improvements in conventionally fuelled aircraft and engines and the contribution of SAF are comparatively lower, reducing to 22% and 33% by 2050. The contribution by improvements in ATM and operations is slightly bigger compared to the results for all flights in scope, reaching 8% between 2040 and 2050. Moreover, net emissions reductions for intra-EU+ flights by 2050 rely less on economic measures (9%, down from 10% for all flights in scope) and also demand impacts are lower, reducing CO_2 emissions by only 13% in 2050. For intra-EU+ flights, residual emissions amount to 10 Mt which is 13% of CO_2 emissions in 2019 (77 Mt).

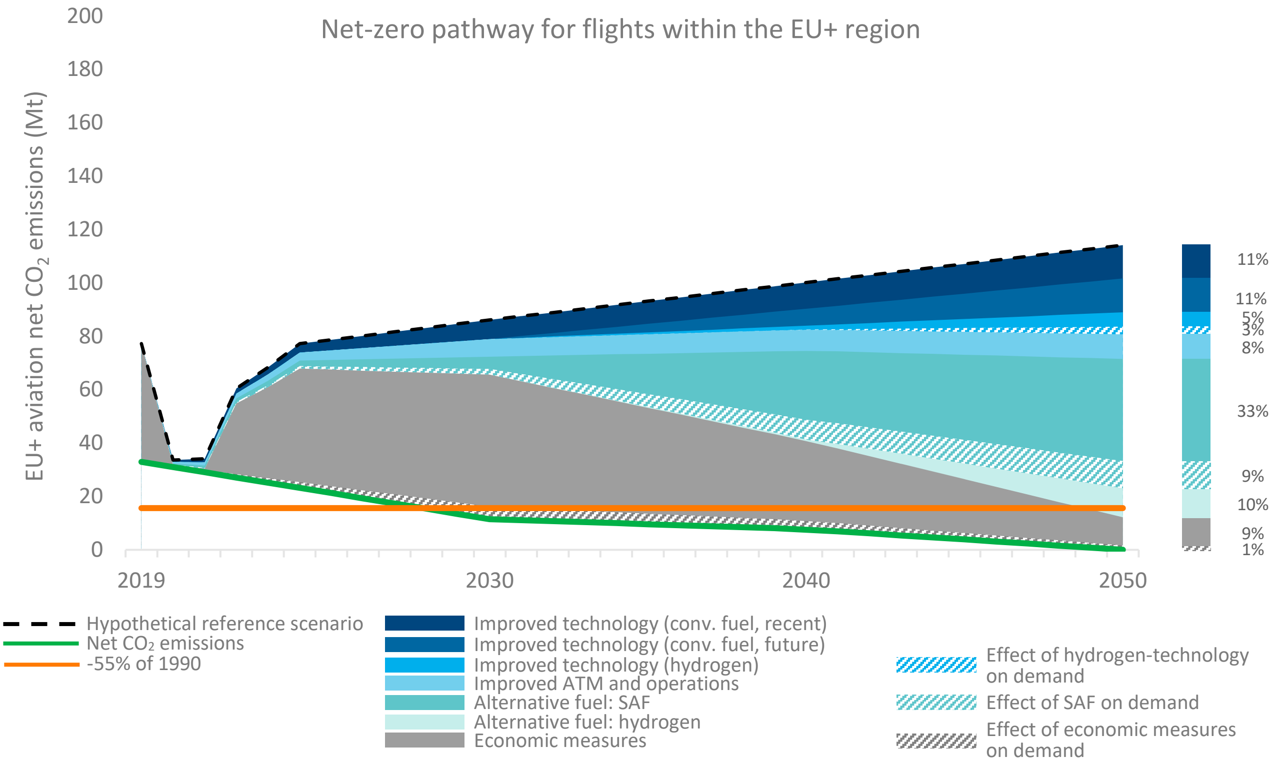

Figure 6: Overall impacts on net CO_2 emissions (TtW) of flights within the EU+ region, for 2030, 2040 and 2050. Sustainability measures are not assessed year by year, as such pathways and contributions of individual measures may differ from the linear interpolation shown in the graph

Especially noteworthy for this subset of flights and emissions is that net CO_2 emissions, so including carbon reductions realised through the EU ETS, reach a value 55% below 1990 emissions by 2028 and reduce to 62% below 1990 levels by 2030. Excluding the effects of EU ETS, net in-sector CO_2 emissions only drop to 55% below the emissions level of 1990 just before 2050.

Flights departing the EU+ region (extra-EU+ flights)

The results for emissions related to intercontinental departures from EU+ airports show a rather opposite picture in Figure 7. By choice, hydrogen plays no role. Rather, improvements in conventionally fuelled aircraft and engine technology and the use of SAF have a much greater impact, accounting for almost two-thirds of total decarbonisation (25% and 37% respectively, excluding demand impacts). Improvements in ATM and operations contribute 5% to the reduction of net CO_2 emissions in 2050, whereas the impact of economic measures (CORSIA, in this case) is unchanged, at 10%. The cumulative impact of CORSIA is however low, and much lower than the total cumulative effect of all economic measures considered. Demand impacts, too, are more dominant for flights departing the EU+ region and reduce net CO_2 emissions by 2050 by 23%, primarily caused by the demand impact of the price premium of SAF compared to conventional aviation fuel.

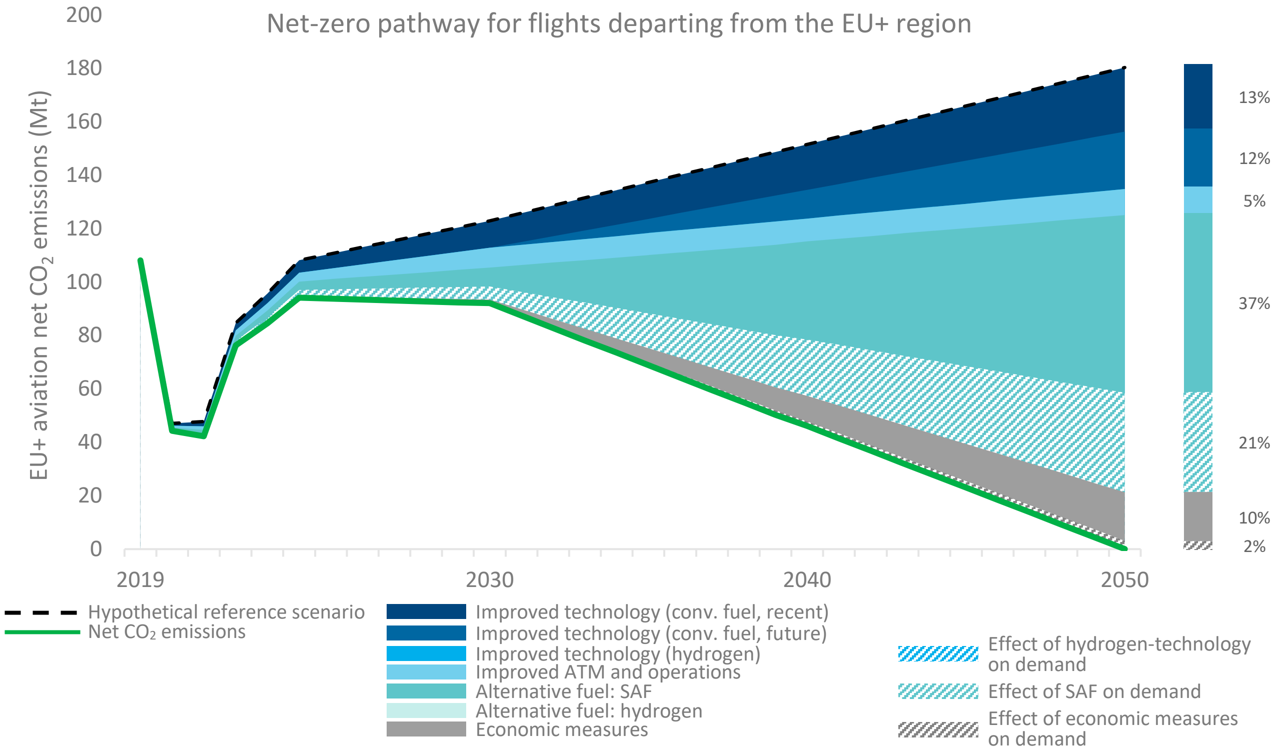

Figure 7: Overall impacts on net CO_2 emissions (TtW) of intercontinental flights departing the EU+ region, for 2030, 2040 and 2050. Sustainability measures are not assessed year by year, as such pathways and contributions of individual measures may differ from the linear interpolation shown in the graph

Well-to-Tank (WtT) emissions related to fuel production are not included in the scope of this research (Section 2.2). Additional actions to the measures detailed in this report are required to reduce these upstream emissions to (net) zero as well.

Detailed results for all three horizon years – 2030, 2040 and 2050 – and for all segments – all flights, intra-EU+ flights and intercontinental departures – are included in Appendix D.2.2, alongside a quantitative overview of the contributions per pillar per horizon year.

2.6.2 Cumulative emissions and comparison to carbon budgets

IPCC global emissions pathways limiting global warming to 1.5°C require net zero CO_2 emissions to be achieved by 2050 (IPCC, 2018), to which the DESTINATION 2050 alliance has also committed (DESTINATION 2050, 2021). This alone, however, is not sufficient, as warming is fundamentally caused by changes in the concentration of greenhouse gases in the atmosphere. As CO_2 molecules remain in the atmosphere for hundreds of years, it is the cumulative amount of CO_2 emission and removal over time that determine the change in CO_2 concentrations in the atmosphere and thus the temperature response. Research has shown that for CO_2 emissions, the climate temperature response is approximately linear (Allen, et al., 2009; Collins, et al., 2013; Friedlingstein, et al., 2014; Gillet, Arora, Matthews, & Allen, 2013; MacDougall, 2015; Matthews, Gillet, & Zickfeld, 2009; Knutti & Rogelj, 2015; Meinshausen, et al., 2009).

Table 11 shows the cumulative emissions studied in the DESTINATION 2050 pathway, both for the entire period considered in the roadmap (2019 up to and including 2050) and for the period between 2020 and 2050. The figures for net in-sector emissions include emissions reductions by improvements in aircraft and engine technology, improvements in ATM and operations and the use of alternative fuels, but exclude contributions by out-of-sector measures. All these figures include the reduction in aviation activity and associated emissions due to COVID-19. *A comparison of the reference scenario with the DESTINATION 2050 pathway suggests that cumulative emissions over both periods can be reduced by at least 50%, if the sustainability measures in this report are realised in time.*

Table 11: Cumulative emissions studied in DESTINATION 2050

	2019 – 2050	2020 – 2050
Reference scenario	7.12 Gt	6.93 Gt
DESTINATION 2050 pathway, net in-sector emissions	3.49 Gt	3.30 Gt

Comparison to carbon budgets

Enabled by the relationship between CO_2 emissions and temperature rise, the IPCC has derived the "remaining amount of CO_2 emissions that can still be emitted while keeping the global average temperature increase due to human activities to below a specific temperature limit" (Rogelj, Forster, Kriegler, Smith, & Séférian, 2019, p. 336). These are the global carbon budgets [17]. In 2022, the IPCC published carbon budgets for the period between 2020 and 2050 for various levels of warming (1.5°C, 1.7°C and 2°C) and various likelihoods of not exceeding these warming levels (33%, 50%, 66% and 83%) (IPCC, 2021). In 2023, these budgets were refined using the updated information in the Working Group 3 contribution to the Sixth Assessment Report (AR6; (IPCC, 2022b; Forster P. M., et al., 2023; Lamboll, et al., 2023)) [18]. These results show that in order to limit global warming to 1.5°C with a likelihood of 50%, global CO_2 emissions between 2020 and 2050 should be limited to 400 Gt. A budget of 600 Gt is available in case global warming is to be limited to 1.7°C with a 66% likelihood.

These are global budgets, that span all sectors of the economy, and all parts of society. Allocating parts of these budgets to individual countries, industries or persons, is a fundamental political and societal choice, for which numerous principles exist – such as grandfathering, equality and cost-optimality (van den Berg, et al., 2020). DESTINATION 2050, as well as the IEA Net Zero Scenario, seem to fit best with that latter approach. Based on the 2023 update of that IEA Net Zero Scenario, which presents a global emissions pathway towards net zero CO_2 emissions in 2050 conceptually in line with DESTINATION 2050 and also explicates the share of emissions from aviation, a share of 4.0% of the global carbon budget is apportioned to global aviation for the purposes of the present work[19]. Specifically for emissions from flights departing from the EU+ region, 0.61% of the global carbon budget would be available[19]. That

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[17] It is stressed that CO_2 budgets are not a legally or scientifically 'binding' CO_2 'allowance', but should rather be seen and used as a concept that allows to check whether (projected) cumulative emissions are (reasonably, i.e., respecting uncertainties and probabilities) in line with temperature targets.

[18] The update includes the largest changes due to emulator update (non-CO_2) and refined historic warming values.

[19] Appendix 4.3.1 provides more detail on this calculation.

figure, in combination with the two aforementioned global carbon budgets, yields EU+ aviation carbon budgets of 2.46 Gt (50% likelihood of 1.5°C) and 3.68 Gt (66% likelihood of 1.7°C [20]) for the period between 2020 and 2050. Given cumulative net in-sector emissions of the DESTINATION 2050 roadmap accrue to 3.30 Gt for this same period[21,22], the pathway can be considered compatible to limiting warming to 1.7°C (66% likelihood) [23], but is not compatible with limiting warming to 1.5°C (50% likelihood)[24] – the maximum temperature rise strived for by the Paris Agreement. Realising compatibility with this 1.5°C scenario would require a reduction of cumulative net in-sector emissions of approximately 25% between 2020 and 2050. Figure 8 shows how annual (reference or net in-sector) emissions sum to cumulative (reference or net in-sector) emissions and compare to 1.5°C and 1.7°C budgets.

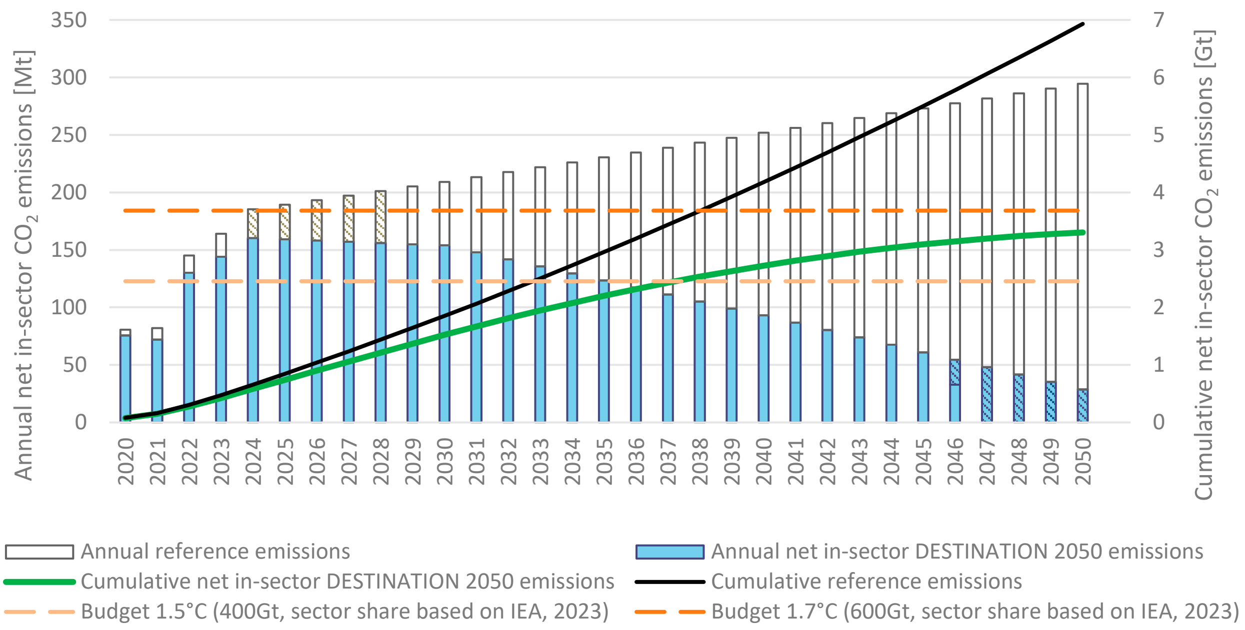

Figure 8: Annual (left axis, in Mt) and cumulative emissions (right axis, in gigatonnes) of the reference scenario (open) and DESTINATION 2050 scenario (filled) compared to the remaining carbon budgets for EU+ aviation with maximum temperature increases of 1.5˚C (400 Gt) and 1.7˚C (600 Gt), both assuming a 4.0% budget share for global aviation and a 0.61% share for EU+ aviation, based on the 2023 of the IEA Net Zero Roadmap. Hatched area shows equal summed emissions between 2024-2028 and 2046-2050

Discussion and implications

The above analysis comes with uncertainties, directly associated to the societal and political complexities of apportioning parts of the global carbon budget to an individual sector. For example, the overall global carbon budget might be smaller than currently estimated[25], society might not ‘allow’ global and EU+ aviation to take the share currently assumed[26], and anticipated cumulative net in-sector emissions in the DESTINATION 2050 pathway might be

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[20] The updated IEA Net Zero Scenario is specifically derived to keep the 1.5°C goal in reach. In this analysis the share of the budget available to aviation is assumed to also hold for pathways striving for a maximum temperature increase of 1.7°C. This is further discussed in Appendix 4.3.1.

[21] The comparison between IEA derived carbon budgets and the DESTINATION 2050 pathway only considers net in-sector cumulative CO_2 emissions, as including out-of-sector CO_2 reductions would risk introducing double-counting of emissions reductions: once by the sector paying for these CO_2 reductions (aviation, in this case), and once more for the sector in which the CO_2 reductions are actually taking place. Based on Asayama et al. (2021, pp. 9, 14), seeing carbon removals as conceptually analogous to “raising additional revenues”, it is considered more transparent to account for any such CO_2 reductions as increases to the carbon budget of the sector realising these removals.

[22] It is noted that the net in-sector cumulative CO_2 emissions calculated for the DESTINATION 2050 do not consider unscheduled flights (as there are out of scope of the roadmap, per Section 2.2), whereas the emissions associated to these flights are to be funded from the budgets computed.

[23] The approximately 10% margin between cumulative net in-sector CO_2 emissions (3.30 Gt) and the 1.7°C-budget (3.68 Gt), and the estimate that unscheduled flights contribute less than 10% to total CO_2, this conclusion is likely to hold, irrespective of the limitation discussed in footnote 22.

[24] Rather, this 1.5°C carbon budget would be exhausted by 2037.

[25] This uncertainty is illustrated by the substantial differences between the Working Group I and Working Group III derived carbon budgets (also presented in Appendix 4.3.2): the updated values for historic warming and emulator-update for non-CO_2 climate effects have resulted in reductions of 20% and 14% of the 1.5°C and 1.7°C carbon budgets, respectively.

[26] The analysis presented assumes a 4.0% share of the remaining budget, compared to a 2.4% to 2.7% share for 2019, for scheduled traffic (Graver, Rutherford, & Zheng, 2020) and all aviation (based on IEA, 2023a; Crippa, et al., 2013), respectively. If carbon budgets would be more formally adopted and included into regional or national polices (as, for example, in the United Kingdom; Government of the United Kingdom, 2016) and budgets get close to exhaustion, government may prioritise the remaining budget to parts of the economy considered more essential than aviation, or on which a larger share of the population (more strongly) feels to depend (such as housing, energy and food production).

larger if decarbonisation actions are delayed[27]. Echoing the introduction of this report, these uncertainties should not lead to inaction. Rather, the fact that current annual net in-sector emission levels are notably higher than those projected for the future (also visualised in Figure 8)– meaning that the remaining budget is consumed more quickly in the next few years than in the last few years of this roadmap period –, only further stresses the need for swift action. Indeed, a delay of 5 years now (returning to the reference scenario between 2024 and 2028, hatched in Figure 8) would increase CO_2 emissions by 165 Mt (an emission amount larger than the total budget required (147 Mt) for the years between 2047 and 2050) and require achieving net zero CO_2 in 2046 to still keep within the 1.7°C budget. Moreover, delaying action to after 2030 (returning to the reference scenario between 2024 and 2030) would lead to an increase in emissions of 281 Mt, whereas, for example, an increase to 100% SAF between 2040 and 2050 would only reduce 221 Mt (not taking into account any further demand effects).

2.6.3 Energy use

In the reference scenario the energy demand of the aviation sector steadily increases from 58.7 Mt aviation fuel in 2019 to 93.2 Mt aviation fuel in 2050. Due to operational improvements and the introduction of new aircraft, i.e., the sustainability scenario, this energy demand is reduced to 45.7 Mt aviation fuel in 2050. Additionally, towards 2050, the energy demand is fulfilled by an increasing amount of SAF and hydrogen, going from 3.6 Mt of SAF to 36.6 Mt of SAF and hydrogen in 2050, see Table 12.

Table 12: Energy demand and fulfilment for 2030 and 2050 as modelled in DESTINATION 2050

Fuel demand	Unit	2019	2030	2050
Reference scenario	Mt	58.7	66.2	93.2
Sustainability scenario	Mt	58.7	52.4	45.7
SAF (non-synthetic)	Mt		3.1	20.6
HEFA	Mt		2.7	4.6
FT	Mt		0.2	8.0
AtJ	Mt		0.2	8.0
SAF (synthetic)	Mt		0.6	16.0
PtL	Mt		0.6	12.5
H_2	Mt (SAF_{eq})		0	3.5
Conventional aviation fuel	Mt		48.7	9.1
Share sustainable fuels	%		7%	80%

The production of these alternative fuels, especially Power-to-Liquids-based SAF, requires energy. For the non-synthetic fuels (most of) this energy comes from the used feedstocks ((advanced) biomass). Some of these conversion processes also require small amounts of hydrogen, which will demand some renewable electricity, like HEFA and AtJ-based SAF production. FT-synthesis does not require external hydrogen, and thus no additional electricity. The production of renewable hydrogen requires renewable electricity, and the subsequent production of PtL-based SAF requires additional electricity. Finally, to remove emissions of the combustion of conventional aviation fuel (CAF), carbon removal technologies also require energy. The total electricity demand for the synthesis of various SAFs and hydrogen in 2050, as well as the electricity demand for carbon removal technologies, is given in Table 13. If renewable energy is not sufficiently available, other low-carbon energy sources must be explored to fulfil the energy demand.

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[27] Of course, quicker decarbonisation would reduce cumulative in-sector estimates below the current estimates, resulting in slower consumption of the remaining budget.

Table 13: Electricity demand in 2050 for the production of SAF, H_2 and carbon removal technologies to reduce emissions of conventional aviation fuel (CAF) in TWh.
** Includes the electricity demand for the production of hydrogen required in the process.*
*** Electricity requirement shown is for carbon removal technologies to reduce emissions related to combustion of CAF, not CAF production*

	Fuel	Unit	Electricity requirement	Unit	Total electricity demand	Unit
SAF (non-synthetic)						
HEFA *	4.6	Mt SAF	6.5	MWh/t SAF	**30**	**TWh**
FT	8.0	Mt SAF	0	MWh/t SAF	**0**	**TWh**
AtJ *	8.0	Mt SAF	2.3	MWh/t SAF	**18**	**TWh**
SAF (synthetic)						
H_2	1.27	Mt H_2	76.3	MWh/t H_2	**97**	**TWh**
PtL *	12.5	Mt SAF	42.9	MWh/t SAF	**538**	**TWh**
CAF **	9.1	Mt CAF	2.8	MWh/t CO_2	**80**	**TWh**
Total	45.7	Mt CAF equivalent			**762**	**TWh**

2.6.4 Expenditures impact

Realising the decarbonisation pathway outlined in this report comes with changes in expenditures – spanning both investments as well as (recurring) costs. Table 14 summarises the cumulative expenditures per pillar for the period 2019 up to and including 2050, and lists the (remaining) cumulative costs for conventional fuel over this period. For each of the pillars, both total expenditures and so-called premium expenditures are shown. Premium expenditures are the additional expenditures directly related to emissions reduction, such as the price premium of SAF and the additional investment required for technology research and development. Premium expenditures total €1,300 bn over this 31-year timeframe; total expenditures add up to €3,135 bn, or €2,400 bn excluding remaining conventional fuel. In case net zero would not be achieved through in-sector investments (requiring the aforementioned premium investments) but through out-of-sector measures, expenditures would total about €2,945 bn.

Figure 9 shows how the expenditures vary over time, with business-as-usual expenditures shown aggregated and avoided costs (reduced fuel consumption due to efficiency improvements, avoided carbon costs due to in-sector decarbonisation). The additional expenditures required are largely determined by the costs related to alternative fuels. Given the relatively gradual increase of their uptake, the additional expenditures also grow relatively gradually with time – varying from some €7 bn annually in 2025 to about €70 bn annually in 2050. By 2048, however, the annual additional expenditures are fully offset by avoided expenditures, meaning that from 2048 onwards, the sustainability pathway is the less expensive option. As one first needs to invest before being able to reap the benefits, cumulative ‘break-even’ – over the entire period – is however not reached before 2050. This is also suggested by the finding that expenditures of a pathway almost fully reliant on out-of-sector measures are somewhat lower (€2,945 bn vs. €3,135 bn) than the cost associated to the DESTINATION 2050 pathway.

Table 14: Expenditures impact of the decarbonisation pathway, showing both total and premium expenditures

Pillar	Cost component	Expenditures (€ bn)		
		DESTINATION 2050 Total	DESTINATION 2050 Premium	Out-of-sector[28]
Improvements in aircraft and engine technology	Future aircraft research and development (R&I + R&D)	16 + 105 = 121	16 + 105 = 121	
	Fleet renewal	890	145	745
	Infrastructure for future aircraft	3.8	3.8	
Improvements in ATM and operations	Airline operations	(cost-neutral)	(cost-neutral)	
	Airspace and air traffic management (EU + non-EU)	24 + 6.3 = 30.3	12 + 3.2 = 15.2	15.1
	Ground operations at airports	7.2	7.2	
Fuels and energy	Sustainable aviation fuels	1,090		
	Price premium w.r.t. conventional kerosene		765	
	Hydrogen	39		
	Price premium w.r.t. conventional kerosene		21	
	Renewable electricity	< 1		
	Price premium w.r.t. conventional kerosene		< 1	
	Conventional kerosene	735		1,455
Economic measures		220	220	730
Total		**3,135**	**1,300**	**2,945**

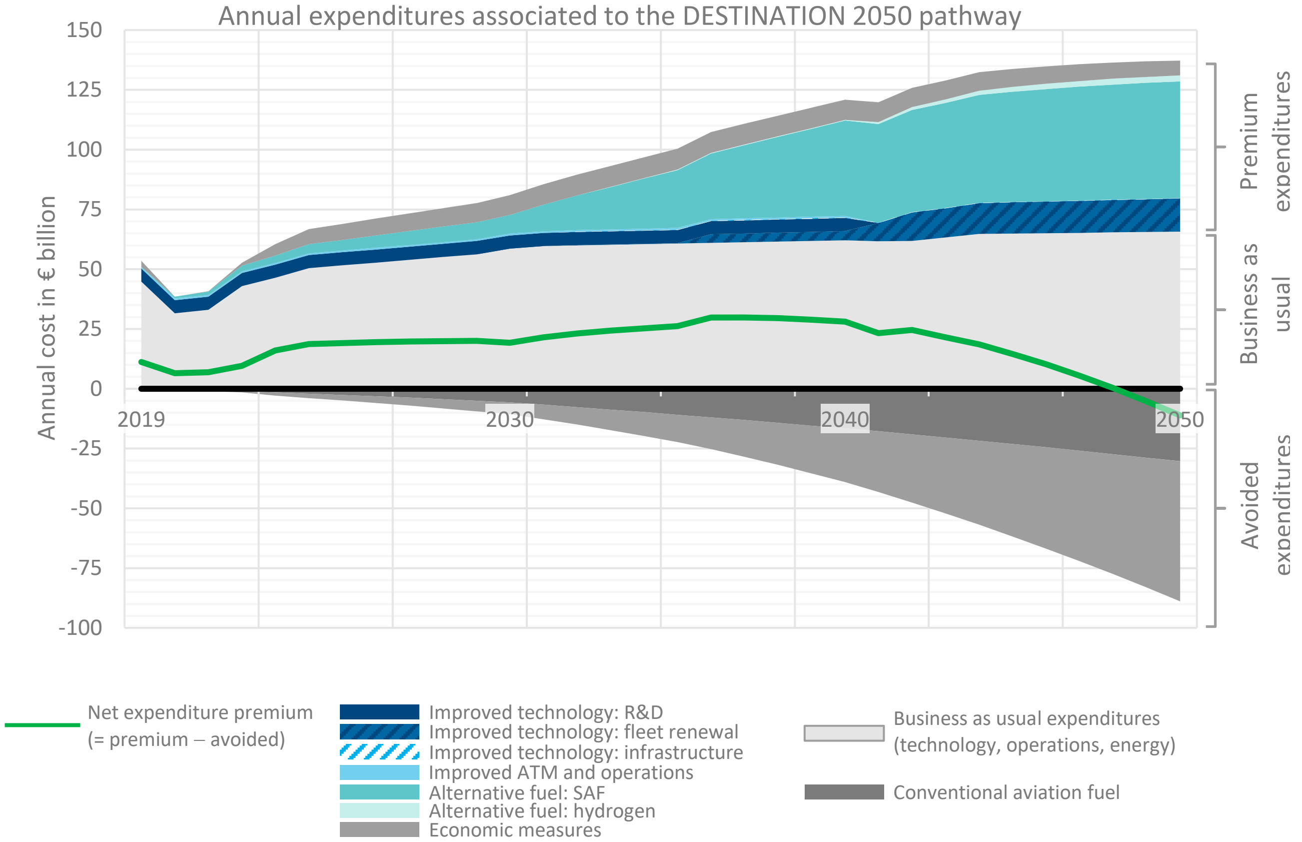

Figure 9: Annual expenditures associated to the DESTINATION 2050 net zero carbon emissions pathway over time, split between 'business as usual' expenditures, 'premium' expenditures and avoided expenditures. Net expenditure premium (green line) shows the differences between the expenditures occurring in the DESTINATION 2050 pathway minus avoided expenditures for conventional aviation fuel and carbon pricing

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[28] As in Adler et al. (2023, Sec. 4.2, scenario FR2), this column shows the expenditures if the transition to net zero CO_2 emission was to fully rely on out of sector emissions reduction, realised through carbon pricing. Fleet renewal costs are still included, as it seems unlikely that all current in-service aircraft will be able to safely operate up to 2050. As airline operators can only purchase recent and imminent aircraft, this still yields some reduction in fuel consumption and CO_2 emissions, which are reflected in the expenditures for conventional kerosene and economic measures shown. In case these fuel efficiency improvements would not be taken into account, these costs would rise to €1,610 and €790 bn, respectively, for an out of sector total of €3,160 bn.

2.6.5 Main differences compared to the initial roadmap

As further detailed in the individual chapters, there are a number of differences between this second edition and the first edition of the DESTINATION 2050 roadmap report, published in February 2021 (van der Sman, Peerlings, Kos, Lieshout, & Boonekamp, 2021). As a result of the changes in scope, approach and modelling inputs, described earlier in this chapter, the main differences in terms of results can be summarised and interpreted as follows:

- Net emissions in 2030 are now estimated to reduce to 103 Mt of CO_2, down from 113 Mt of CO_2 in the first edition of the roadmap. Related to this, net emissions for intra-EU+ flights reach -55% compared to 1990 levels somewhat earlier (2027 vs. 2030).
- The contribution by hydrogen-powered aircraft and the switch to hydrogen as fuel is notably reduced, from 20% in the first edition to 6% in this second edition (both for 2050, both excluding demand impacts). This is due to the lower anticipated market share of hydrogen-powered aircraft (50% vs. 100% in each applicable segment) and the later entry into service of the hydrogen-powered single-aisle (2040 vs. 2035). If market introduction would be pushed back even further, only a marginal contribution by 2050 remains, such that the return on current R&D investments being made would only come in the second half of this century.
- The contribution by sustainable aviation fuels is somewhat increased from 34% to 36%. Due to the lower contribution by hydrogen-powered aircraft, which also reduces the total contribution by improvements in aircraft and engine technology (24%, down from 37%), SAF now makes the largest contribution by 2050, highlighting the dependency of the aviation sector on energy companies. Although some dependencies are to be expected in the globalised economy we live in, this growing dependency combined with the notion that aviation's licence to operate hinges on its ability to decarbonise, this is identified as a substantial risk. Next to the higher blending ratios, SAF has been modelled to reduce tank-to-wake emissions by 100%, consistent with relevant EU regulations.
- By 2050, economic measures are now required for both intra-EU+ and extra-EU+ flights to reach net zero. In the first edition, the contribution of economic measures on intra-EU+ flights was only 1%, whereas this share has now increased to 9%. A key explanation for this change is that SAF used to be prioritised to intra-EU+ flights in the first edition, whereas it is now modelled to be used on intra-EU+ and extra-EU+ flights in similar amounts (consistent with ReFuelEU Aviation).

In terms of expenditures, previously analysed and assessed in The Price of Net Zero (Adler, et al., 2023, pp. 35-37), the following differences are noted. Jointly, these differences show the 'business case' of sustainability is more difficult than previously expected. The Price of Net Zero (Adler, et al., 2023), for example, found the DESTINATION 2050 pathway to be less expensive compared to a scenario mostly reliant on out-of-sector measures, whereas this report finds the opposite to be true. Despite limitations of the current research, this implies that economic conditions are not (yet) sufficiently driving the sustainability transition.

- The total sum of expenditures related to DESTINATION 2050 has notably increased, from approximately €2,620 bn to €3,135 bn – a difference of €515 bn or almost 20%. Disregarding the costs for conventional fuels, this version of the DESTINATION 2050 roadmap report finds a total expenditure of €2,400 bn, up €510 bn from the almost €1,890 bn (+27%) found in The Price of Net Zero. Most of the cost increase (€480 bn) is related to premium expenditures, which rise from €820 bn to €1,300 bn (+57%).
- The primary cause for the increased premium and total expenditures are the updated – and increased – cost estimates for sustainable aviation fuels. Previously estimated to cause a cost premium with respect to conventional kerosene of €440 bn, this figure has grown to €765 bn to a total cost of €1,090 bn (up from about €690 bn), and thereby explaining more than half of the €510 bn total cost increase.

- Across other pillars and measures, smaller increases are observed. Technology R&D costs increase due to a larger variety of future aircraft, fleet renewal costs slightly increase due to a larger amount of aircraft, and investments related to infrastructure for alternatively fuelled aircraft reduce due to a lower share of hydrogen-powered types in the fleet. Consistent with that, the costs of hydrogen (as energy carrier) also reduce. Last, ATM and operational expenditures slightly reduce, whereas costs for economic measures increase (from just over €152 bn to €220 bn).

As cumulative emissions and energy use have not been assessed in the first edition of the DESTINATION 2050 roadmap, there are no previously results to compare current findings to.

2.6.6 Progress report

A lot has happened since the publication of the first DESTINATION 2050 roadmap report in 2021, as Section 2.3 already noted. However, and especially due to the heavy impact of COVID-19 on the industry, it is too early to conclude with certainty whether the decarbonisation of European aviation is on track, compared to the pathway outlined in the first DESTINATION 2050 roadmap report.

Figure 10 compares indexed CO_2 emissions as forecast in this DESTINATION 2050 roadmap report to CO_2 emissions as modelled in the 2025 European Aviation Environmental Report (EASA; EEA; EUROCONTROL, 2025) and the EUROCONTROL Aviation Intelligence Portal (EUROCONTROL, 2024b) over the past few years[29]. Emission quantities are normalised to 2019-levels, to enable the comparison of these three reports, which all (slightly) vary in scope: the European Aviation Environmental Report excludes flights departing from the UK, and only the DESTINATION 2050 figures pertain to scheduled traffic. As UK emissions can be expected to have developed in line with those in the rest of Europe (EU27 + EFTA) and as unscheduled operations are only a small share of total traffic, these differences are deemed unlikely to invalidate the comparison.

The results show that between 2020 and 2022, DESTINATION 2050 forecast lower CO_2 emissions than the other two sources. This might be caused by a different-than-modelled recovery from COVID-19. However, a deviation from the decarbonisation pathway outlined in DESTINATION 2050 could also explain the difference. It is promising to see that for 2023, the DESTINATION 2050 forecast figures align well with modelling from the European Aviation Environmental Report – although they deviate from EUROCONTROL modelling results, indicating a larger amount of CO_2 emissions.

In summary, the quantitative analysis supports the conclusion that it currently is too early to deduce with certainty whether the decarbonisation of European aviation is on track. As such, this report includes a qualitative progress assessment.

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[29] Since the present report uses 2019 as a baseline year, CO_2 emissions are estimated from 2019 onwards, as noted in Section 2.4.1.

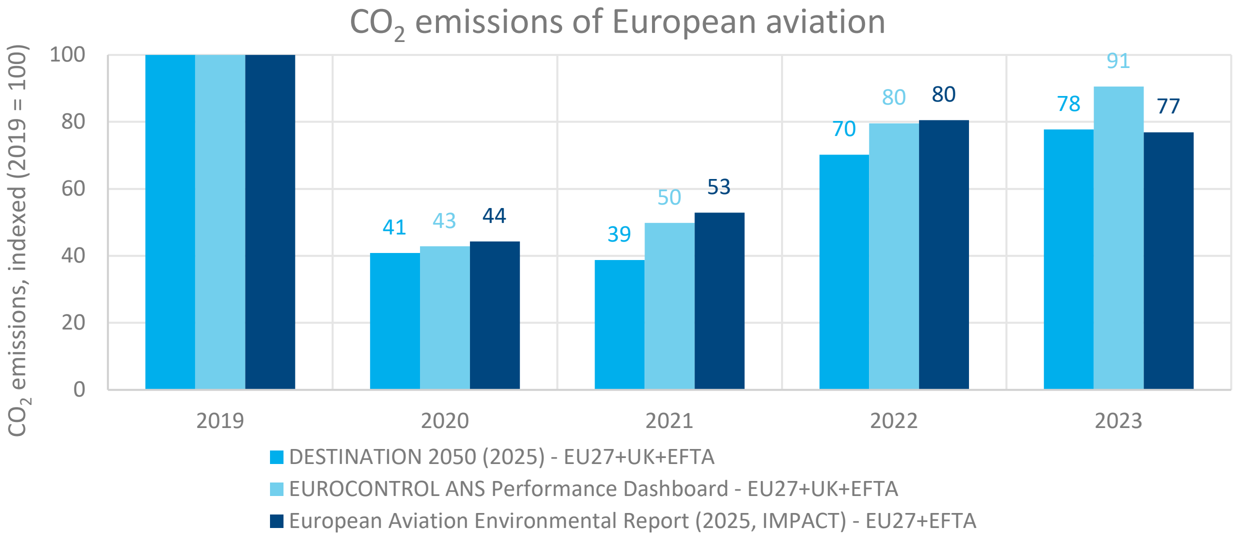


Figure 10: Comparison of indexed CO_2 emissions as forecast in this DESTINATION 2050 roadmap report (2025) and as modelled in the 2025 European Aviation Environmental Report (EASA; EEA; EUROCONTROL, 2025; based on the IMPACT model, EUROCONTROL, n.d.) and the EUROCONTROL Aviation Intelligence Portal (EUROCONTROL, 2024b).

Figure 11 shows a qualitative progress assessment. Distinguishing between progress in preparatory work (research and development, policy implementation, …) and the delivery of emissions reductions, and between various groups of measures, it paints a mixed picture. Thanks especially to progress on the development of relevant European policies and regulations, preparations are mostly progressing on track. To deliver results, more action, policy and funding (both in Europe as well as at global level) is needed across all groups of sustainability measures. Implementing the recommended actions ensures the updated DESTINATION 2050 pathway can be followed as outlined in the current roadmap.

		Preparations (R&D, policies, …)	**Delivery**	**Recommended actions for industry and government**
Improvements in aircraft and engine technology	Recent and imminent aircraft	*Not applicable*	🟧 Delays in entry-into-service of new types and supply-chain challenges	▪ Ensure that aircraft not yet introduced enter into service as planned
			🟩 Fleet renewal maintained through COVID	▪ Maintain fleet renewal by airlines, facilitated by aircraft production and robust supply chains
	Future aircraft	🟩 Clean Aviation and Clean Hydrogen research programmes started, focused on Regional and Single-Aisle segments.	*Too early to tell, as projects are still to deliver first results.*	▪ Ensure focused and collaborative R&D to ensure technology gains and timely deployment on new products ▪ Realise at-scale industrialisation and delivery of new technologies
		🟨 R&I funding gap for twin-aisle.		▪ Mitigate any possible funding gaps to prevent delays in R&D
Improvements in ATM and aircraft operations	Airline operations	*Not applicable*	*Ongoing*	▪ Further push advanced flight planning, weight reduction and aircraft condition and maintenance
		🟩 ReFuelEU Aviation limits tankering		
	Airspace and air traffic management (ATM)	🟩 SES2+ regulation SESAR3 JU	🟧 CP1 improvements alone not sufficient to reach overall European ATM Master Plan efficiency targets until 2035/2050	▪ Timely implementation of ATM Master Plan objectives ▪ Faster implement SESAR solutions and enabling technologies
	Ground operations at airports	🟩 AFIR, TEN-T regulations	🟨 E-taxi implementation lagging, uncertainty about usage FEGP/PCA	▪ Monitor FEGP/PCA usage
Alternative fuels and sustainable energy		🟩 ReFuelEU Aviation implemented; Zero-rating of SAF in EU ETS; SAF Allowances; CAAF/3; ICAO LTAG	🟩 Ramp-up in production facilities (compared to 2021)	▪ Support scale-up of production through supply chain development, increase feedstock availability and significant renewable energy deployment
			🟧 Investment decisions postponed; facility development pushed back	▪ Develop financial support system for investments in production facilities
			🟩 Demonstrate the technical feasibility of increasing the blending limit to 100% for various types of SAF	
Economic measures	EU ETS	🟨 No clarity on eligibility and availability of Direct Air Carbon Capture	🟩 Stronger target, reflected by higher prices	▪ Maintain and monitor integrity of system ▪ Alignment of UK ETS in price and cumulative emission target towards net zero ▪ Set policy for integration of high-quality carbon removals
	CORSIA/MBM	🟧 CORSIA currently not aligned with net zero 2050 and Paris agreement	🟧 ▪ Carbon offset effectiveness insufficient ▪ Low prices do not stimulate in-sector decarbonisation	▪ Increase ambition level to net zero ▪ Increase quality / effectiveness of offsets ▪ Incorporate the use of carbon removals

Figure 11: Qualitative progress assessment and recommended actions. Colours indicate urgency of actions:
🟩 on track; no action needed / 🟨 on track, action needed / 🟧 not on track, imminent action needed

2.7 Conclusions and Implications

In 2021, the first DESTINATION 2050 roadmap report “A Route To Net Zero European Aviation” was published. Based on the latest insights on technologies, markets and policies, this report presents an updated version of the DESTINATION 2050 pathway. The report is based on a bottom-up analysis of measures that increase energy efficiency and reduce net CO_2 emissions. It includes an impact assessment of emission reduction measures, the associated requirements and implications, and a cost assessment.

Progress report and short-term actions

Compared to the first edition, progress has been made in Europe in terms of research and development (e.g. Clean Aviation, national research programmes and SESAR3), policy implementation (e.g. the Fit for 55 package) and implementation of CO_2 reduction measures (e.g. fleet renewal, initial uptake of SAF and deployment of ATM solutions). However, the impact of COVID-19 makes it difficult to compare projected and actual CO_2 emissions quantitatively and assess if European aviation is on track to meet the DESTINATION 2050 pathway. Nevertheless, it is clear that without short-term action from both industry and policymakers on all groups of sustainability measures, this ambitious decarbonisation pathway will become increasingly more difficult, or even impossible to follow. To deliver emission reductions, short-term actions are required:

Pillars	Short-term actions for meeting the roadmap pathway
Aircraft and engine technology	– Ensure that aircraft not yet introduced enter into service as planned – Mitigate any possible funding gaps to prevent delays in R&D
ATM and operations	– Timely implementation of ATM Master Plan objectives – Implement SESAR solutions and enabling technologies more quickly
Alternative fuels	– Support for supply chain development, increased feedstock availability and renewable energy deployment to increase SAF uptake – Develop a financial support system for investments in production facilities
Economic measures	– Establish a net zero target for all market-based measures – Increase quality/effectiveness of carbon offsets within CORSIA – Set policy for high-quality carbon removals within the EU Emissions Trading System (EU ETS)

The decarbonisation pathway

The outcome of this updated DESTINATION 2050 roadmap report is that it is still possible to reach net zero in 2050, if the short-term actions are taken and the measures are implemented on time. CO_2 emission reductions can be achieved through four groups of sustainability measures (improvements in aircraft and engine technology, improvements in ATM and operations, alternative fuels and economic measures). Each of these pillars contributes at various levels of effectiveness over time. The sustainability measures and their impact on air transport demand result in the following net CO_2 emission reductions in the year 2050 compared to a hypothetical no-action reference scenario:

- 26% (76 $MtCO_2$) through improvements in aircraft and engine technology (12% conventionally-fuelled aircraft, recent and imminent, 12% conventionally-fuelled aircraft, future and 2% hydrogen-powered aircraft);
- 6% (19 $MtCO_2$) through improvements in air traffic management (ATM) and aircraft operations;
- 39% (116 $MtCO_2$) through using alternative fuels (35% SAF and 4% hydrogen);
- 10% (29 $MtCO_2$) through economic measures (carbon removal projects only).
- 19% (55 $MtCO_2$) through the impact of sustainability measures on air transport demand (1% technology, 16% SAF and 2% economic measures).

Improved technology, ATM and aircraft operations, and increased SAF uptake will progressively drive net emissions reductions. Improvements in fuel efficiency enabled by technology and ATM measures are therefore important not only for their direct CO_2 reductions but also in the longer term for reducing the amount of SAF required. By 2030, economic measures are by far the biggest driver of net emission reductions (24%), followed by the introduction of the latest generation of more efficient conventionally fuelled aircraft (8%) and improvements in ATM and operations (7%). The cost of implementing these sustainability measures is expected to lower the annual passenger growth rate from 2.0% in the reference scenario to 1.4% per year.

Ensure that sustainable fuels make up 80% of the fuel pool by 2050

SAF will make the largest contribution to emission reductions by 2050. As such, the aviation sector depends on the energy sector and the sustainable fuels policy framework to reach its decarbonisation objectives. The ReFuelEU Aviation regulation mandates at least 70% SAF in the fuel pool by 2050. To achieve climate goals and lower the reliance on carbon removal technologies, an additional 10% of SAF should be added to the fuel pool by 2050. This equals a total of 37 Mt of sustainable fuels by 2050. By 2050, the total electricity demand for various SAF types, hydrogen and carbon removal technologies will be 762 TWh. This electricity will mainly be used for producing synthetic fuels and carbon removal technologies.

Sufficient feedstock availability is crucial for upscaling. It needs to be assessed further by considering expanding the scope of feedstocks within the defined sustainability criteria and developing novel SAF production technologies. As SAF will remain more expensive than conventional aviation fuel, policy support is crucial for encouraging uptake, as well as for reducing the price gap in balance with the other sustainability measures outlined in the report.

Ensure that market-based measures are aligned with the net zero goal

The DESTINATION 2050 pathway relies on market-based measures to bridge the gap until other emission reduction pillars such as alternative fuels can have sufficient impact. For flights within the European Economic Area (EEA), the European Union Emission Trading System (EU ETS) provides a net zero mechanism once high-quality carbon removal methods are incorporated. For international flights, this roadmap assumes an agreement on a net zero target for the Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA) and an increase in the quality and effectiveness of the associated carbon credits, aspects that are both still outstanding in the current regulations.

Enhanced global cooperation within the International Civil Aviation Organisation (ICAO) is needed to translate the long-term aspirational goal into a more ambitious CORSIA implementation. For flights leaving the EEA, either carbon credit effectiveness can be improved in the short-term or the EU commission can set carbon offset standards in line with the net zero target. The fallback option, a unilateral expansion of the scope of the EU ETS, only reduces aviation emissions for flights leaving the EEA. Therefore, it would fall short of the global climate goals of the Paris Agreement.

Enhance research and innovation efforts for future aircraft

Aircraft and engine manufacturers, backed and encouraged by policymakers, face two urgent tasks if future aircraft are to deliver targeted CO_2 reductions. On the one hand, they must ensure that sufficient latest-generation aircraft are produced and in good time – which is made more difficult by supply chain problems currently being observed. On the other, the industry must simultaneously develop new aircraft technologies, products and infrastructure to launch future generation aircraft products from 2030 onwards, including electric, hybrid electric or hydrogen-powered types. In parallel, certification authorities such as the European Union Aviation Safety Agency (EASA) must have adequate resources and be ready to test, certify and approve the large number of (often disruptive) new products expected, and to do so in good time. Additionally, authorities must be ready to approve airport infrastructure for alternatively powered aircraft, enabling it to be deployed in time.

Various publicly supported research programmes at the global, European (e.g. Clean Aviation, Clean Hydrogen) and national levels are already contributing to technology development and demonstration, as are the efforts of various manufacturers. It is crucial that these efforts are and remain coordinated and that possible gaps in funding are addressed, and that both public and private funding bodies remain informed about and engaged with aviation-specific challenges. For example, these gaps include research and innovation activities for scaling and transferring Clean Aviation technologies to twin-aisle platforms, and for driving the development and maturation of disruptive technologies at higher technology readiness levels. Public innovation funds to boost financing for the industrial capacity for new entrants are considered helpful.

Whereas reductions in CO_2 emissions in the single-aisle and twin-aisle classes will play the biggest role in absolute terms in decarbonising European aviation, regional segments (seating up to 100 passengers) are key in developing aircraft with alternative propulsion, as such radical innovations will start at smaller scales before moving to larger segments.

Operations to allow emission reductions in the short and medium term

Improvements in Air Traffic Management (ATM) and aircraft operations are ongoing and can be actioned over a relatively short period. The direct improvement potential from decarbonisation measures in aircraft operations and ATM increases from 14 Mt CO_2 by 2030 to 19 Mt CO_2 by 2050. Over time, this will enable a 7.8% improvement in the fuel burn on average per flight by 2030 and an 11.6% improvement on average per flight by 2050. Decarbonisation activities in ATM and operations should be supported and fostered. A genuine seamless European Sky is the most prominent, providing potential for optimum (unconstrained) flight routings and efficiency improvements from the network. Continued investment in the development and fast deployment of SESAR solutions, air traffic management systems and flight planning systems is recommended.

Continue to invest substantially in decarbonising European aviation

The premium expenditure associated with realising this DESTINATION 2050 roadmap pathway has increased compared to the first edition, published in 2021. The additional expenditure related to decarbonisation over business-as-usual has risen from €820 bn to €1,300 bn (+57%), mainly due to higher SAF prices (including mark-ups by suppliers). By 2048, the sustainability pathway becomes the less expensive option, on an annual basis. However, cumulative savings exceeding the cumulative premium should occur beyond 2050. This implies that economic conditions are not (or not yet) driving the sustainability transition enough. Policies that lower the investment risks and that provide a financial support system designed to achieve the net zero aims are therefore essential for implementing the measures outlined in this roadmap. Examples are financial support for innovation and earmarking the revenues of market-based measures aiming for climate sustainability.

Reflections on how to go beyond the Roadmap pathway

Reduce CO_2 emissions further in both the short and long term

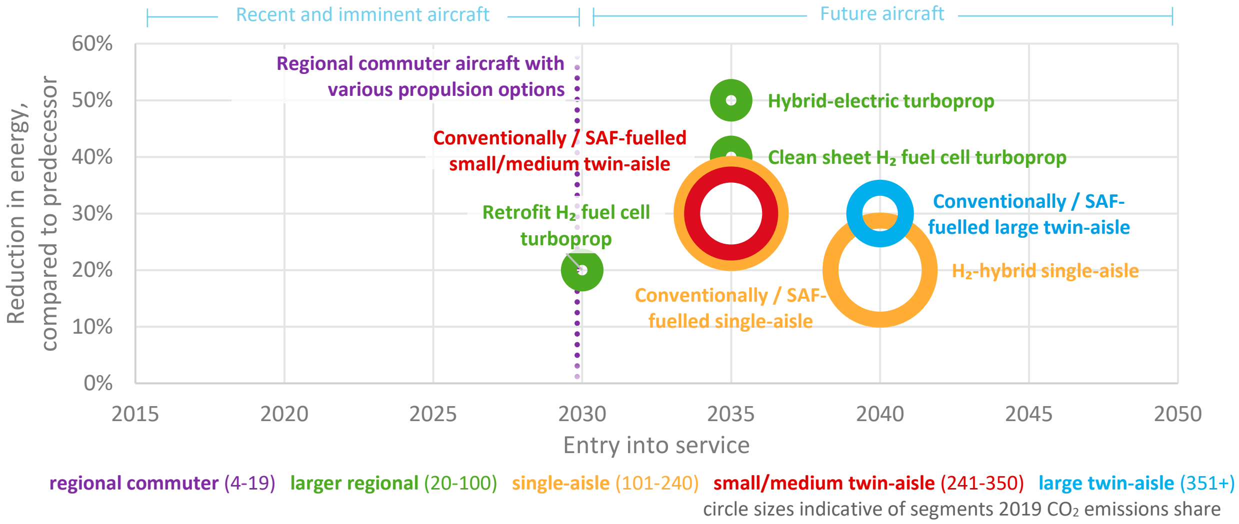
Accelerating the implementation of decarbonisation measures is also beneficial in the long term. Today's CO_2 emissions will contribute to the warming of the planet for hundreds of years. As such, the cumulative amount of CO_2 emitted is what causes the temperature rise. Limiting cumulative carbon emissions is essential for adhering to carbon budgets, such as for example derived for the Paris Agreement temperature goals. Implementing the decarbonisation measures at the scale and speed outlined in this roadmap is considered compatible with a 1.7°C pathway (66% likelihood) with a sectoral allocation based on the IEA Net Zero scenario. Additional measures would be required to be compatible with carbon budgets in line with a 1.5°C pathway (50% likelihood).

3 Improvements in aircraft and engine technology

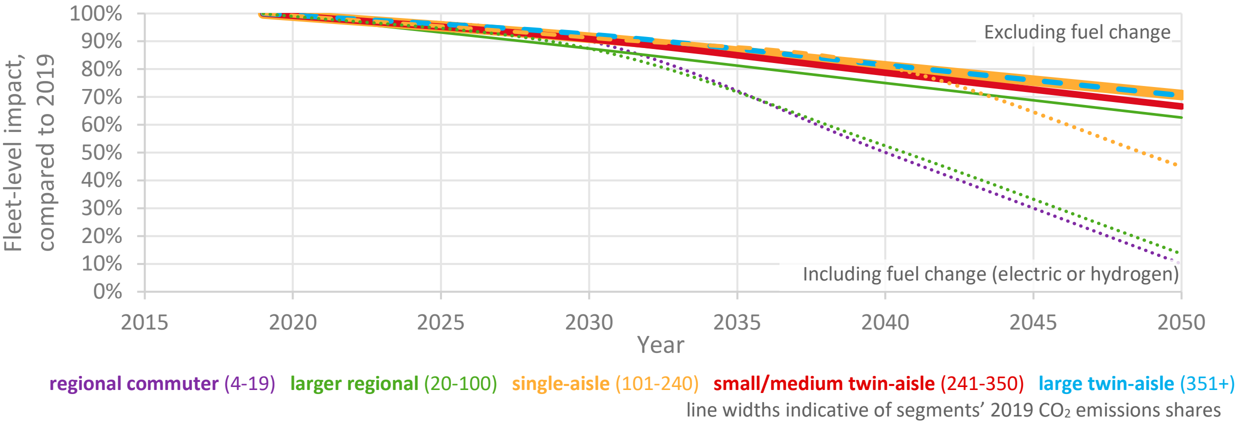
Improved technology is a crucial component on the road to net zero CO_2 by 2050

① New technologies are developed and tested through **research and innovation actions**; this requires €16 bn

② **New aircraft** with lower energy consumption and emissions can then be developed; this requires €105 bn



③ Following **market uptake**, these aircraft reduce fleet-level CO_2 emissions; this requires €890 bn



Alternatively-fuelled aircraft require dedicated **hydrogen-refuelling and recharging infrastructure** at airports (€3.8 bn).

All these activities require a **cumulative investment of €1,015 bn** between 2019 and 2050 (€20 to €40 bn per year), of which **€270 bn is directly sustainability-related** and in addition to a 'business as usual' situation.

**To realise net zero CO_2 by 2050,
joint actions by industry and government are needed that are coordinated and decisive**

① **Focused and collaborative R&D efforts to ensure technology gains and timely deployment on new products**

② **At-scale industrialisation and delivery of new technologies**

③ **Entry into service and ambitious fleet renewal by airlines**

The emission reductions shown are compared to a hypothetical scenario with no measures implemented, assuming a 1.4% annual increase in flight movements. Sustainability-related investment follows from an estimated €745 bn associated with fleet renewal by currently available technology.

3.1 Introduction

This chapter presents possible technological improvements to aircraft and engines that could contribute to the reduction of emissions of aircraft between 2019 and 2050 through improving energy efficiency and the implementation of alternatively-powered aircraft. These energy efficiency improvements are realised through weight reductions, improvements in aerodynamic performance and increased engine (or powertrain) efficiencies. Hybrid-electric and hydrogen-powered aircraft are considered as more disruptive options to reduce CO_2 emissions. Whereas continuous fleet replacement – and therefore availability of new aircraft – is necessary to guarantee new products enter into service and reduce operational fuel consumption, research and development activities are required to ensure that a next generation of aircraft and engines achieve further improvements in energy efficiency, while remaining competitive enough to ensure market uptake.

On the next pages, Section 3.2 first discusses notable developments since the first edition of the DESTINATION 2050 roadmap report was published in February 2021. Section 3.3 then details the analysis approach taken for the current report, based on which Section 3.4 lists the decarbonisation measures identified. Section 3.5 presents modelling results and draws conclusions, indicating the contribution of improvements in aircraft and engine technology to the overall decarbonisation of European aviation. Last, Section 3.6 provides implications for realising these improvements.

Scope and relation to other pillars

This chapter only discusses improvements to aircraft and engines that are introduced through fleet renewal or major upgrades to in-service aircraft. Such improvements should lead to lower in-flight energy consumption and/or enable the use of alternative energy carriers, such as hydrogen or batteries. Smaller upgrades to in-service aircraft, such as weight savings in the cabin, are discussed as part of the pillar ‘Improvements in Air Traffic Management (ATM) and aircraft operations’ (Chapter 4). Energy availability and fuels are also treated separately, as part of the pillar ‘Alternative fuels and sustainable energy’ (Chapter 5).

> **RELEVANCE TO NON-CO_2 CLIMATE EFFECTS OF AVIATION**
> The improvements discussed as part of this pillar could impact the non-CO_2 climate impact of aviation in multiple ways.
>
> Possible future battery-electric aircraft, which do not cause any in-flight emissions, would also have zero non-CO_2 climate effects. Hydrogen-powered aircraft using fuel cells do not emit any NO_X or soot, but do emit more water vapour (Lammen, Peerlings, van der Sman, & Kos, 2022). Nevertheless, the total climate impact of hydrogen-powered aircraft is lower compared to conventionally fuelled ones (Gierens, 2021; Bier, et al., 2024). For aircraft using hydrogen for combustion in gas turbine engines, water vapour emissions are higher, but in contrast to fuel cell powered ones, NO_X and soot emissions may still occur.
>
> For conventionally-fuelled aircraft, reductions in NO_X and soot emissions are subject of further research and development. A promising option of reducing soot in such aircraft would be through a reduction of the aromatic content of fuels – a development that is foreseen to go hand in hand with increased usage of sustainable aviation fuels further discussed in Chapter 5. For all aircraft using gas turbine engines, it is noted that an isolated increase in engine thermal efficiency – which lead to lower fuel consumptions and CO_2 emissions – increases, at a given altitude, the likelihood of contrail formation and subsequent climate impact due to lower-temperature exhaust gases (Schumann, 2005). As these increases in engine thermal efficiency also reduce soot emissions (which typically yields a reduction in contrail climate impact), the additional effect from the larger number of contrails might, to some extent, be counteracted. Moreover, improved engine efficiencies might also enable other aircraft-level or operational improvements, potentially affecting the non-CO_2 climate impact.
>
> Overall, developments in engine technologies for reducing CO_2 emissions are likely to have both positive and negative impacts on non-CO_2 climate effects. Airframe improvements, such as for example with respect to improved aerodynamics or weight reduction, that reduce in-flight energy consumption, can however have a positive (reducing) impact on non-CO_2 climate effects. Dedicated innovation, mainly with respect to compatibility of aircraft and engines with zero-aromatics SAF, is required to unlock non-CO_2 climate benefits of such alternative fuels.

3.2 Developments since the initial roadmap

The first edition of the DESTINATION 2050 roadmap report, launched in February 2021, indicated that improvements in aircraft and engine technology could reduce CO_2 emissions in 2050 by 37%, compared to a hypothetical 'no-action' growth reference scenario. Continued fleet replacement with currently or shortly available models would reduce emissions up to 2040. The development and introduction of ultra-efficient 'future' aircraft and engines between 2030 and 2040, including the introduction of a hydrogen-powered single-aisle aircraft for intra-European routes, would contribute to decarbonisation in the longer run. The report also provides some key implications, with respect to technology development for hydrogen-powered aircraft, the need for collaborative European as well as national R&D programmes and maintaining fleet renewal rates. The timeline below (not exhaustively) shows several notable developments that have taken place in the past three years, including the follow-up of several recommendations. It distinguishes between **developments in government and policy**, **industry progress** and **joint actions**.

02/2021: Launch of DESTINATION 2050 and the first European Aviation Net-Zero roadmap

06/2021: Launch of the RISE programme

GE Aviation and Safran have launched the *Revolutionary Innovation for Sustainable Engines* research and demonstration programme (Safran Group, 2021). It is focused on open fan architectures, hybrid-electric capabilities and possibly hydrogen, aiming to reduce CO_2 emissions by 20%.

06/2021: Successful first flight of Boeing 737 MAX 10

(Boeing, 2021)

2021: European fleet renewal remains ongoing

New Eurostat data on the age the European fleet of aircraft shows fleet renewal remains ongoing. Compared to 2017 data, the share of oldest aircraft (15+ years) reduced from 34% to 32%, whereas the share of new aircraft (0 – 5 years) slightly increased from 22% to 23% (Eurostat, 2019; 2023).

11/2021: Launch of Clean Hydrogen Partnership

The Clean Hydrogen Partnership aims to "strengthen and integrate EU scientific capacity" with respect to the development of clean hydrogen applications (Clean Hydrogen JU, n.d.). Aviation is also in focus, as evidenced by the funding of projects relating to on-board hydrogen storage and aircraft fuel cell power generation systems.

12/2021: Launch of Clean Aviation Joint Undertaking

Building on the Clean Sky and Clean Sky 2 programmes, the Clean Aviation Joint Undertaking was launched (Clean Aviation, 2022a). Through a combination of €1.7 bn of public funding and a €2.4 bn in-kind contribution from industry, it supports technology development for a next generation of regional and single-aisle aircraft.

03/2022: First call in Clean Aviation

Clean Aviation launched its first call for proposals (Clean Aviation, 2022b). In September 2022, more than €700 m of funding was approved for projects on hybrid-electric aircraft (propulsion, thermal management and electrical (power) distribution) and hydrogen-powered aircraft (direct combustion and multi-MW fuel cell propulsion), as well as projects focused on improving engine and airframe efficiency (Clean Aviation, 2022c).

CLEAN AVIATION

05/2022: ATR announces plans for ATR 'EVO'

Targeted for entry into service for 2030, the aircraft should further reduce CO_2 emissions and introduce hybridisation (ATR, 2022).

06/2022: Successful first flight of Airbus A321XLR

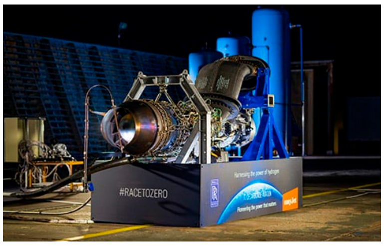
(Airbus, 2022b)

06/2022: Launch of AZEA

Various public and private partners, including the European Commission and DESTINATION 2050 organisations, launched the Alliance for Zero-Emission Aviation to prepare the entry into service of electric and hydrogen-powered aircraft (EC, 2023b). Six working groups address several priorities, such as regulation and certification, airport infrastructure, and energy supply (AZEA, 2023c). As of November 2023, AZEA brings together over 160 members (AZEA, 2023d).

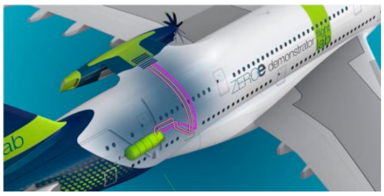
11/2022: Rolls-Royce and easyJet run H_2 gas turbine

Rolls-Royce and easyJet have successfully operated a converted gas turbine engine used for regional jets on hydrogen in a ground test (Rolls-Royce, 2022).



12/2022: Airbus reveals ZEROe engine

During the 2022 Airbus Summit (Airbus, 2022e), the company revealed that it is developing a hydrogen-powered fuel cell propulsion system as part of its ZEROe programme (Airbus, 2022d). The previously announced Airbus A380 hydrogen demonstrator (Airbus, 2022a) is to be modified for in-flight testing of hydrogen storage and fuel-cell propulsion systems (Airbus, 2022c).



01/2023: Boeing and NASA announce X-66A transonic truss-braced wing demonstrator

Boeing was awarded a NASA-contract for the building, testing and flying a full-scale demonstrator aircraft using a transonic truss-braced wing (NASA, 2023). Such a configuration with extra-long and slender wings reduces drag, such that CO_2 emissions could be reduced by 30%, compared to today's most efficient single-aisle aircraft.

02/2023: Second call in Clean Aviation

One year after the first, Clean Aviation launched its second call for proposals (Clean Aviation, 2023a), which led to the approval of €152 m of EU-funding in September of 2023 (Clean Aviation, 2023b). Representing a value of €380 m including private contributions, the eight projects address all three thrusts of the Clean Aviation Strategic Research and Innovation Agenda.

02/2023: Launch of Dutch national research programme for sustainable aviation

Following national research programmes in Germany (LuFo), France (CORAC), and the United Kingdom (ATI), the Netherlands launched the research programme 'Aviation in Transition' (Luchtvaart in Transitie, 2023). Focused on hydrogen storage and propulsion and high-power cabling and including research into non-CO_2 climate effects, it complements efforts undertaken at European level. This follows up on one of the recommendations made in the first edition of the DESTINATION 2050 roadmap report, launched February 2021.

04/2023: Aviation is included in EU taxonomy

The European Commission published draft technical screening criteria for including aviation in the EU Taxonomy Regulation (Delegated Act EU 2021/2139). Certain aviation activities, such as the manufacture, purchase and operation of zero-emission aircraft or (until 2028 or 2032, the latter if compatible with 100% SAF) best-in-class conventionally fuelled ones, are included (Giddings, 2023). This is likely to result in easier access to finance for such activities and hence, for example, support fleet renewal.

09/2023: Hydrogen in Aviation alliance launched

Several UK aviation and energy companies, including easyJet, Rolls-Royce, Airbus and GKN Aerospace, have launched the Hydrogen in Aviation alliance with the objective "to accelerate the delivery of zero carbon aviation" (Airbus, 2023b).

09/2023: First piloted flight on liquid hydrogen

As part of the European-funded project HEAVEN, H2FLY and partners (including DLR, Pipistrel and others) completed the world's first piloted flight of a liquid hydrogen-powered electric aircraft (H2FLY, 2023), thereby bringing hydrogen-powered aviation a tangible bit closer to reality.

06/2024: Launch of AZEA Vision Document 'Flying on electricity and hydrogen in Europe'

At the ILA in Berlin, the Alliance for Zero-Emission Aviation launched its vision (AZEA, 2024). Describing two scenarios for roll-out of electric and hydrogen-powered aircraft, it outlines what flying on electricity in hydrogen in Europe might look like – and what is considered necessary to get there.

10/2024: AURA AERO granted €95 m from European Innovation Fund

As one of 85 companies, AURA AERO was granted €95 m from the European Innovation Fund to support the company in further developing its ERA regional aircraft (Aura Aero, 2024).

3.3 Approach

The approach for identifying the decarbonisation potential of improvements in aircraft and engine technology, as well as the methods used to determine the overall contribution of this, closely resembles the first edition of the DESTINATION 2050 roadmap report. As such, it maintains the aircraft size class definition of that report, the distinctions between recent and imminent aircraft[30] and future aircraft types and one-to-one or class-based aircraft replacement and also retains the fleet renewal period of 22.5 years.

Aircraft size classes

Table 15 reiterates the aircraft size class definition used (although now using the terms 'Regional commuter' and 'Larger regional' rather than 'Small' and 'Regional' for the two smallest segments, and starting at 4-seat aircraft), and shows the shares of flights, available seat kilometres (ASKs) and CO_2 emissions of these segments in 2019. It is noted that these seat segments are selected for modelling purposes, but that in reality, these segments are less clearly defined. For example, various regional aircraft operators use 19-seater aircraft in addition to larger models and some of the smaller single-aisle aircraft in operation are, in terms of their overall design, more similar to regional jets rather than larger single-aisle aircraft.

Table 15: Aircraft classes and share of 2019 flights, ASKs and CO_2 emissions within the scope defined in Section 2.2

Class (abbreviation)	Seating capacity	Example(s)	2019 shares of		
			Flights	ASKs	CO_2 emissions
Regional commuter (C)	4 – 19	Beechcraft 1900	1.1 %	0.02 %	0.06 %
Larger regional (R)	20 – 100	ATR42, ATR72, Embraer E175	21.0 %	2.75 %	3.55 %
Single aisle (SA)	101 – 240	Airbus A320 family, Boeing 737	72.1 %	56.0 %	51.2 %
Small/medium twin aisle (SMTA)	241 – 350	Airbus A330, Boeing 787	4.6 %	29.2 %	31.6 %
Large twin aisle (LTA)	351 +	Airbus A350, Boeing 777	1.3 %	12.1 %	13.7 %
Total			100 %	100 %	100 %

Recent and imminent aircraft and future aircraft

This study distinguishes between recent and imminent aircraft[30] on one hand and future aircraft on the other. Recent and imminent aircraft are defined as aircraft that have already entered into service and are still in production, or are projected to enter into service in the next few years – although uncertainties about these exist. The improvement potential of these products is relatively well-known and is determined based on results from operational experience, or direct or media claims from OEMs[31]. For future aircraft, the uncertainties are larger – both in improvement potential as well as timelines. As such, modelling choices for future aircraft are often based on targets and at the level of aircraft classes rather than of specific products. It also means that entry into service years are estimated only at a 5-year interval.

One-to-one and class-based aircraft replacement

For flights that are currently operated by legacy aircraft that have a direct successor in the group of recent and imminent aircraft (such as a 'neo' or a 'MAX'-version), one-to-one replacement is modelled[32]. The performance of flights operated by current or previous generation aircraft that are not replaced by a designated successor, an improvement based on the class-average is assumed. For the generation of future aircraft, class-averaged figures are always used.

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[30] In the first edition of the DESTINATION 2050 roadmap report, these were referred to as 'upcoming aircraft'.

[31] Only products from organisations that have a Design Organisation Approval (or equivalent) from a relevant authority (e.g. EASA, FAA, …) are included. Based on an evaluation in November 2023, that means that products proposed by e.g. Aura Aero, Beyond Aero, Fokker Next Gen, Heart Aerospace, Maeve Aerospace, Vaeridion, VoltAero and ZeroAvia are not included in the category of recent and imminent aircraft. In the set of future aircraft, concepts similar to the ones studied or developed by these OEMs are included. Some examples are mentioned in Section 3.4.2.

[32] This implicitly assumes that historic market shares are maintained.

Fleet renewal period

Fleet renewal is modelled to occur linearly over a 22.5-year period, starting from the year a new aircraft enters service. This is based on historic average aircraft retirement ages of 25 years (Jiang, 2015; Forsberg, 2015), typical depreciation periods of 20 to 25 years (KPMG & IBA, 2017) and a fairly even distribution of European-registered aircraft over age bins (Eurostat, 2019; 2023), illustrated in Figure 12. Early replacement, possibly incentivised by rising fuel and fuel-related costs, is not considered.

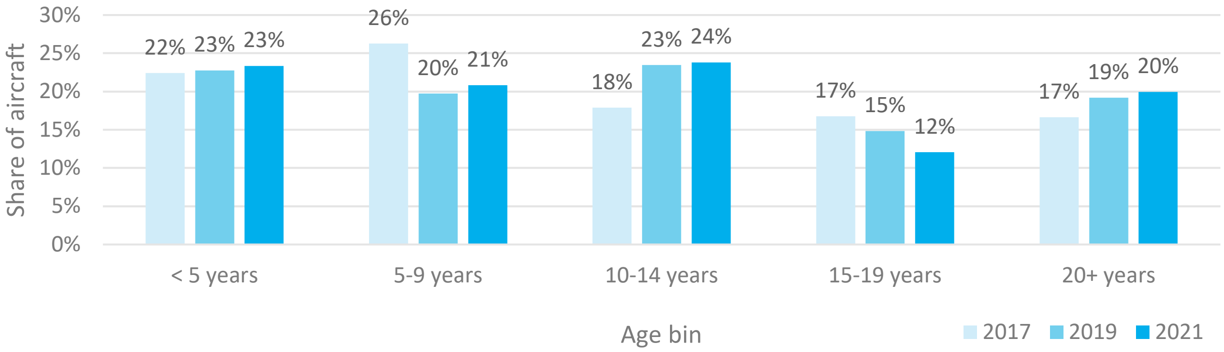

Figure 12: Share of aircraft registered in the EU/EFTA per age group in 2017, 2019 and 2021 (Eurostat, 2023)

Expenditures

The expenditure assessment follows the approach laid out in the DESTINATION 2050 study ‘The Price of Net Zero’, which investigated the expenditures (investments and costs) associated with the first edition of the DESTINATION 2050 roadmap report. Accordingly, the present report distinguishes between cost for research and innovation (technology development; up to TRL 6; based on Clean Aviation Partnership, 2020), cost for product development (from TRL 7 onwards; based on Clean Aviation Partnership, 2020; Bowen, 2010; Rodrigue, 2020; ICAO, 2022e), cost for fleet renewal (based on Schonland, 2016; Clean Aviation Partnership, 2020) and cost for ground infrastructure for future aircraft. Appendix D.4.1.2 provides further details.

3.4 Decarbonisation measures

This section summarises the decarbonisation measures that are part of the technology pillar of this roadmap report. Specifically, Section 3.4.1 deals with recent and imminent aircraft, whereas Section 3.4.2 is focused on future aircraft.

> **PRODUCT ENHANCEMENTS AND RETROFITS**
> Besides completely new aircraft or engine options, manufacturers provide smaller product enhancements during an aircraft’s and engine’s production cycle and retrofits can (and should) be carried out on aircraft and engines that are already in production. As currently no product enhancements or retrofits that would reduce fuel consumption by more than 5% are anticipated over the next few years, such product enhancements or retrofits are not included in the modelling in this chapter. More modest changes that are made to in-service aircraft, such as the installation of lighter weight seats or drag reduction technology, are included in Chapter 4, dealing with improvements in ATM and aircraft operations.

3.4.1 Recent and imminent aircraft

Current status

In 2019, 14% of ASKs were produced by the recent and imminent aircraft listed in Table 17. Jointly, these flights contributed 13% of the overall amount of CO_2 emissions associated with flights departing from the EU+ region. For the share of aircraft registered in the EU/EFTA[33], Figure 12 shows that the share of aircraft below 5 years of age has slightly grown, whereas the share of aircraft between 15 and 19 years has reduced – possibly due to the increased phase-out of older aircraft observed during COVID-19 (Reed, 2020; Kingsley-Jones, 2020; Pallini, 2020). The underlying data furthermore indicates the total fleet has decreased in size: from approximately 7800 aircraft in 2019 to 6800 in 2021. If the fleet grows again as traffic further recovers from COVID-19, the share of recent and imminent aircraft can be expected to increase.

Potential impact on emissions and expenditures

Table 17 provides an overview of recent and imminent aircraft as they are modelled, showing their fuel efficiency improvement as expressed with respect to a reference aircraft type. Changes in this table compared to the version published as part of the first edition of the DESTINATION 2050 roadmap report are bold-faced (and listed in more detail in Appendix D.4.1.1), and mainly involve the addition of several new types (e.g. Deutsche Aircraft D328eco and ATR EVO) and the update of (mostly postponed, by 2 years on average) entry-into-service dates for previously identified products (Embraer E195-E2, Airbus A321XLR, Boeing 737 MAX 7 and MAX 10, Boeing 777-9). Besides the changes that apply to specific aircraft, the method used to convert fuel efficiency improvements per ASK to fuel efficiency improvements per flight has been improved[34]. The class-averaged improvement data that is derived from the updated list of recent and imminent aircraft is shown in Table 16, suggesting an average fuel efficiency improvement of some 20%.

Table 16: Class-averaged fuel efficiency improvement potential and entry into service of recent and imminent types for aircraft classes considered

Class (abbreviation)	Fuel efficiency improvement per flight	EIS (recent / imminent)
Regional (R)	29%	2019
Single aisle (SA)	17%	2019
Small/medium twin aisle (SMTA)	18%	2016
Large twin aisle (LTA)	19%	2021

All recent and imminent aircraft are compatible with existing airport infrastructure, such that no further investments are required. Similarly, for the recent and imminent aircraft that have already entered service or are about to this or next year, research and development costs will have been incurred. For the recent and imminent aircraft that have yet to enter service (D328eco, ATR EVO, a generic turboprop project[35], Embraer E175-E2, Airbus A321XLR, Boeing 737 MAX 7 and MAX 10, and Boeing 777X), a total investment of approximately €11.5 bn is estimated (Appendix D.4.1.2). No substantial changes in aircraft acquisition cost or overall cost per ASK are assumed.

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[33] Approximately one-third of the ASKs and CO_2 emissions are produced by aircraft from non-EU+ operators using non-EU+ registered aircraft. These are not included in the fleet statistics shown.

[34] Fuel burn improvement (FBI) figures are typically presented per available seat kilometre (ASK) and are as such dependent on the seating configuration: even at (theoretically) unchanged fuel consumption per flight, an increase in seats reduces fuel consumption per ASK. For the modelling in this work, improvements per ASK have been converted to improvements per flight, using the formula $\% \, FBI_{flight} = \% \, FBI_{ASK} - \% \text{ seats} + \% \, FBI_{ASK} \times \% \text{ seats}$.

[35] Modelled based on a concept aircraft announced by Embraer. During the finalisation of this report, personal communication with Embraer suggests this aircraft is no longer planned to be introduced. As it has been included in the modelling on which the results presented in Section 2.6 are based, its (modelled) performance figures are still included in this report.

Table 17: Fuel efficiency improvement potential and entry into service of recent and imminent aircraft types, relative to reference types. For one-to-one replacements, legacy types are indicated. Values identified with a superscript T are typical values; values in bold indicate changes with the first edition of the DESTINATION 2050 roadmap report

Class	Recent / imminent			Legacy		Reference			Fuel efficiency improvement		Source(s) and remarks
	Type	EIS	Seats	Type	EIS	Type	EIS	Seats	Per ASK	Per flight	
R	**Deutsche Aircr. D328eco**	**2026**	**40**	**Do328**	**1993**	**Do328**	**1993**	**32**	**14%**	[36]	**Deutsche Aircraft** (2023)
R	ATR 72-600	2011	72			Generic RJ				**35%**	Based on Babikian (2002) and internal analyses
R	**ATR EVO**	**2030**	**72**	**AT72-600**	**2011**	**ATR 72-600**	**2011**	**72**	**20%**	**20%**	**ATR** (2022)**; Schuurman** (2022b; 2023)
R	**Turboprop project** [35]	**2030**	**74**			**ATR 72-600**	**2011**	**72**	**15%**	**10%**	**Embraer** (n.d.)**; Flottau & Anselmo** (2023)**; Hamilton** (2021)**; Hemmerdinger** (2021)
R	Embraer E175-E2	**2027**	80	E175	2005	E175	2005	76	16%	**12%**	Embraer (2016, p. 20); **Schuurman** (2022a)
R	Embraer E190-E2	2018	97	E190	2005	E190	2005	97	17%	17%	Embraer (2016, p. 20); Gerzanics (2018)
SA	Airbus A220-100	2016	120^{T}			E190 (est.)	2005	106	20%	**9.4%**	Bombardier (2015); Embraer (2016, p. 20)
SA	Airbus A220-300	2016	140			E190	2005	100	40%	**16%**	Bombardier (2015); Embraer (2016, p. 20)
SA	Embraer E195-E2	**2019**	120	E195	2006	E195	2006	106	25%	**16%**	Embraer (2016, p. 20); Hemmerdinger (2019)
SA	Airbus A319neo	2019	160	A319	1996	A319	1996	156	19%	**17%**	Aviation Week & S. T. (2007, p. 63); Leahy (2016, p. 18)
SA	Airbus A320neo	2016	189	A320	1988	A320	1988	180	20%	**16%**	Aviation Week & S. T. (2007, p. 63); Leahy (2016, p. 18)
SA	Airbus A321neo	2016	240	A321	1994	A321	1994	220	23%	**16%**	Aviation Week & S. T. (2007, p. 63); Leahy (2016, p. 18)
SA	Airbus A321neoLR	2018	206			757-200	1983	200^{T}	30%	**28%**	Airbus (2023d); Boeing (2007); Leahy (2016, p. 20); Polek (2015); Sustainable Aviation UK (2016, p. 68);
SA	Airbus A321XLR	**2024**	200^{T}			757-200	1983	200^{T}	**30%**	**30%**	**Airbus** (2023c)**;** Boeing (2007); **Kaminski-Morrow** (2022)
SA	Boeing B737MAX7	**2024**	153^{T}	B737-700	1997	737 NG	1997 / 2014	128^{T}		14% [37]	Boeing (2013; 2014; 2019a); **Hemmerdinger** (2022); **Insinna & Shepardson** (2023)**.** Fuel efficiency improvement with respect to winglet-equipped 737 Next Generation.
SA	Boeing B737MAX8	2017	178^{T}	B737-800	1998			160^{T}			
SA	Boeing B737MAX9	2018	193^{T}	B737-900 / -ER	2001 / 07			177^{T}			
SA	Boeing B737MAX10	**2024**	204^{T}								
SMTA	Airbus A330-800	2020	250	A330-200	1998	A330-200	1998	246	14%	13%	Fehrm (2017)
SMTA	Airbus A330-900	2018	294	A330-300	1994	A330-300	1994	290	14%	**12%**	Leahy (p. 10)
SMTA	Boeing B787-8	2011	242^{T}			767-300ER [38]	1988	261^{T}	20%	**26%**	Boeing (The Boeing 767 Family; 787 Dreamliner; 2005; 2018); Norris (2012); Trimble (2014)
SMTA	Boeing B787-9	2014	290^{T}			767-400ER (est.)	2000	296^{T}	20%	22%	Boeing (The Boeing 767 Family; 787 Dreamliner; 2005; 2018); Russell (2018)
SMTA	Boeing B787-10	2018	330^{T}						25%	**16%**	
LTA	Airbus A350-900	2015	314			777-200ER	1995	301	23%	**20%**	Leahy (2007, p. 26)
LTA	Airbus A350-1000	2018	369			777-300ER	2004	360	25%	**23%**	Hepher (2013)
LTA	Boeing B777-8X	**2027**	**384**	B777-200 (ER / -LR)	1995 / 2006	777-200ER	1995	375	22% [39]	**20%**	Boeing (777, n.d. - a; 1998; 2015); Norris (2020); Norris & Anselmo (2016); **Perry** (2023)
LTA	Boeing B777-9X	**2025**	395	B777-300 (ER)	1998 / 2004	777-300ER	2004	365	20% [40]	**11%**	**Aviation Week** (2022); Boeing (2009); Hepher (2013); Norris & Anselmo (2016); **Villamizar** (2022)

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[36] Due to the large increase in seats (+25%), the fuel efficiency improvement potential of the D328eco with respect to the Dornier D328 is modelled per seat rather than per flight. As such, no fuel efficiency improvement per flight is computed.

[37] Given a 14 to 20% increase in fuel efficiency per ASK would be largely negated by the increased seat count, it is assumed these numbers hold per flight.

[38] The 20% fuel efficiency improvement realised by the 787-8 over the 767-300ER is with respect to a reference aircraft without retrofitted winglets (Trimble, 2014).

[39] Norris & Anselmo (2016) state the 777-8 is 13% more efficient than the 777-300ER, which is 10% more efficient than the 777-200ER. As such, the difference between the 777-200ER and the 777-8 is (1 – 0.87 × 0.90) = 21.7%.

[40] Leeham News (2014) shows data from which the 777-9 (395 seats) can be derived to be 8.3% more efficient compared to a 777-300ER (configured with 344 seats). As this data is so different compared to other sources, this estimate is assumed to be erroneous and as such neglected. Recent fuselage stretch assumed to not affect fuel burn improvement figures per flight (Perry, 2023).

3.4.2 Future aircraft

Current status

With the launch of the Clean Aviation Joint Undertaking, the Clean Hydrogen Partnership and various national research programmes for sustainable aviation (highlighted in Section 3.2), research and development activities for future aircraft and engines have received another impulse. The Clean Aviation Partnership (2020) projects a €12 bn effort for research and innovation up to 2028 [41], in which relevant technologies for regional and single-aisle aircraft will be developed and matured up to TRL 6. For scaling and further R&D for twin-aisle aircraft, an additional investment of €4 bn is estimated. As the first Clean Aviation projects have only started recently, it is too early to evaluate whether R&D activities are on track to deliver on their objectives. That also means that the outlook presented in the first edition of the DESTINATION 2050 roadmap report, which is also in line with the objectives of Clean Aviation, is largely maintained. However, due to developments particularly in the lower seat classes, some refinements have been made.

> **NEXT-GENERATION AIRCRAFT CONCEPTS ON THE HORIZON**
>
> As noted in Section 3.3, this work models the decarbonisation impact of future-generation aircraft in an aggregated way, estimating the potential contribution of various technologies and mapping these technologies to aircraft size classes, to ultimately arrive at particular 'nameless' concepts. These are, nevertheless, inspired by various concepts studied and developments. Some examples are listed in the table below. Even though these concepts are not reflected in the modelling one-to-one, these developments all stress the disruptive innovations that will help realise the DESTINATION 2050 objectives.

Aircraft concept	Powertrain	Capacity	Planned entry into service	Source
Vaeridion Microliner	Battery-electric	Up to 9 passengers	< 2030	Vaeridion (2023)
AURA AERO ERA	Hybrid-electric	19 passengers	2028	Aura Aero (2023)
Cosmic Aerospace	Battery-electric	24 passengers	2029	Cosmic Aerospace (2024)
Heart Aerospace ES-30	Hybrid-electric	30 passengers	2029 (certification target)	Heart Aerospace (2024)
Maeve M80	Hybrid-electric	80 passengers		Maeve (2024)
Elysian Aircraft E9X	Battery-electric	90 passengers	2033	Elysian Aircraft (2024)
Fokker NextGen	Hydrogen		2035	Fokker NextGen (2024)
ZeroAvia	Hydrogen	Various		ZeroAvia (2024)
Airbus ZEROe	Hydrogen	Various	2035 (ambition)	Airbus (n.d.)
Embraer Energia	Various	Up to 50 passengers	2030+ (technology readiness)	Embraer (2024)

Modelled decarbonisation potential and associated financial impact

The decarbonisation potential of future aircraft is evaluated for each of the aircraft (seat) classes defined in Table 15. Changes in in-flight energy consumption, in-flight (i.e., Tank-to-Wake) CO_2 emissions and, if applicable, in cost per available seat kilometre (CASK, but without considering energy prices) are provided with respect to recent and imminent aircraft. For the expenditure assessment, development costs (from TRL 7 onwards) and purchase price (including discounts and rounded) are estimated[42]. Further details are provided in 0 and Appendix D.4.1.3.

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[41] This report only considers research and innovation action and associated investment need up to approximately 2030, as by that year, the technologies to be introduced on the future generation of aircraft modelled have to be ready. Further research and innovation efforts are required for subsequent generations of aircraft.

[42] Besides the cost changes associated specifically to the hydrogen-powered aircraft, aircraft acquisition cost for all future aircraft types is anticipated to increase by 25% compared to current (upcoming) types (Adler, et al., 2023; Clean Aviation Partnership, 2020). This is assumed to be balanced by the fuel efficiency improvements that these aircraft bring, leading to reduced energy cost, such that net costs do not increase (except for hydrogen-powered aircraft). This also holds for the listed aircraft product development costs, which are assumed to be funded from sales revenue, such that these investments do not necessitate further cost pass-through to the public.

REGIONAL COMMUTER

In the regional commuter class (ranging from 4 to 19 seats[43]; 1.1% of 2019 flights, 0.02% of 2019 ASKs and 0.06% of 2019 CO_2, per Table 15 [44]), a combination of aircraft types with different energy storage and propulsion systems is forecast to be introduced[45]. This is also supported by various concepts being developed by new manufacturers. These aircraft, or ones compatible with 100% SAF, are estimated to completely mitigate (net) CO_2 emissions and are modelled to enter into service from 2030 onwards[46]. Table 18 summarises this. Changes in energy efficiency and financial impact are not assessed, as these could vary widely between (technological) solutions.

Table 18: Summarised decarbonisation potential and associated financial impact of future aircraft in the commuter class

Class	Energy and propulsion	Applicability	EIS	Δ energy (in-flight)	Δ CO_2 (incl. SAF)	Δ CASK (excl. fuel)	Cost	
							Developm.	Purchase
C	Various	Depending on energy carrier and propulsion	2030	not assessed	– 100%	not assessed	not assessed	not assessed

LARGER REGIONAL

In the larger regional class (from 20 up to and including 100 seats; 21% of 2019 flights, 2.75% of 2019 ASKs and 3.55% of 2019 CO_2, per Table 15), three future aircraft types are modelled, summarised in Table 19 and described below. The innovations, technologies and improvements modelled for these specific types are deemed applicable for other aircraft sizes grouped in this category.

First, and different with respect to the previous first edition of the DESTINATION 2050 roadmap report, advances by ZeroAvia (2023) and Universal Hydrogen (2023) – even though the latter has since shut down[47] – are the reason for including a **retrofit hydrogen fuel cell-powered regional turboprop** aircraft as well. CO_2 emissions would be reduced by 100% and per-trip energy efficiency is estimated to improve by 20% compared to the ATR72-600 [48], or 30% compared to the average fleet in the regional class in 2030. The aircraft is modelled to carry 55 passengers and enter into service on three in eight of suitable intra-EU+ routes of at most 700 km from 2030 onwards (Appendix D.4.1.3). This timeline is ambitious, but is supported by fact that existing aircraft would be retrofitted. Furthermore, it needs to be considered that these regional developments are a relevant intermediate step towards larger hydrogen-powered regional and single-aisle aircraft expected to enter service by 2035 and 2040 (discussed next). Due to the retrofit nature of these programs, product development costs are estimated at €5.0 bn, half of those for the clean-sheet hybrid-electric turboprop. As the lower seating capacity reduces productivity (amount of seat kilometres produced per hour) and maintenance costs are assumed to increase, costs per ASK (without considering energy cost) are anticipated to increase by 28% (Appendix D.4.1.3). The purchase cost, for the combination of base aircraft and retrofit, is estimated at €25 m (Appendix D.4.1.3).

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[43] The smallest aircraft operated on the flights included in the scope of this work (Section 2.2) has 4 seats.

[44] Whereas the 'Commuter'-class forms a negligible contribution to the CO_2 emissions studied in this work (also see footnote 45), risks associated to the development of new (disruptive) technologies are typically smaller. As such, decarbonising this class of aircraft is likely relevant beyond addressing its direct CO_2 emissions as breeding ground or testbed for new technologies.

[45] It is stressed that, as noted in Section 2.2, this report only considers scheduled flights. For this particular seat segment, it means that business aviation, which is typically unscheduled, is not included.

[46] It is noted that this is somewhat later than the targeted entry into service dates of some of the listed products. This is due to the fact that future aircraft EIS dates are only modelled at 5-year intervals and that, as the manufacturers listed do not have a Design Organisation Approval (or similar), their products are not included in the overview of upcoming aircraft.

[47] During the time this report was prepared, Universal Hydrogen filed for bankruptcy after running out of money (Hardee, 2024). Despite that setback, the company has made relevant advances in terms of technology development and demonstrating the possibility of retrofitting existing aircraft with a hydrogen-powered propulsion system.

[48] Or, equivalently, 5% compared to an upcoming turboprop such as the ATR EVO.

Second, a **clean-sheet hydrogen fuel-cell powered regional turboprop** is modelled to enter service from 2035, seating 100 passengers. It is modelled to operate on one-eighth of intra-European routes of up to 1000 kilometres. CO_2 emissions will be zero and in-flight energy consumption will be reduced by 40%, compared to recent and imminent aircraft (Appendix D.4.1.3). Product development cost is estimated at €15 bn. As seating capacity is at the top of the regional class, productivity would not be reduced, such that changes to cost per ASK are anticipated to be negligible (Appendix D.4.1.3).

> **HYDROGEN: BRAND-NEW OR AGE-OLD?**
> Whereas the use of hydrogen as fuel in aviation is new (with the exception of experimental aircraft in the 1950s and 1980s, as mentioned by TU Delft & NLR, 2021, p. 34), other industries are well-accustomed to working with (mostly gaseous, but also liquid) hydrogen. Key examples are the petrochemical industry, oil refinery and fertiliser production (Liebreich, 2021; Liebreich, 2023), as well as rocketry, and more recently, also mobility. As such, the key technological challenges of hydrogen-powered aviation are hence not so much related to hydrogen generation[49] and handling itself, but its use in the aviation domain, for example with respect to the availability and reliability of technologies in the particular aviation environment (with lower temperatures and pressures compared to ground-level applications) and the applicability of aerospace (safety) standards and system weight, due to the impacts thereof on aircraft performance (energy efficiency, storage, …).

Third and last, a **hybrid-electric turboprop** aircraft combining kerosene or SAF with energy storage in batteries, as targeted in Clean Aviation, is modelled to enter service in 2035, without range capabilities in line with current aircraft. Excluding possible benefits of SAF, it is estimated to reduce CO_2 emissions by 50% compared to the 2020 state of the art, understood as upcoming regional jets[50]. With 10% of the energy is stored in the batteries (Adler, et al., 2023, p. 13), the reduction in energy consumption is modelled at 45%. Compared to the average fleet used in 2030 (which is anticipated to include an increased share of turboprops), this is equivalent to an improvement of 35%. Product development cost is estimated at €10 bn; acquisition cost at €30 m (Appendix D.4.1.2).

Table 19: Summarised decarbonisation potential and associated financial impact of future aircraft in the regional class

Class	Energy and propulsion	Applicability	EIS	Δ energy (in-flight)	Δ CO_2 (excl. SAF)	Δ CASK (excl. fuel)	Cost	
							Developm.	Purchase
R	Retrofit H_2 fuel cell	Intra-EU+ flights <700 km, 55 pax	2030	– 30%	– 100%	+ 28%	€5 bn	€25 m
	Hybrid-elec. w/ CAF / SAF	80 pax	2035	– 45%	– 50%	+/-	€10 bn	€30 m
	Clean sheet H_2 fuel cell	Intra-EU+ flights, 100 pax, <1000 km	2035	– 40%	– 100%	+/-	€15 bn	€30 m

SINGLE-AISLE

In the single-aisle-class (101 to 240 seats; 72% of 2019 flights, 56% of 2019 ASKs and 51% of 2019 CO_2, per Table 15), two aircraft types are modelled. Both designs would incorporate the latest innovations in terms of aerodynamic and propulsive efficiency and weight, but one would enter into service around 2035 and be powered by conventional fuel, whereas the other would enter into service in 2040 and use hydrogen in a hydrogen-hybrid configuration (direct combustion of hydrogen in a gas turbine scaled for cruise performance, assisted by a hydrogen fuel cell for flight phases with higher power requirements). Both types benefit from ultra-efficient and ultra-high bypass (possibly open rotor or fan) thermal engines and airframe improvements, such as natural or hybrid laminar flow, increased aspect ratio wings, fuselage weight reductions and smaller aerodynamic improvements to the tail. Their decarbonisation potential and the associated financial impact is summarised in Table 20.

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[49] Except for (further) technology development and scale-up for the production of green hydrogen, of course.

[50] The 50% emissions reduction target is aligned with the original Clean Aviation Strategic Research and Innovation Agenda (SRIA) (Clean Aviation Partnership, 2020, p. 19). During the preparation of this updated DESTINATION 2050 roadmap report, a revised SRIA was published, with a 30% emissions reduction target for the hybrid-electric regional aircraft. As the 50% is however also still targeted, although with "H_2-electric power injection", the 50% estimate has been maintained in the modelling of this work (Clean Aviation, 2024, p. 22).

The **conventionally fuelled** aircraft would improve energy efficiency by 30% (based on Clean Aviation Partnership, 2020), yielding the associated reduction in CO_2 emissions. In terms of range and payload capacity, it will continue trends observed over the past few decades. Product development cost was previously estimated at €15 bn, acquisition cost at €65 m (Appendix D.4.1.2).

A **hydrogen-powered** aircraft seating 165 passengers with a range of 2000 kilometres (following McKinsey & Company, 2020) is anticipated to operate solely on intra-EU+ flights (as hydrogen availability outside Europe is more uncertain). Of these applicable routes, it is assumed to ultimately (i.e. 22.5 years after entry into service, in the first half of the 2060s) be able to capture a market share of 60% [51]. The energy efficiency improvement of the hydrogen-powered single-aisle is estimated at 20% [52], with CO_2 emissions being mitigated completely (Appendix D.4.1.3). Excluding energy costs, higher aircraft acquisition and insurance cost (+31%; estimated at €85 m), higher maintenance cost (+47%) and a lower productivity (–18%) compared to a traditional single-aisle, lead to an increase in cost per ASK of 21% (Appendix D.4.1.3). Associated to the higher acquisition cost, product development cost was previously estimated at €17.5 bn.

Table 20: Summarised decarbonisation potential and associated financial impact of future aircraft in the single-aisle class

Class	Energy and propulsion	Applicability	EIS	Δ energy (in-flight)	Δ CO_2 (excl. SAF)	Δ CASK (excl. fuel)	Cost	
							Developm.	Purchase
SA	Conventional fuel or SAF	Unchanged	2035	– 30%		+/-	€15 bn	€65 m
	H_2 hybrid (fuel cell + combustion)	60% of intra-EU+ flights <2000 km, 165 pax	2035	– 20%	– 100%	+ 21%	€17.5 bn	€85 m

TWIN-AISLE

In the **small/medium twin-aisle** (SMTA, 241 to 350 seats; 4.6% of 2019 flights, 29.2% of 2019 ASKs and 31.6% of 2019 CO_2, per Table 15) and **large twin-aisle**-classes (LTA, more than 350 seats; 1.3% of 2019 flights; 12.1% of 2019 ASKs and 13.7% of 2019 CO_2, per Table 15), equivalent improvements in energy efficiency and reductions in CO_2 emissions (30%) are modelled. These are to be delivered by much of the same technologies as used on the ultra-efficient conventionally fuelled single-aisle type, such as ultra-high bypass ratio thermal engines (e.g. the Ultrafan by Rolls-Royce, 2023a), high aspect ratio wings with (hybrid-)laminar flow technologies, aerodynamic improvements to the tail (hybrid-laminar flow), a reduction of the fuselage weight and hybridisation of APU-functions. Entry-into-service for the SMTA-aircraft is modelled by 2035, whereas the LTA-type is modelled to begin operations 5 years later, from 2040. This also acknowledges the fact that recent and imminent aircraft in the LTA class are (anticipated to be) entering into service later than in the SA and SMTA classes. Product development costs were previously estimated at €20 bn and €22.5 bn, respectively, and acquisition costs at €165 m and €200 m (Appendix D.4.1.2). Table 21 summarises these results.

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[51] As the fleet penetration during initial phases is likely somewhat slower and because the modelling assumes linear phase-in rates, a final market share of 50% is modelled.

[52] The energy efficiency improvement for the kerosene-powered aircraft (30%) is higher than for the hydrogen-powered aircraft (20%) due to the added weight of the hydrogen powertrain and tank and the increased drag following from the larger fuselage (required to house the hydrogen tanks), following e.g. Lammen et al. (2022). For both aircraft, a similar level of technology improvement is anticipated.

Table 21: Summarised decarbonisation potential and associated financial impact of future aircraft in the twin-aisle classes

Class	Energy and propulsion	Applicability	EIS	Δ energy (in-flight)	Δ CO_2 (excl. SAF)	Δ CASK (excl. fuel)	Cost	
							Developm.	Purchase
SMTA	Conventional fuel or SAF	Unchanged	2035	– 30%		+/-	€20 bn	€165 m
LTA	Conventional fuel or SAF	Unchanged	2040	– 30%		+/-	€22.5 bn	€200 m

> **HYDROGEN-POWERED TWIN-AISLE AIRCRAFT?**
>
> Similar to the first edition of the DESTINATION 2050 roadmap report (van der Sman, Peerlings, Kos, Lieshout, & Boonekamp, 2021, p. 41), hydrogen-powered twin-aisle aircraft are not modelled for two reasons in particular. First, the increase in energy consumption associated to the integration of a hydrogen-based powertrain is considered too large[53]. Second, using hydrogen-powered aircraft for long-haul routes requires hydrogen availability and associated infrastructure around the world which is, at least currently, considered unrealistic.

OTHER FINANCIAL IMPACTS

Besides the cost changes at aircraft-level, investments in ground infrastructure are required to accommodate the alternatively fuelled aircraft – notably recharging stations and hydrogen refuelling infrastructure. Based on the use of these aircraft and their energy consumption, the required investment for such infrastructure is computed based on data collected in Appendix D.4.1.4, and presented as part of Section 3.5.

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[53] This has, for example been quantified by McKinsey & Company (2020). Substantial breakthroughs in tank gravimetric index, yielding a much lighter tank, could change this.

3.5 Results and conclusions

Decarbonisation impact

Improvements in aircraft and engine technology reduce CO_2 emissions through better fuel efficiency and enabling the use of new energy carriers, such as hydrogen or the use of unblended SAF in conventionally-fuelled aircraft. As shown in Figure 13, the contribution to decarbonisation delivered by improvements in technology increases from 8% in 2030 to 18% in 2040 and up to 27% in 2050 – comprising contributions from recent and imminent as well as future aircraft using conventional fuel and hydrogen. This trend is a direct consequence of the time required for newer aircraft to (further) penetrate airlines' fleets.

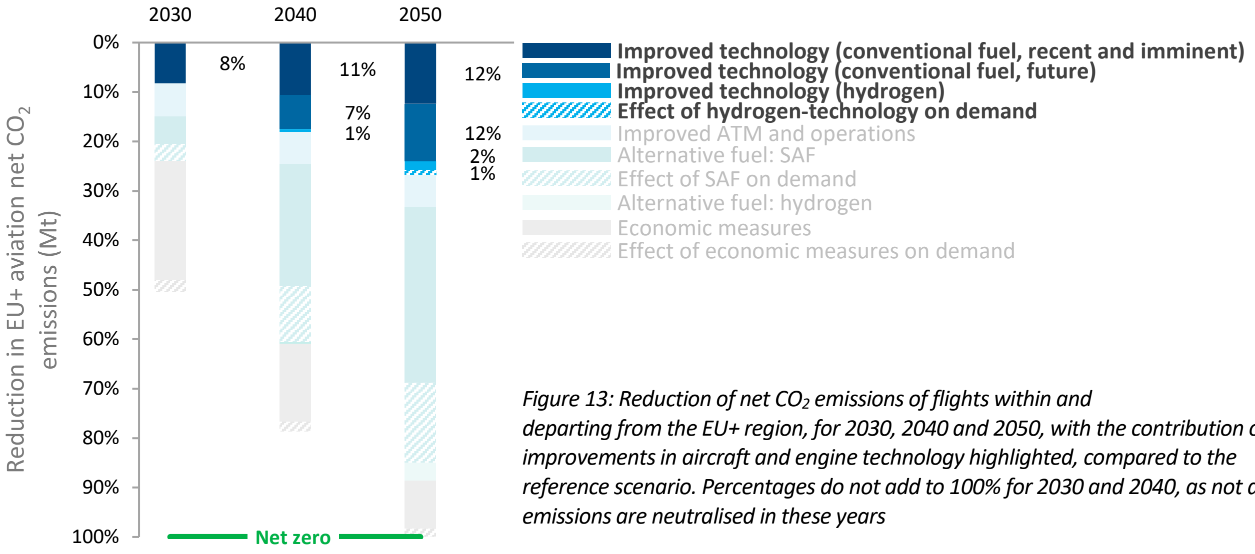

Figure 13: Reduction of net CO_2 emissions of flights within and departing from the EU+ region, for 2030, 2040 and 2050, with the contribution of improvements in aircraft and engine technology highlighted, compared to the reference scenario. Percentages do not add to 100% for 2030 and 2040, as not all emissions are neutralised in these years

Compared to the first edition of the DESTINATION 2050 roadmap, a large part of the contribution previously anticipated to be delivered by hydrogen-powered aircraft is now realised by an increased reliance on conventionally fuelled aircraft. This, in turn, follows from delayed entry into service of a hydrogen-powered single aisle and a lower anticipated market share. The pass through of higher costs of operating hydrogen-powered aircraft, resulting in increased ticket prices and associated reductions in demand (as discussed in Section 2.4.2), yield a 1% reduction in CO_2 emissions from 2040 onwards.

Table 22 shows the CO_2 emissions reduction per class for each of the three horizon years, compared to the fleet in 2019, excluding the effect of SAF or hydrogen. Figure 14 visualises these results, and for aircraft classes including alternatively-fuelled aircraft also illustrates the additional impact of this fuel change on decarbonisation. Fleet level CO_2 emissions reductions are largest in the regional class, due to the increasing use of more fuel-efficient turboprop aircraft, and the introduction of a hybrid-electric one from 2035. Compared to improvements in the small/medium twin aisle class (Airbus A330 and Boeing 787), fleet-level reductions for single aisle (Airbus A320 and Boeing 737) and large twin aisle (Airbus A350 and Boeing 777) are somewhat lower. In the former category, this is a result of the lower energy efficiency improvement anticipated for the hydrogen-powered single aisle (compared to a conventionally-fuelled aircraft with the same technological advancement). In the latter class, it follows from the later entry into service of the future aircraft (2040, compared to 2035 for the small/medium twin aisle class). Including the effect of a change in fuel (electric or hydrogen), fleet-level impacts grow. For commuter and regional-class aircraft (types seating up to 100 passengers), a very similar trend is observed, showcasing the potential of alternative means of propulsion in these two classes of aircraft and underlining their similarity in that regard.

Table 22: Class-averaged CO_2 emissions reduction at fleet level, per flight with respect to the fleet in 2019, taking into account the time required for fleet replacement (22.5 years). 2019 shares of CO_2 emissions, from Table 15, are shown for reference purposes

Class	Seating capacity	2019 share of CO_2 emissions	Fleet level CO_2 emissions reduction (excl. SAF and hydrogen), vs. 2019		
			2030	2040	2050
Larger regional (R)	20 – 100	3.55 %	12.6%	25.0%	37.4%
Single aisle (SA)	101 – 240	51.2 %	8.7%	19.0%	29.3%
Small/medium twin aisle (SMTA)	241 – 350	31.6 %	9.2%	21.3%	33.4%
Large twin aisle (LTA)	351 +	13.7 %	7.5%	18.5%	29.5%
Entire fleet (weighted by ASK)			**8.8%**	**19.7%**	**30.1%**

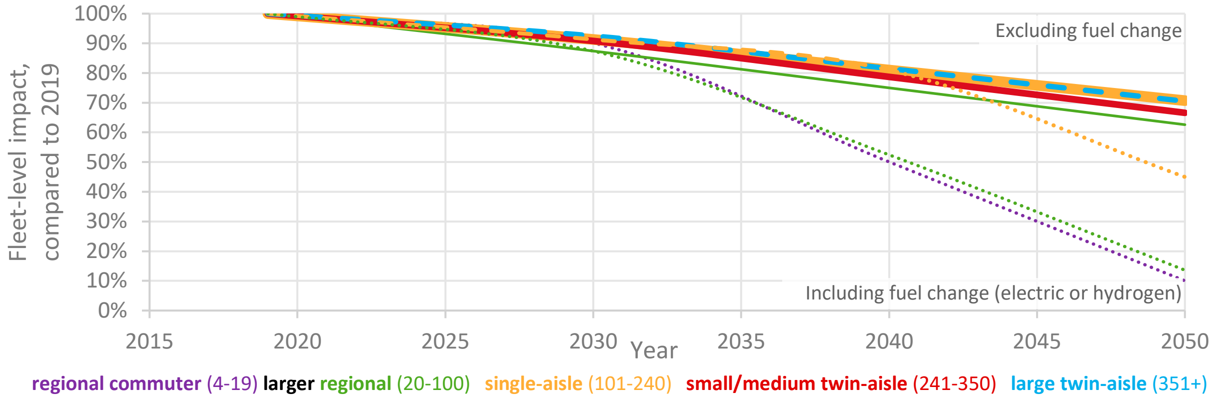

Figure 14: Class-averaged CO_2 emissions reduction at fleet level, per flight with respect to the fleet in 2019, taking into account the time required for fleet replacement (22.5 years). Top group of lines excludes the CO_2 reductions associated to a change in fuel (to electric or hydrogen); bottom (dotted) group of lines includes these, for applicable segments (commuter, regional and single-aisle). Line widths are indicative of 2019 shares of CO_2 emissions per segment

Expenditures impact

The costs associated to realising the aforementioned reduction in CO_2 emissions are comprised of several parts. The required investment in research and innovation for the future aircraft modelled in this work is estimated at €16 bn. For the further maturation and application of these innovations to new aircraft products, an investment of approximately €105 bn – found by summing the estimated product development costs for all future aircraft discussed – is deemed necessary. Both of these expenditures occur once during the roadmap period – although they might very well be spread out over more than a decade. Fleet renewal (i.e., purchasing new aircraft) is the largest expenditure. Based on a fleet replacement period of 22.5 years and limited activity growth, the fleet is anticipated to develop as shown in Figure 15. Combined with estimates per unit costs per aircraft, the cumulative investment between 2019 and 2050 for fleet renewal is approximated at €890 bn. This figure also includes the investments made by non-EU+ operators for the extent these have operations in scope of this report (departing from EU+ airports) and incorporates the 'business as usual' costs of fleet renewal. Last, infrastructure costs are estimated at a total of €3.8 bn - comprised of approximately €910 m for equipment to recharge hybrid-electric aircraft and €2.9 bn for hydrogen refuelling facilities. This yields a total expenditure of €1,015 bn. As fleet renewal in a business-as-usual scenario would already require an investment of €745 bn [54], a total figure of €270 bn (some 26% of the overall expenditure) can be considered a sustainability-related premium.

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[54] This is computed by not taking into account any cost increases specifically related to the future aircraft as modelled in this work, such as the 25% cost increase anticipated by the Clean Aviation Partnership (2020). Comparing this €745 bn with the total €890 bn also signifies a sustainability-related premium of €145 bn.

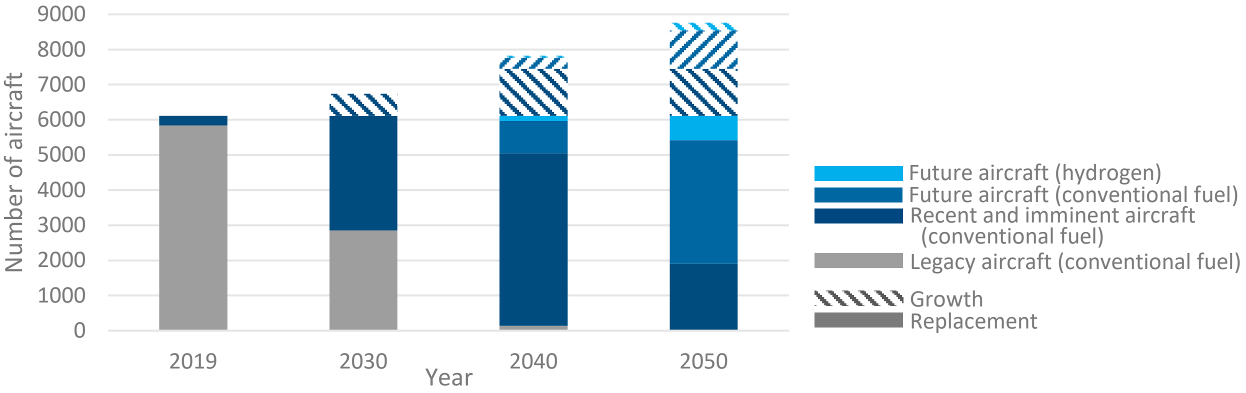

Figure 15: Anticipated fleet composition per aircraft generation and type of fuel for 2019, 2030, 2040 and 2050

To satisfy the demand illustrated in Figure 15, an average of 350 to 400 aircraft must be produced per year – summed across all classes – for operating the flights within and departing from Europe modelled in this report. Given the fleet growth, production figures rise from some 300 per year up to 2030 to 350 between 2030 and 2040, and up to 450 units per year in 2050. Conventionally-fuelled single-aisle aircraft make up approximately half of that. Necessary production of hydrogen-powered aircraft would start at some 20 aircraft per year in the 2030s, rise to 60 per year by 2040 and continue to grow to about 80 aircraft per year by 2050. For larger regional hybrid-electric aircraft, as modelled in this work, annual production figures would grow from approximately 35 to 50 units, complemented by production output in the smaller classes.

3.6 Implications

In order to realise the modelled efficiency improvements and subsequent reductions in CO_2 emissions, a number of steps are required. Although some steps relate to actions to increase the share of recent and imminent aircraft in operators' fleets and others to develop and introduce the next generation of future aircraft, it is key to stress that both these action lines are of crucial importance to decarbonise European aviation. This means that actions aircraft manufacturers and their supply chain partners are taking to get current types into the market cannot distract from the technology development required for (disruptive) next generation designs.

Increasing the share of recent and imminent aircraft in operators' fleets

For achieving the sustainability benefits offered by recent and imminent aircraft, three things need to be achieved:

1. Not-yet-introduced aircraft must be brought into service as modelled. Delays therein, which this updated roadmap report shows to be not unlikely[55], directly hamper the decarbonisation of European aviation (Pfeifer, Georgiadis, & Bushey, 2024).
2. Manufacturers must ensure a steady and sufficient output of airframes, such that fleet renewal plans become fleet renewal realities. This also requires healthy supply chains.
3. Aircraft operators must continue fleet renewal efforts, at least maintaining an ideally even increasing the rate at which new aircraft enter their fleets.

Realising future aircraft for entry into service from 2030 onwards

To ensure that future aircraft – entering into service from 2030 – make their contribution towards reducing fuel consumption and CO_2 emissions, another set of steps need to be taken. In the shorter term, these relate to technology research and development, aircraft certification and infrastructure deployment for alternatively-fuelled aircraft. In a next phase, product development, industrialisation and ensuring sufficient production become key.

> **DIFFERENT CONTRIBUTIONS BY DIFFERENT CLASSES**
> As shown in Tables 15 and 22, the single-aisle and small/medium twin-aisle classes of aircraft jointly contribute more than 80% to CO_2 emissions from flights within and departing from Europe, with the remaining sharing produced by aircraft in regional commuter, larger regional and large twin-aisle classes. Whereas decarbonising the larger segments (single-aisle and small/medium twin-aisle especially) hence makes the largest impact on absolute emissions, the regional segments are key in the development of alternatively propelled aircraft, as such radical innovations will start at smaller scales, before moving to larger segments.

TECHNOLOGY RESEARCH AND DEVELOPMENT FOR FUTURE AIRCRAFT

Research and innovation, followed by aircraft and engine product development, is the seed to develop and deliver the technologies that enable the CO_2 emissions reductions modelled in this work. Key contributions towards lower energy use are expected from lighter weight structures (composites) and aerodynamic improvements (natural or hybrid laminar flow, increased aspect ratio wings, possibly truss-braced). For engines powered by thermal engines, cycle improvements and increases towards ultra-high bypass ratio engines (possibly open rotor or fan) hold the greatest promise. In the smaller classes, alternative energy storage (batteries, liquid hydrogen) and propulsion systems (electric motors, fuel cells, power distribution systems) need to be developed and matured, so that they can subsequently be scaled up to larger amounts of energy and power.

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[55] Of eight recent and imminent aircraft to enter service in or after 2020 identified in the first version of the DESTINATION 2050 roadmap report (then referred to as 'upcoming' aircraft), five entry into service dates have been pushed back (Appendix D.4.1.1).

Besides private research and development initiatives, funded by numerous established and start-up companies and their investors, many of the aforementioned technologies are focus points of the European Clean Aviation research funding programme (already mentioned in Section 3.2), with Clean Hydrogen supplementing activities focused on (technologies for) hydrogen-powered aviation. Whereas other (larger) classes are expected to benefit through scaling and technology transfer, no dedicated European funding programme exists that is focused on the next generation of twin-aisle aircraft, although some national aerospace research programmes do take that segment into consideration.

The above observations lead to implications on two key – and closely related – aspects.

1. **Ensure coordination of global, European and national research efforts** to avoid duplication of efforts, while at the same time ensuring compatibility between developments. The creation of several industry alliances, the launch of dedicated national research programmes and differences in research focuses between for example Europe (notable emphasis on hydrogen-powered aviation) and the United States (pronounced efforts on high-aspect ratio wings) as listed in Section 3.2 is in that regard promising. To further streamline this, the development of consistent, detailed and regularly updated roadmaps[56] for technologies on the critical path towards net zero CO_2 emissions – ideally by neutral research groups rather than parties with a direct interest in any of these – is recommended. Such roadmaps could be expanded with information about required and committed resources, such that funding gaps can be identified and mitigated early on. For battery-electric, hybrid-electric and hydrogen-powered aviation specifically, AZEA is already working towards this, based on the recently published Vision Document (AZEA, 2024).
2. Identify and **mitigate any possible funding gaps** in time, to prevent delays in research activities, which would directly hamper the decarbonisation of European aviation. This implication holds for both government funding, as well as for private funding. Given the focus of current (European) funding programmes, lower TRL research and development of technologies for twin-aisle aircraft is identified as an area where such a funding gap exists.

> **FUNDING, INCENTIVES AND STIMULUS FOR HIGHER-TRL PRODUCT DEVELOPMENT**
> Whereas the aforementioned Clean Aviation and Clean Hydrogen programmes provide funding to lower-TRL research activities, these programmes typically stop at a technology readiness level of 6. An even larger funding requirement, however, exists in subsequent phases (Section 3.5). Although not studied in detail in this work, stakeholders spoken to note – and various examples show – that it is unlikely that the private sector is able to independently fund this. Rather, government support might be necessary. Depending on applicable regulations, this could be in the form of grants or direct investments, but also of incentives or state-backing to commercial loans. Further and more detailed research is recommended in that area.

CERTIFICATION OF FUTURE AIRCRAFT

Besides the development of new technologies, updated and/or entirely new certification standards are required – for which, in Europe, the European Union Aviation Safety Agency (EASA) has responsibility. Alignment, harmonisation and collaboration are key in these developments, due to the limited resources available and wide array of technologies being proposed. AZEAs Working Group 4 has published overviews of the current regulatory and standardisation landscapes for (hybrid-)electric and hydrogen-powered aircraft (AZEA, 2023a; AZEA, 2023b). With respect to (airworthiness) regulation, it notes that no certification standard currently exists for hydrogen-powered aircraft (AZEA, 2023a). For hybrid-electric propulsion systems, a Special Condition published in 2021 provides certification requirements for such systems in case an aircraft application has already been identified (EASA, 2021) [57]. Furthermore, EASA has launched pre-application service contracts to involve certification managers already in an early phase of an aircraft programme work, ultimately aiming to prevent hurdles or delays later on in the certification

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[56] As an example, the EU-funded research project TRANSCEND derived an integrated roadmap for the development of (cryogenic) fuel tanks, fuel cells and hydrogen combustion technologies, as well as powertrain and aircraft integration (Kos, et al., 2022, pp. 20-22), which is helpful for tracking progress of developments in this domain.

[57] It is noted that this special condition does not contain the additionally required certification requirements for the integration of such a hybrid-electric propulsion system in an aircraft, and explicitly excludes the use of hydrogen. A certification specification for electrically powered light sports aircraft is available (EASA, 2013), but only applies to such very small aircraft.

process. Whereas most of current developments take place in the domain of regional commuter aircraft (certified based on CS-23), it is important to ensure these learnings are ultimately also applied to larger aircraft segments (CS-25), as these disruptive propulsion technologies are also anticipated to find their way to these larger aircraft.

In terms of standardisation, AZEA has also provided an overview of the activities performed by, for example, EUROCAE on (hybrid-)electric (WG-113) and hydrogen-based (WG-80) propulsion, SAE and ASTM for hydrogen (re)fuelling, and several others (such as ISO, CEN-CENELEC and IEC) for topics more widely shared across industries (AZEA, 2023b). Several projects in Clean Aviation also contribute to the development of certification, such as the (co-)development of certification standards (CAVENDISH) or novel certification methods (CONCERTO).

ENTRY INTO SERVICE OF ALTERNATIVELY POWERED AIRCRAFT

For alternatively powered aircraft to enter into service, supporting infrastructure must also be in place. As shown in Section 3.4.2 (and more extensively in Appendix D.4.1.4), this is no trivial task and requires substantial investment. Over the last couple of years, various studies have investigated steps to take, for example by comparing various hydrogen supply pathways (McKinsey & Company, 2020; ACI World & ATI, 2021; Postma-Kurlanc, Leadbetter, & Pickard, 2022; Hyde, et al., 2023; Hosker, et al., 2023) or developing roadmaps for electric aviation (Driessen & Hak, 2021). With these publications converging on the feasibility and applicability of particular implementation concepts[58], the uncertainty around these high-level aspects also reduces. That means focus can – and should – shift to more specific challenges, starting with the most influential ones before moving on to optimising. Three key priorities are identified:

1. For hydrogen-powered and (hybrid-)electric aircraft: putting in place the right incentives to help first operators overcome initially higher costs (Hao & Lammen, 2023), for example through dedicated government subsidies (as studied for battery-electric aircraft by e.g. Thomson, Sachdeva, & Lammen, 2021), private stimuli (e.g. exempting first aircraft from airport charges), or through so-called ‘green’ Public Service Obligation (PSO) contracts (ERA, 2024). Alternatively, a smaller number of larger grants can be considered to kick-start operations and speed up commercialisation[59], furthering demonstrations planned in current European projects as STARGATE, TULIPS and OLGA. Reserving airport slots specifically for alternatively powered aircraft could be a non-financial stimulus, but might require a change to currently applicable regulations and policies.
2. For hydrogen-powered aircraft: resolving uncertainty about refuelling safety clearance zones and working to realise acceptable levels of safety with smaller clearance zones. Especially for regional aircraft and, to a lesser extent, single-aisle types, the often-cited 20-metre radius (e.g. Postma-Kurlanc, Leadbetter, & Pickard, 2022) has a notable impact on space requirements and the ability to perform other aircraft handling activities simultaneously which, in turn, impacts airport space requirements and aircraft turn-around times. Specifically, public or private support to currently ongoing standardisation working groups (e.g. SAE AE-5C and AE5-CH, AZEA, 2023b) and closer involvement of relevant authorities is recommended.
3. For hydrogen-powered aircraft: developing effective and well-insulated small(er)-scale storage facilities. As initial hydrogen uptake volumes will be limited, storage systems will also be smaller – and thereby more difficult to maintain at a cryogenic temperature. Besides increasing the cost of the operation, the subsequent need to boil-off excess gaseous hydrogen has a climate impact potentially ten times worse than CO_2 (Sand, et al., 2023).

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[58] Focus on liquid rather than gaseous hydrogen, reliance on truck delivery of hydrogen to the airport (especially in the early years and/or for smaller airports), aircraft refuelling through trucks rather than hydrant systems, etc.

[59] Especially in such a case, a preparatory study to identify which airports are best-positioned to kick-start the start of hydrogen-powered aviation in Europe is recommended, to prevent such grants awarded to locations where the infrastructure might be underused.

4 Improvements in Air Traffic Management (ATM) and aircraft operations

Improved ATM and aircraft operations deliver fuel savings starting from the short term

1 Measures to reduce fuel burn are needed by various stakeholders (airlines, ANSPs, airports, technology providers, maintenance companies, researchers, policymakers etc.), which makes it a collaborative effort. Broken down by group, the measures are:

Airlines

- Improve flight planning
- Reduce cruise speeds
- Flight management system updates
- Weight reductions
- Reduced tankering
- Airframe condition and maintenance

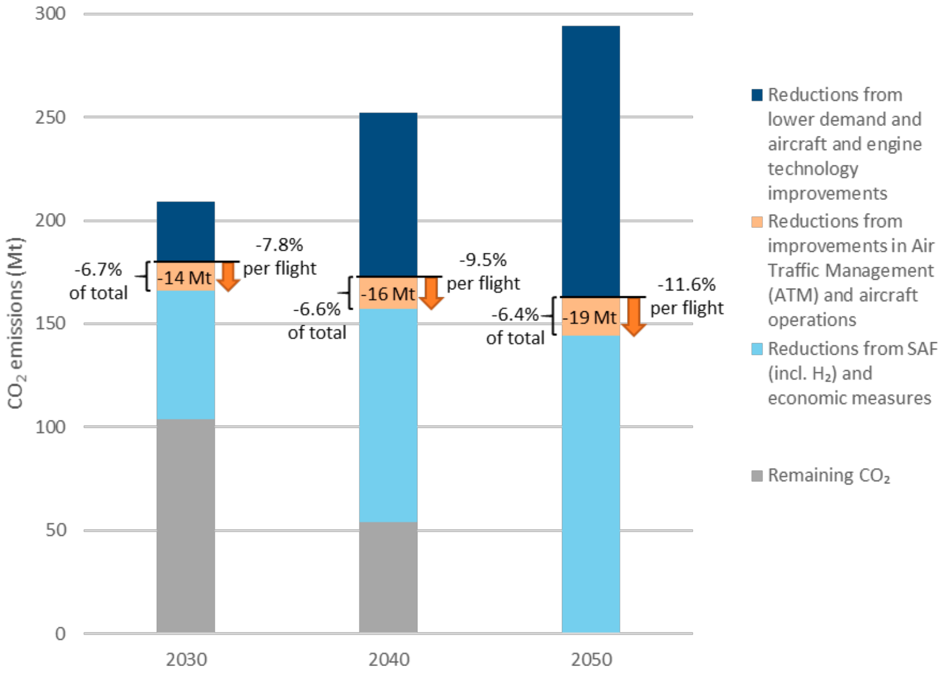
Air traffic management (ATM)

- Single European Sky and SESAR
  - Intra-EU+
  - Going to outside EU+
- Improved North Atlantic flight efficiency
- Wake energy retrieval

Ground operations at airports

- Reduced engine taxiing
- Operational towing
- Reduced APU usage

2 Absolute and per-flight emission reductions will increase over time as measures become more widely implemented. However, compared to the total CO_2 emission reductions, the proportion of CO_2 reductions from ATM and operations goes down slightly because the reductions caused by lower demand and aircraft and engine technology improvements grow significantly.



The cumulative cost for improvements in ATM and aircraft operations through to 2050 is estimated at **€37.6 bn**

To realise net zero CO_2 by 2050, joint actions are needed by industry and governments that must be coordinated and decisive

1 **Timely implementation of ATM Master Plan objectives**

2 **Prioritise fuel-efficient airline operations**

3 **Reduce taxiing emissions and APU run time**

The emission reductions shown are compared to a hypothetical scenario with no implemented measures, assuming a 1.4% annual increase in flight movements, and considering the effects of reduced demand due to increased costs.

4.1 Introduction

This chapter presents the improvements that can be achieved in air traffic management (ATM) and the operation of currently in-service aircraft to reduce CO_2 emissions up to the year 2050. Operational improvements offer a quicker reduction in CO_2 emissions as the implementation timeline is shorter than the development of new aircraft or fuels. However, it needs to be considered that ATM is a highly integrated system, that can be difficult to change, and in which the compatibility of different measures needs to be taken into account. Progress in advanced operations and innovation is anticipated from all involved stakeholders such as airlines, air traffic service providers, ATM infrastructure providers and airports.

This chapter is structured as follows. Section 4.2 presents the developments since the release of the first edition of the DESTINATION 2050 roadmap report published in February 2021. Section 4.3 gives insight to the approach used, based on which Section 4.4 presents the various anticipated decarbonisation measures and the expenditure assessment. With these improvements taken into account in the modelling, Section 4.5 unveils the outcomes, draws conclusions and places the improvements in ATM and operations in proportion with the other pillars. Finally, Section 4.6 provides overall implications.

Scope and relation to other pillars

This chapter focuses on the decarbonisation potential brought to aircraft that are in operation today. Examples of measures include improved flight planning and fuel burn reduction from more efficient air traffic management. Changes to in-service aircraft, for example by reducing cabin weight and improving airframe condition and maintenance, are included in this chapter as well; the development and introduction of new types (including their weight saving compared to current aircraft) is considered as part of Chapter 3, dealing with improvements in aircraft and engine technology. Retrofits for efficiency improvements fall under the present chapter as improvements for operations.

With respect to ground operations, only measures that reduce aircraft fuel burn are considered, such as more sustainable taxiing or reduced APU usage. Irrespective of their relevance to the total decarbonisation challenge, other airport related emissions, like the emissions from heating of the buildings or transport to and from the airport are out of scope of this chapter and report.

> **RELEVANCE TO NON-CO_2 CLIMATE IMPACT OF AVIATION**
> Reducing fuel burn and CO_2 emissions leads to a reduction of certain non-CO_2 effects, but not necessarily all of them. Flight trajectories with lower fuel burn and CO_2 emissions sometimes have higher non-CO_2 effects than other flight trajectories. In these cases, a trade-off needs to be made and the comparability between the effects must be guaranteed. This is currently one of the biggest issues and widely discussed in the scientific community as well as among policy makers (EASA, 2020).
>
> Effective non-CO_2 mitigation strategies from an operations point of view often target the avoidance of climate sensitive areas. These are areas in the atmosphere where non-CO_2 effects are more likely to occur or where the non-CO_2 effects have a bigger climate impact. One method which got much attention lately is contrail avoidance. When contrail avoidance is performed, aircraft are rerouted around certain areas in the atmosphere which are prone to the formation and persistence of contrails which – generally speaking – have a net warming effect on the Earth's climate. Not only is there a potential trade-off with additional fuel burn and CO_2-emissions to avoid these areas but it can also come with operational implementation issues. Higher complexity for air traffic controllers and air traffic management in general, increased flight times (including consequences for slots, time costs and network effects) and capacity issues are some of the limiting factors. So far, strategies for contrail avoidance were simulated, airlines performed flight trials and tests from an air traffic control perspective were performed in Europe (Sausen, et al., 2023). An application on the larger scale for commercial aviation is not implemented yet.
>
> Fewer pollutants in the exhaust jet of aircraft during ground-operations will lead to an improvement in local air quality. Some examples are lower NO_X emissions and less soot emissions.

4.2 Developments since the initial roadmap

The first edition of the DESTINATION 2050 roadmap report was launched in February 2021. Since then, other roadmaps and reports covering the anticipated decarbonisation potential of ATM and operations were released, new operational concepts were demonstrated and technologies that will have an impact were presented. The following timeline gives an overview of key developments since the release of the first edition of the DESTINATION 2050 roadmap. This will presumably have effects on many areas of this chapter and recalibrate the ambitions in CO_2 emission reductions. The timeline distinguishes between **developments in government and policy**, **industry progress** and **joint actions**.

02/2021: Launch of the DESTINATION 2050 alliance and the first European Aviation Net-Zero roadmap

09/2021: "Perfect flight" demonstration by British Airways involving NATS (National Air Traffic Services in the UK), Heathrow and Glasgow airports, Airbus and bp

The efforts to reduce the emissions were combined in this flight to demonstrate the emission reduction potential under optimal conditions. It was up to NATS to provide the optimal routing and optimal flight profile. (NATS, 2021)

10/2021: Complete Air Traffic System (CATS) Global Council launches vision for the skies of 2045

The forum of industry bodies believes in joint action to make sure that the skies of the future are efficient, clean, safe and contribute to global economic prosperity and social welfare. The vision includes that developments in flight path optimisation and airspace design improve the environmental sustainability of the industry and help to achieve the climate targets. (CANSO, 2021)

11/2021: Launch of SESAR 3 Joint Undertaking

The European institutional public-private partnership Single European Sky ATM Research 3 Joint Undertaking (SESAR 3 JU) was launched as a successor to the earlier SESAR programmes. Its goal is the acceleration of research and innovation in ATM and the introduction of the "Digital European Sky" to further increase the efficiency and environmentally-friendliness of the air traffic in Europe. (SESAR, n.d.)

11/2021: Airbus demonstrates wake energy retrieval in regulated airspace

As part of the fello'fly project, two Airbus A350s performed a trans-Atlantic flight in which wake energy retrieval was demonstrated. (Airbus, 2021b)

04/2022: ICAO publishes LTAG report

ICAO published the LTAG feasibility report, providing technical analyses of future international aviation CO_2 emission out to 2070. Operational measures are also discussed. (ICAO, 2022e)
In October 2022 the 41st ICAO Assembly adopts LTAG for international aviation of net zero carbon emissions by 2050 (ICAO, 2022a)

05/2022: EUROCONTROL investigates practical consequences of a 55% CO_2 reduction

In the Objective Skygreen 2022-2030 report, EUROCONTROL (2022) found that reducing European aviation CO_2 emissions by 55% compared to 1990 levels in 2030 is achievable, relying heavily on market-based measures.

06/2022: CANSO launches the Environmental Accreditation Programme GreenATM

Within the programme, the direct environmental footprint of ANSP and their efforts to facilitate minimising excess emissions in their airspace is evaluated. All performance indicators used to monitor the environmental performance of ANSPs are influenced by the performance areas of safety, capacity and cost-efficiency. As the responsibility for performance is shared with other stakeholders it is difficult for ANSPs to determine the remaining pool of performance improvements. The GreenATM accreditation scheme lists all the performance enablers that can be implemented by ANSPs and the programme supports the efforts to reduce airspace users' emissions and their own environmental footprint. (CANSO, 2022a)

06/2022: CATS Global Council launches its roadmap to deliver the skies of 2045

The roadmap includes goals on environmental sustainability and actions moving towards net zero emissions of the aviation sector (CANSO, 2022b).

06/2022: Launch of SESAR Deployment and Infrastructure Partnership (SNIP) Consortium

It acts as SESAR Deployment Manager, the industrial partnership responsible to support the timely and synchronised deployment of Common Project 1, a package of ATM functionalities helping to improve the performance of ATM in Europe. (EC, 2022)

09/2022: European Aviation Environmental Report 2022 by EASA

Overview of the environmental performance of the aviation sector in Europe, highlighting trends, challenges and opportunities for reducing its environmental impact.
(EASA; EEA; EUROCONTROL, 2022)

05/2023: SkyTeam-airlines participate in Sustainable Flight Challenge

The airlines “compete” with each other to achieve flying in the most sustainable way and they are for example awarded for lowest CO_2 intensity and largest CO_2 intensity reduction compared to a set of reference flights. (Skyteam, n.d.)

06/2023: Safran unveils in-wheel electric taxiing system

The new electric taxiing concept promises CO_2 reductions associated with aircraft ground movements. (SAFRAN, 2023a)

07/2023: Alternative fuels infrastructure regulation (AFIR) adopted

From January 1st 2025 electricity should be supplied to stationary aircraft at contact stands and from January 1st 2030 electricity should be supplied to aircraft remote stands. By January 1st 2030 it is also required that the electricity should come from the grid or should be generated on-site without fossil resources. The regulation does not set requirements for infrastructure provision for pre-conditioned air.

10/2023: ReFuelEU Aviation limits fuel tankering

The ReFuelEU Aviation SAF mandate has been adopted (European Council, 2023b). ReFuelEU Aviation also makes a push against fuel tankering, in which aircraft operators adapt their refuelling strategy for economic reasons which results in higher CO_2 emissions due to the extra weight. Exceptions to the regulations can be made in justified cases e.g. for safety reasons.

10/2023: Joint discussion paper by SESAR, EASA and EUROCONTROL on an efficient and environmentally friendly European Sky

The goal is to start a discussion on efficiency and environmental-friendliness of the European Sky prior to the European ATM Master Plan Update. (SESAR, EASA, EUROCONTROL, 2023)

10/2023: Supporting statement to make Europe the most efficient and environmentally friendly sky to fly in the world by ACI Europe, A4E, AIRE, ASD, CANSO Europe, EBAA, ERA and IATA

The industry supports the European goal to become climate neutral by 2050 and puts emphasis on the discussion prior to the European ATM Master Plan update. (ACI Europe, A4E, AIRE, ASD, CANSO, EBAA, ERA, IATA, 2023)

10/2023: Clean ATM Project

EU-funded initiative bringing together operational stakeholders from across the European aviation ecosystem towards achieving further decarbonising ATM operations, with a special focus on the implementation of Cross-Border Free Route. (SESAR DM, 2023)

12/2023: Launch of Airport Carbon Accreditation Level 5

One requirement is that airports address their Scope 3 emissions and are committed to Net Zero in Scope 3 by 2050 or sooner. (Airport carbon accreditation, n.d.)

03/2024: Provisional agreement on Single European Sky 2+ (SES 2+) package

The Single European Sky (SES) initiative seeks to modernise air traffic management in Europe and thereby improving airspace efficiency and reducing the environmental impact. The SES 2+ builds on the earlier adopted legislative packages SES I and SES II. (European Parliament, 2024)

06/2024: TEN-T regulation

The Trans-European Transport Network (TEN-T) includes the obligation for the Member States to ensure that airports of the core network (by end of 2030) and comprehensive network (by end of 2040) with more than four million passengers to provide pre-conditioned air supply (PCA) to stationary aircraft at aircraft contact stands. (EP & CEU, 2024)

07/2024: ACI Europe Resolution

303 European airports have committed to achieve and maintain net zero carbon emissions from operations within their control by 2050 at the latest, and also disclosed their roadmap(s) towards such goal. (ACI Europe, 2024)

10/2024: Clean ATM 2 project

EU-funded initiative bringing together operational stakeholders from across the European aviation ecosystem, in particular increasing efficiency and sustainability of airport operations in Europe with and Extended Airport Operations Plan and its integration with the Network Operations Plan for the major European hubs. (SESAR DM, 2024b)

12/2024: European ATM Master Plan 2025 Edition

Strategic roadmap for the modernisation and harmonisation of European air traffic management which connects ATM research and development activities with deployment scenarios to reach the performance objectives of the Single European Sky. (SESAR JU, n.d. - a)

4.3 Approach

The approach is consistent with the first edition of the DESTINATION 2050 roadmap report, but improvement potential estimates and timelines are updated with more recent sources. Prior to the modelling, the reduction of the fuel burn per flight and associated CO_2 emissions is estimated for each measure for the years 2030 and 2050. The value for 2040 is an indication which is not further modelled but linearly interpolated for the results. Moreover, a weight reduction is directly inserted into the model for certain measures. The measures are clustered by stakeholder group to be able to trace back where the improvements will need to come from.

As load factor increases are already included in the baseline traffic scenario in Section 2.4.1, these are not seen as an additional decarbonisation measure.

In the modelling, the improvements from operations are applied once the demand reduction and the aircraft and engine technology improvements have been subtracted from the baseline scenario CO_2 emissions leading to a "reduced baseline scenario" to which the decarbonisation measures from Section 4.4 are applied. New aircraft and engines come with an inherent CO_2 saving, and are subsequently operated. Flights that do not take place due to demand reduction do not need air traffic management and operations.

The expenditure assessment from Adler et al. (The Price of Net Zero : Aviation Investments towards Destination 2050, 2023) is used with an update on a few assumptions.

4.4 Decarbonisation measures

The potential CO_2 emission reductions delivered by improvements in ATM and operations are clustered into three blocks: airline operations, airspace and air traffic management, and ground operations at airports.

PERFECT FLIGHTS

Recently, so called "perfect flights" got more attention[60], where airlines, airports and ANSPs work together to reach the highest operational fuel savings possible. This is a positive development as it stimulates to get the most out of currently available technology and it is estimated that the improvement potential could be as high as 11.2% (EUROCONTROL, 2021) or 15% (Sustainable Aviation, 2023) for individual flights. Furthermore, environmental benchmarking and knowledge sharing enhance collaboration and raise awareness of the environmental impact reduction of flying.

However, certain aspects need to be considered: There are different metrics or perspectives to measure the "perfectness" / optimality of a flight: CO_2 emissions, CO_2 intensity, total climate impact or noise performance, and whether ATM-constraints apply or not. Moreover, the improvement potential depends on the chosen reference/baseline flight that it is compared to. So, one perfect flight is not like the other and the results cannot always be generalised.

Also, these improvements are targeted to individual flights, which can be more seen as a demonstrator or test case. The implementation on the network scale would come with additional challenges. The savings of a few "perfect flights" are ultimately negligible on the network scale. In addition to that, there is the risk of double-counting the savings from "perfect flights" with for example SES(AR) measures or weight reduction measures of airlines which are explicitly modelled. For these reasons, the perfect flights are not included as a separate decarbonisation measure.

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[60] Examples are the flights from British Airways (NATS, 2021) and the Sustainable Flight Challenge by SkyTeam (Skyteam, n.d.), where airlines are for example awarded for lowest CO_2 intensity and largest CO_2 intensity reduction compared to a set of reference flights.

INTERMEDIATE STOP OPERATIONS

Intermediate stop operations refer to a flight operation where an aircraft lands at one or more intermediate airports between its origin and destination airports, before continuing to its final destination. This type of operation allows for less fuel to be carried, which reduces fuel burn. However, it also requires two or more starts and landings, which increases fuel burn due to the additional energy required for these phases of flight. A disadvantage from an implementation point of view is that the intermediate airports would need to be upgraded to accommodate the additional starts and landings which seems challenging. (Climate optimised) intermediate stop operations are not taken into account in the modelling performed in this report, but identified as further opportunity for the future. Despite being strongly linked to ATM and operations, it would have large implications beyond that. New aircraft designs could even be adjusted to shorter ranges to obtain maximum efficiency on these flights.

Moreover, intermediate stop operations are often not compatible with other measures that are presented in this chapter and can therefore not be quantified and added to the other CO_2 emission reductions. Another problem occurs in emission counting and scope: for the DESTINATION 2050 roadmap the scope is departing flights from the EU+ region. When a long-haul flight is split into two short-/medium-haul flights, this would mean that just the first leg is eligible to be counted[61]. This would drastically lower the CO_2 emissions in the model even though the emissions of the second leg still occur leading to “carbon leakage”. For these reasons, the concept is not discussed further in this report.

4.4.1 Airline operations

Improved flight planning

Airlines typically plan their flights to minimize the costs – primarily: fuel costs, time costs and ATM charges – associated to the operation of such a flight. Dedicated flight planning software tools are used to find this optimum. Accurate aircraft performance data allows to better identify changes in the flight trajectory that can save fuel, costs, and CO_2 emissions. The cost-optimal trajectory, however, might not be identical to the minimum-fuel (and CO_2 emission) trajectory. A reduction in cruise speed, for example, can reduce fuel burn and CO_2 emissions, at the cost of extra time[62].

EUROCONTROL’s Objective Skygreen 2022-2030 report (EUROCONTROL, 2022) analysed the impacts of a **lower cruise speed** on CO_2 emissions and cost on the network scale. By reducing the nominal speed[63] to Long Range Cruise (LRC)[64] speed, fuel burn and CO_2 emissions can be reduced by 0.3%, while the costs stay nearly constant. For United States airspace, Jensen et al. (2013) even found a fuel consumption reduction of 0.89% at negligible impact on average flight time. Due to the scope with focus on Europe, the EUROCONTROL numbers are used in this report.

Using advanced **flight planning** software is estimated to enable fuel savings of 2.6 to 3% (GreenAir Communications, 2018; Honeywell, 2019). As some improvements are not mutually compatible[65] this estimation is lowered to 2% and because some airlines already use advanced flight planning software in the baseline year 2019, this value is applied to 75% of the flights, culminating in an average improvement of 1.5% per flight. In the first edition of the DESTINATION 2050 roadmap report, reduced cruise speeds were included in this measure as the flight planning software can also calculate the cost-optimal speeds. This report takes reduced cruise speeds as a separate category and the 0.3% that they could mean as a CO_2 reduction potential are subtracted from the measure “Improved flight planning” leading to 1.2%/flight.

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[61] This is true under the assumption that the intermediate stop airport is outside of the EU+ region.

[62] It is acknowledged that extra flight time might have an impact on possible transfer flights and network connectivity.

[63] Nominal speed is the cruise speed as defined in the aircraft flight manual.

[64] Long range cruise speed (LRC) is the speed which is faster than the speed for maximum range but which still achieves 99% of the efficiency. It is a trade-off between shorter flight times and increased fuel consumption.

[65] With better flight planning, the improvement potential of better flight management systems is likely to be reduced and vice versa.

For on-board **flight management system updates**, estimations range between 3% and 4% which is corrected for already implemented improvements to 1% (Thisdell, 2020; Sheppard, 2019). As hardware updates are necessary, the delivery is estimated for the period between 2025 and 2035.

The CO_2 emission reduction of improved flight planning is summarised in Table 23.

Table 23: Potential CO_2 emission reductions to be delivered by airline operational improvements in flight planning

Measure	2030	2040	2050
Improved flight planning	1.2%/flight	1.2%/flight	1.2%/flight
Reduced cruise speeds	0.3%/flight	0.3%/flight	0.3%/flight
Flight management system updates	0.5%/flight	1%/flight	1%/flight

Weight reduction

While weight reduction is a key objective of new aircraft developments (as discussed in Chapter 3 and specifically in Section 3.4.2), it is also a focus strived for in-service aircraft. Actions such as the paperless cockpit, digitalising passenger information and entertainment e.g. replacing newspapers with mobile apps, lower weight cargo containers, bring-your-own-device policies, lighter cabin trolleys, lighter crew equipment, lower weight seats, carbon brakes, “rightsizing” (or even reusing[66]) water and supplies (helped by pre-ordering of meals and retail purchases) are already applied by many – although not all – airlines to reduce on-board weight and, hence, fuel burn and CO_2 emissions.

For the weight reduction a saving potential of 10 kg per seat was assumed in the first edition of the DESTINATION 2050 roadmap report. The ICAO LTAG report (ICAO, 2022e) gives a quantification of fuel savings due to weight reductions in aircraft operations of on average 0.75% fuel reductions per flight which is deemed to be valid for Europe as well[67]. Applicability figures (75%, 85% and 95% of flights in 2030, 2040 and 2050) are sourced from ICAO (2022e) and are reflected in the estimates in Table 24.

Table 24: Potential CO_2 emission reductions to be delivered by weight reduction

Measure	2030	2040	2050
Weight reduction	0.56%/flight	0.64%/flight	0.71%/flight

Reduce tankering

Another option for in-service weight saving is to reduce tankering. Tankering is a practice in which airlines tank more fuel than needed for the upcoming flight, leading to a higher in-flight weight, extra fuel burn and additional CO_2 emissions. The reason can be operational (e.g. when little to no fuel supply is available at the destination, there are technical failures, fuel contamination or strikes) or economic[68], when the lower fuel prices at the departure airport compared to those at the destination airport outweigh the additional costs resulting from the additional fuel burn. Economic tankering accounts for about 90% of the tankering cases and can be performed partially or fully to cover the round trip without the need to refuel (EUROCONTROL, 2019b), and is widely used on short- and medium-haul routes[69].

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[66] One example is the reuse of the water from the lavatory to flush the toilet, leading to weight savings (Diehl, n.d.).

[67] A rough estimation whether a 10kg weight saving per seat or a 0.75% fuel burn saving per flight is higher is the following: a small/medium range aircraft with 150 seats would save 1500kg. With the modelled 3.5% cost of weight that means that 52.5kg are saved per block hour. On a 3-hour flight that’s around 150kg. With a rough estimation of a small/medium range aircraft burning 2500kg/hour the weight saving would lead to a 150kg/7500kg=2% fuel burn reduction. Thus, a 0.75% fuel burn saving per flight is estimated to have a smaller impact than a 10kg weight saving per seat.

[68] Tabernier et al. (2021) estimated that fuel tankering is economically beneficial for 21% of ECAC flights under 1500 and 2500 nautical miles (3000 and 5000 kilometres, approximately) in 2018.

[69] Tankering mostly happens on short-haul flights as enough tank volume is available and the extra weight does not have as a high fuel burn penalty as it would have on a long-haul flight.

Reducing economic tankering can yield further weight reduction. EUROCONTROL (2019b) modelled that in the ECAC area[70] 136 kg fuel can be saved per concerned flight that performs tankering. EUROCONTROL (2021) and Tabernier et al. (2021) list a fuel saving potential of 89kg per flight up to 2500 NM, which corresponds to 0.54% of CO_2 savings per flight (averaged on all flights in the ECAC area). Article 5 of ReFuelEU Aviation limits tankering practices and allows it just in the cases that it is required for safety, fuel availability in remote regions or turnaround times. Thus, it seems likely that economic tankering will indeed reduce. This report assumes economic tankering will not happen anymore in 2030 on intra EU+ flights, such that total tankering will be reduced by 75% compared to today[71].

Table 25: Potential CO_2 emission reductions to be delivered by reduced tankering

Measure	2030	2040	2050	Remarks
Reduced tankering	0.41%/flight	0.41%/flight	0.41%/flight	Intra EU+ flights

Airframe condition and maintenance

Keeping the aircraft in good condition minimises the reduction in efficiency over the lifetime. Examples include cleaning of the engines or the correct setting of the control surface rigging. Engine performance improvement packages (PIP) for currently in-production aircraft are measures which can enhance the durability and increase the efficiency of engines[72]. They can also be applied during maintenance as a retrofit to in-service aircraft to increase the engine's lifetime and reduce efficiency losses by e.g. replacement of blades. Washing and maintenance of the aircraft's outer hull saves fuel as a deteriorated exterior skin quality with dents or dirt decreases the aerodynamic efficiency. Drag reducing films (also called shark skin) can be applied as a retrofit which lead to reductions of the fuel burn of up to 0.8% (Lufthansa Technik, n.d.). This is just valid for a few individual aircraft under certain operating conditions (e.g. cleaned surfaces).

The decarbonisation potential of airframe condition and maintenance was formerly modelled as 0.2% per flight, delivered between 2020 and 2050. ICAO (2022e) anticipates greater opportunity for maintenance and technology related modifications to aircraft, varying from 0.2% to 1.9% per flight. This report uses the average value of 1.05% per flight. Following ICAO (2022e), these savings are applied to 50% of the flights in 2030, 70% of the flights in 2040 and 100% of the flights in 2050.

Table 26: Potential CO_2 emission reductions to be delivered by airframe condition and maintenance

Measure	2030	2040	2050
Airframe condition and maintenance	0.53%/flight	0.74%/flight	1.05%/flight

Expenditure assessment

The introduction of the measures reduction of cruise speeds and reduced tankering will lead to higher costs for airlines. Flying with higher speeds than the optimal fuel burn speed and tankering practices are performed nowadays for economic reasons. However, the fuel saving potential from airframe condition and maintenance is increased which also leads to a cost saving assuming that the savings outweigh the costs for the maintenance. It seems to be likely that all together, the investments can be covered by cost reductions of fuel burn reducing measures so that the cost neutral assumption is retained.

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[70] The European Civil Aviation Conference (ECAC) area is with 44 countries larger than the EU+ area (EU27+UK+EFTA) which is used as the scope of this report.

[71] 0.54% x 0.75 = 0.41%. The 75% reduction is a conservative estimation compared to the estimation of 90% economic tankering to take the exceptions from ReFuelEU Aviation into account. The remaining 25% of tankering cases may still happen for safety reasons, operational difficulties such as disproportionately longer turnaround times which can have an impact on connectivity or fuel supply shortages at remote regions including the competitive disadvantage compared to market conditions.

[72] This can for example mean that advanced coatings and high-temperature materials are used for in-production engines which are then built on in-production aircraft. (Perry, 2024)

4.4.2 Airspace and air traffic management (ATM)

When looking at the decarbonisation related to ATM, the Single European Sky and the associated SESAR research programme cover large parts of the European-focused scope of this assessment. Additionally, non-European ATM efficiency improvements, such as improved North Atlantic flight efficiency and wake energy retrieval are relevant measures that may apply to some of the departing flights and are treated in dedicated sub-sections.

Single European Sky and SESAR

CURRENT STATUS

The continuous support to improve the efficiency in the European sky manifests itself in the continuation of the Single European Sky (SES, political agreement on the newest update SES2+ has been reached in March 2024 (European Parliament, 2024)) and associated ATM Research (SESAR) programmes. Performance ambitions are set for capacity, cost efficiency, operational efficiency, environment, safety and security, and military contribution to network performance (SESAR JU, 2019a), and KPIs have been defined as part of the SES Performance Scheme[73] (EASA; EEA; EUROCONTROL, 2022). As of 2024, there is a multitude of 191 SESAR solutions[74] which either have already been developed or are still in development. 68 of them (about 36%) are actively contributing to reducing fuel consumption and emissions (SESAR JU, 2024). The latest improvement strategy incorporates the term *Digital European Sky* reflecting the increasing focus on digital innovation in ATM and flight operations in general.

The European ATM Master Plan is a roadmap and the main planning tool for the modernisation and harmonisation of European air traffic management connecting ATM research and development activities with deployment scenarios to achieve the SES performance objectives (SESAR JU, n.d. - a; SESAR JU, 2019a). The ATM Master Plan 2020 Edition performance target for 2035 is a reduction of the gate-to-gate CO_2 emissions by 5 to 10% compared to 2012. The modelling in this edition of the DESTINATION2050 Roadmap is based on the figures from the ATM Master Plan 2020 Edition but a comparison with the European ATM Master Plan 2025 Edition is provided:

> **ALIGNMENT OF THE DESTINATION 2050 ASSUMPTIONS WITH THE EUROPEAN ATM MASTER PLAN 2025 EDITION**
> The methodology chosen for this DESTINATION 2050 roadmap is to make a split between the main stakeholders in the field of operations: airlines on the one hand, airspace and air traffic management (ATM) on the other hand. Ground operations at airports are treated as a separate section. This way more concrete actions can be allocated to the stakeholder groups.

The European ATM Master Plan 2025 Edition efficiency improvement numbers are measured with a gate-to-gate indicator that encompasses potential improvements from all stakeholders together. The total benefit pool (e.g. quantified as 9.3% in 2050 compared to 2023) consists of 'ATM and Network constraints', and 'Flight planning and execution' (EUROCONTROL, 2024a).

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[73] Although fixed for the remainder of the third reference period (RP3, up to the end of 2024), the possible update of KPIs is currently discussed. EUROCONTROL & EASA (2023) give an overview of currently discussed metrics and indicators and conclude that there is no single indicator which can measure environmental ANSP performance sufficiently. Rather, a set of indicators would be needed.

[74] As of October 2024: 54 Ongoing, 66 Delivered and 70 Delivered and Deployed functionalities (SESAR JU, 2024).

Table 27 gives an overview of the improvement potentials that are assumed for intra-EU+ flight in this DESTINATION 2050 roadmap based on the ATM Master Plan 2020 Edition. The figures of the European ATM Master Plan 2025 Edition are linearly interpolated for the target years 2030, 2040 and 2050. In comparison, the fuel burn improvements per flight of the whole pillar 'Improvements in operations and ATM' includes the measures from all stakeholders and takes additional measures into account e.g. operational towing and wake energy retrieval. The DESTINATION 2050 SES(AR) improvements are included in the total DESTINATION 2050 improvements.

Table 27: Comparison of DESTINATION 2050 improvement potentials and the European ATM Master Plan 2025 Edition

	Geographical scope	Stakeholder scope	Baseline year	Estimated improvement potential		
				2030	2040	2050
DESTINATION 2050 SES(AR) improvements	Intra-EU+	Only ATM	2019	3.9%/flight	5.7%/flight	5.7%/flight
European ATM Master Plan 2025 Edition	EUROCONTROL area	All stakeholders	2023	0.93%/flight[75]	5.45%/flight[76]	9.3%/flight
DESTINATION 2050 total pillar ATM & operations	Intra-EU+ and departing from EU+	All stakeholders + additional measures	2019	7.8%/flight	9.5%/flight	11.6%/flight

For a direct comparison, the values of the European ATM Master Plan 2025 Edition would need to be corrected upwards to include the improvements that happened between 2019 and 2023. However, it can be seen that in 2030, the European ATM Master Plan 2025 Edition includes significantly lower improvement potentials than this edition of the DESTINATION 2050 roadmap. In 2050, the European ATM Master Plan 2025 Edition figure is aligned with the DESTINATION 2050 roadmap as the improvement figure lies between the value for ATM-related improvements for intra-EU+ flights and the total improvements from all stakeholders including additional measures.

The SESAR Deployment Manager is in charge of coordinating the implementation of the solutions developed in the scope of SESAR that require a synchronised approach at European level. The deployment of these ATM functionalities, derived from mature SESAR solutions, is mandatory under the Common Project 1 (CP1) Regulation (EC, 2021a). The implementation activities are carried out through a set of over 350 projects involving ANSPs (civil and military), airport operators, airspace users (civil and military) and the Network Manager.

MOST PROMISING SESAR SOLUTIONS

The two most promising SESAR solutions to reduce fuel consumption and CO_2 emissions on the short-term are Free Route Airspace (FRA) and Continuous Climb and Descent Operations (CCO/CDO) (EUROCONTROL, 2021). Free Route Airspace gives airspace users more choices to optimise their flight plans and improves the overall horizontal en-route flight efficiency. The airspace user enters the airspace via a defined entry point and leaves the airspace via a defined exit point. Within the airspace, the airspace user does not need to stick to the Air Traffic Services (ATS) route network but can freely choose his route while still being monitored by air traffic control. Therefore, the airspace user gets a benefit from the more optimised cruise phase. At the end of 2023, FRA has been implemented in much of northern, south-east and central south-east Europe – both above individual countries and in cross-border initiatives[77] (EUROCONTROL, 2023c).

Continuous climb and descent operations (CCO/CDO) enable aircraft to fly an optimal flight path during the flight phases climb and descent. During climb, it allows aircraft to fly the optimal flight path with the optimum engine thrust, climb speeds and without levelling-off on certain flight levels. During the descent, idle engine thrust can ideally be set from top of descend on and the aircraft can fly in a low drag configuration without levelling-off which saves fuel burn (EUROCONTROL, 2023b). It needs to be noted that speed restrictions or rate of climb/descent restrictions set limits to the optimal flight path.

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[75] 1.6% improvement between 2023 and 2035 (linearly) scaled with 7/12 to get the 2030 improvement.

[76] 1.6% improvement from CP1+Phase C and 50% of Phase D improvements counted.

[77] The CLEAN ATM initiative will further expand and enhance the availability of cross-border Free Route across Europe (SESAR DM, 2023).

Another concept which will lead to fuel burn reductions is the flexible use of airspace (FUA) in which the military parts of airspace, normally closed to civil aviation, can be opened to other airspace users when not in active use by the military[78]. The operational shift to use the 4D (space and time) information of aircraft and an improved exchange between the aircraft and the ground[79] is called Trajectory Based Operations (TBO; Nunez, 2023). TBO focuses on trajectories rather than individual flight segments allowing an optimisation from the system perspective. The flight trajectories are shared between airspace users and ANSPs and optimised during all phases of a flight. Flight & Flow Information for a Collaborative Environment (FF-ICE) is an ICAO concept that aims to facilitate the transition to a collaborative environment enabling TBO (ICAO, n.d. - d).

POTENTIAL IMPACT

To determine the anticipated benefits of the Single European Sky and SESAR, the European ATM Master Plan 2020 Edition Companion Document (SESAR JU, 2019b) is used, assuming that the improvement potential found in the Master Plan region (ECAC) is representative for the EU+ region studied in this report. At the point of modelling, the improvements of the European ATM Master Plan 2025 Edition efficiency improvements were not available yet.

Within a gate-to-gate scope, the average fuel burn per flight depends on the evolution of the average aircraft size, the fuel efficiency of the average aircraft, the evolution of the averaged flight distances and the evolution of the trajectory efficiency. The aim of ATM improvements is to act on the trajectory efficiency component which includes for example horizontal and vertical flight (in)efficiency.

The “additional average ATM-related inefficiency”, referring to the gate-to-gate fuel burn per flight, was about 6% in 2012 [80]. This means that in comparison to the reference trajectory, the so-called unimpeded trajectory[81], the average fuel burn is 6% higher. On top of that, the fuel burn for the unimpeded trajectory which uses as en-route distance the great circle distance could further be improved, if e.g. wind effects are taken into account[82]. The optimal trajectory would save even 0 – 4% more fuel burn than the unimpeded trajectory (Vranjkovic & Brain, 2020). This adds up to an inefficiency of 6 – 10%. Further improvements which go beyond the flight of a single aircraft like wake energy retrieval or concepts like operational towing are for this report considered out-of-scope of the trajectory efficiency improvements by SES(AR) and treated as separate emission reduction measures in this report.

It needs to be noted that there are limitations to ATM improvements. It is not possible to reduce inefficiencies completely to zero because of safety requirements (e.g., separation minima, rerouting around adverse weather, …). The optimal trajectory forms a limit, and no improvements better than that are achievable on a single flight basis. However, looking at one single flight is not enough and network effects play a role if several flights are carried out and assessed. In the whole aviation system, a traffic growth is expected which needs to be accommodated. This makes the optimisation of single flights more challenging. ATM efficiency improvements have an interdependency with noise effects and other performance parameters like capacity and punctuality. This leads to the fact that the inefficiencies can just be partly and not completely reduced. If air traffic increases in the future, inefficiencies will likely also increase unless measures are taken.

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[78] As mandated in the Common Project 1 Regulation, flexible use of airspace is available in the whole European Union airspace (SESAR DM, 2024a).

[79] Before, in-flight changes were only possible between flight crew and ATC via voice, just the portion of the trajectory visible to ATC could be revised and only simple clearances were possible as the delivery took place via voice. With TBO, the trajectory could be revised at any time during the flight, there is an improved system to communicate the clearances and tactical changes are still possible and managed by air traffic control (Nunez, 2023).

[80] Figure 6 in European ATM Master Plan 2020 Edition Companion document (SESAR JU, 2019b): 311kg additional ATM-related fuel burn compared to 5280kg fuel on average in 2012 equals 5.9% additional average ATM-related inefficiency

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

[82] Another example on how to improve the unimpeded trajectory is if an airport builds a new runway with a shorter taxi way. Then the taxi emissions will be reduced, even though earlier, there could have been zero additional taxi time.

For the DESTINATION 2050 baseline year 2019 the average CO_2 emissions per flight were 17000 kg and the additional ATM-related inefficiency 1071 kg CO_2/flight (EASA; EEA; EUROCONTROL, 2022). These values are based on the geographical scope of the European Civil Aviation Conference (ECAC) area and it is assumed that the numbers are valid for the intra-EU+ flights in the DESTINATION 2050 roadmap. The additional ATM-related fuel burn in 2035 will be 138 kg per flight which corresponds[83] to 435 kg CO_2 per flight. The improvement potential for the additional ATM-related fuel burn is thus (1071kg – 435kg) / 17000kg = 3.7% [84].

For the unimpeded improvement potential, it is assumed that from the maximum 4% unimpeded inefficiency, half can be eliminated, which leads to an improvement potential of 2%. In contrast, the claimed 330kg / 5280kg = 6.25% of unimpeded improvement potential of the European ATM MP Companion Document (SESAR JU, 2019b) seem quite optimistic.

An implementation of the SES(AR) measures until 2035 is forecasted, so that from 2035 on the estimated improvement is 3.7% + 2% = 5.7%. The 2030 value is linearly interpolated between 2019 and 2035 and thus 3.9% per flight.

Table 28: Potential CO_2 emission reductions to be delivered by the Single European Sky / SESAR

Measure	2030	2040	2050	Remarks
Single European Sky / SESAR – intra-EU+	3.9%/flight	5.7%/flight	5.7%/flight	Intra EU+ flights

> **COMPARISON WITH EUROPEAN ATM NETWORK FUEL INEFFICIENCY STUDY (EUROCONTROL, 2020) AND THE PERFORMANCE REVIEW REPORT (PRR 2023) (EUROCONTROL, 2024c)**
> In the first edition of the DESTINATION 2050 roadmap an additional improvement potential of 2% was estimated based on the European ATM Network Fuel inefficiency study (EUROCONTROL, 2020) which estimated average fuel inefficiencies of between 8.6% and 11.2%. It compares flights with the 5th or 10th percentile of lowest fuel burn per city pair today[85] and does not anticipate future system improvements. The Performance Review Report (PRR 2023) (EUROCONTROL, 2024c) also uses a percentile approach (10th percentile) of gate-to-gate fuel burn for trajectories within the EUROCONTROL area and indicates a benefit pool of 9.3%.
>
> The main reason that this is not applied as further CO_2 emissions reduction potential in this report is that it is based an indicator directly relating to fuel burn which captures system inefficiencies in the whole system from a multi-stakeholder view. It includes for example taxi improvements at airports and weight reductions by airlines, which are split from ATM improvements in DESTINATION 2050 and covered as separate measures. Therefore, the outcomes of the European ATM Network Fuel Inefficiency Study and the Performance Review Report (PRR 2023) can be better compared to the total outcome of the “ATM and operations” pillar instead of including this in the SES(AR) improvements[86].

Departures to outside EU+ destinations will benefit to a lesser extent from SES(AR) improvements as they perform just a part of their flight through European airspace and they do not benefit from the SES(AR) improvements at their arrival airport outside the EU+. For the additional ATM-related improvements, improvements from taxi-out, climb and 50% of the en route are counted giving 1.4% and for the unimpeded improvements 1% are taken, leading to a 2.4% improvement until 2035. This calculation is further explained in Appendix D.4.2.1.

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[83] Factor 3.15 kg CO_2 per kg fuel burnt used. The value of 138 kg per flight is taken from the ATM Masterplan 2020 Companion Document (SESAR JU, 2019b) with the note that gate-to-gate values are somewhat lower because intercontinental and overflights have less than two departures/arrivals with associated inefficiencies.

[84] This is in line with (Vranjkovic & Brain, 2020).

[85] Flights are directly compared with each other per city pair and not corrected for favourable weather conditions such as tailwinds or that other flights could be less efficient due to adverse weather conditions, traffic conditions with delays or strikes.

[86] The average fuel inefficiency of 8.6% to 11.2% with the excess fuel burn indicator is in the same order of magnitude as the average CO_2 emission savings per flight from all decarbonisation measures (including future system improvements) of 7.8% in 2030, 9.5% in 2040 and 11.6% in 2050, as presented in Section 4.5.

Non-European ATM efficiency improvements

To include the improvement potential for departures from the EU+ region to a destination outside of the region, efficiency improvements of airspace beyond Europe is considered. In parts of the world outside Europe, efficiency improvement of the airspace is also pursued. In the United States, the Next Generation Air Transport System (NextGen) is an initiative to modernise the air traffic system. In other regions and countries, the airspace modernisation is also driven forward: Asia Pacific Seamless Air Traffic Management (APAC SATM), the Single African Air Transport Market (SAATM), INSPIRE for flights above the Indian Ocean and CARATS in Japan (ICAO, 2019). Flights departing from the EU+ region to a destination on another continent will benefit from these improvements. This improvement potential is just applied to intercontinental departures, as intercontinental arrivals and overflights are out of scope of this work.

The estimated value of possible efficiency improvement outside of Europe is 3%, based on the global ATM efficiency goals for 2020 (93%-95%) and 2050 (95%-98%) (CANSO, 2012). Efficiency numbers from 2017, analysed and presented in the 2019 ICAO Environmental Report (2019) are slightly higher (between 94% and 98%) but only include horizontal flight efficiency and not vertical flight efficiency.

To avoid double counting with the anticipated SESAR CO_2 reductions, the 3% reduction is scaled down by 50% leading to 1.5% non-European ATM efficiency improvements. Given the fact that ICAO CAEP has set operational efficiency goals for 2026 (ICAO, 2019) and large parts of SES(AR) implementation is foreseen by 2035, a similar implementation timeline as the SES(AR) is modelled. Together with the 2.4% from SES(AR) improvements for flights to outside EU+, this leads to 2.4% + 1.5% = 3.9% delivered by 2035. The 2030 value is linearly interpolated. This is shown in Table 29.

Table 29: Potential CO_2 emission reductions to be delivered by SES(AR) and non-European ATM efficiency improvements

Measure	2030	2040	2050	Remarks
Single European Sky / SESAR – extra-EU+ including non-European ATM efficiency improvements	2.7%/flight	3.9%/flight	3.9%/flight	Departure flights to outside EU+

Improved North Atlantic flight efficiency

In the past, air traffic above the North Atlantic Ocean was predominantly organised on pre-defined tracks, because there was no means to accurately track the location of aircraft. In order to maintain a high degree of safety, this application of procedural control implied fewer crossing aircraft trajectories. As aircraft flew on the tracks with the same speed, longitudinal separation could be reduced. Airlines could always request their optimal trajectory across the North Atlantic, but constraints like flight level capacity and flight planning system limitations prevented them from flying these optimal performance routes. The reduction of the Organised Track System (OTS) will lead to a significant easing in these constraints, allowing more user preferred routings outside of an OTS structure. This reduction is primarily enabled by space-based automatic dependent surveillance-broadcast (ADS-B) technology, which captures the aircraft’s position with the help of satellites, allowing ATC to have full surveillance capabilities and markedly reduced crossing separation standards, leading to more fuel-efficient trajectories. (NAV Canada, 2021; Young, 2021)

The reduction of the North Atlantic track system could lead to efficiency improvements as there will be more options to fly with optimal trajectories. Assessments are currently underway through the IATA North Atlantic OTS Development Focus Group. The consideration of several sources in the first edition of the DESTINATION 2050 roadmap report lead to a saving potential of 2.9% which was corrected to 1.3% assuming that 45% of the North Atlantic flights used the tracks in the baseline year. A full implementation is foreseen before 2030. A study by Wells (2021) concludes that the improvement potential is 1.7% for aircraft flying towards the west (departing from Europe).

Considering that network effects and certain operational circumstances[87] can occur, the lower value (1.3%) is chosen. This reduction potential is applied to flights from Europe to North-America and is additional to the non-European ATM efficiency improvements.

Table 30: Potential CO_2 emission reductions to be delivered by improved North Atlantic flight efficiency

Measure	2030	2040	2050	Remarks
Improved North Atlantic flight-efficiency	1.3%/flight	1.3%/flight	1.3%/flight	Flights from Europe to North-America

Wake energy retrieval

Wake energy retrieval is a disruptive concept where aircraft fly in an extended formation which leads to benefits in fuel consumption of the follower aircraft. This is due to the aerodynamic updraft that the follower aircraft can benefit from and is inspired by migratory birds that travel long distances. Boeing showed a 10% fuel burn benefit for the follower aircraft in flight tests in 2018 with two Boeing 777 freighter aircraft (Norris, 2019). In the project fello'fly, Airbus assessed a concept of operations that also comprised flight tests with two A350 aircraft. It was found that a fuel burn reduction of 5 - 10% for the follower aircraft is achievable. The lower bound of 5% is the more realistic fuel reduction potential under operational conditions accounting for the part of the flight where the aircraft are not engaging in wake energy retrieval (Airbus, 2021a). Based on the assumption that two aircraft fly in formation and not more than two, this leads to 2.5% per aircraft per flight. The SESAR project GEESE will elaborate the concept of operations and further assess the open questions for the implementation including the regulation and standards aspects (SESAR JU, n.d. - b; SESAR JU, 2023). The implementation of wake energy retrieval is expected to start in 2030, first on North Atlantic routes, because of the predominantly bi-directional traffic flow. In 2040, an implementation on 40% of the flights and in 2050 an implementation on 80% of the North Atlantic flights is foreseen[88]. ICAO (2022e) estimates for 2040 that 3% and for 2050 that 15% of the flights per region will benefit from wake energy retrieval[89] which is applied to intra-European flights and departing flights to other world regions than North-America. These values are significantly lower than for flights above the North Atlantic Ocean as an organised structure like the North Atlantic Track System favours the pairing probability as the aircraft fly close and well-arranged after one another.

Table 31: Potential CO_2 emission reductions to be delivered by other airspace and ATM decarbonisation measures

Measure	2030	2040	2050	Remarks
Wake energy retrieval	0%/flight	1%/flight	2%/flight	Flights from Europe to North-America
	0%/flight	0.08%/flight	0.38%/flight	Other flights

Expenditure assessment

In Adler et al. (2023) the investments for ATM improvements are based on the European ATM Master Plan 2020 Edition Business View chapter (SESAR JU, 2019a). As the ATM improvements in this report are also based on the European ATM Master Plan 2020 Edition, the numbers are considered to still be valid.

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[87] For example, adverse weather conditions in addition to the already investigated wind fields.

[88] This leads to 2.5% × 0.4 = 1% / flight and to 2.5% × 0.8 = 2% / flight for flights above the North Atlantic Ocean.

[89] This leads to 2.5% × 0.03 = 0.075% / flight and to 2.5% × 0.15 = 0.38% / flights.

4.4.3 Ground operations at airports

Reduced Engine Taxiing

Reduced, or single-engine taxiing is a procedure which is already largely implemented to save fuel. The thrust to move the aircraft during the taxi phase at the airport is generated by only one engine (in the case of a two-engine aircraft) [90]. When certain situations or procedural requirements do not allow reduced engine taxiing, such as low visibility, strong winds or specific taxi routes, taxiing is performed with all engines.

Compared to the first edition of the DESTINATION 2050 roadmap report, this updated edition refines the method of taxi fuel burn calculation to estimate the impact of alternative taxiing solutions. Rather than relying on empirical data, taxi burn has now been modelled based on historical taxi times by EUROCONTROL (2019a) and the ICAO/EASA Emissions Databank (ICAO; EASA) for a schedule of planned flights for the year 2019. The outcome is that the taxi fuel burn compared to the whole mission fuel burn is 6.3% for regional aircraft, 5% for small- and medium-range aircraft and 1.3% for long-haul aircraft. These numbers are inserted in the calculations[91].

For reduced engine taxiing, the improvement potential of 30% for arriving and 35% for departing aircraft from the DESTINATION 2050 Roadmap is maintained. As it is a common practise, it is assumed that 40% of all flights already perform reduced engine taxiing and that the share will rise to 80% [92] in 2030. This yields a reduction in mission-level fuel consumption for short-haul taxi-out of 0.42% and taxi-in of 0.24%. For long-haul, the values are smaller because of the lower share of taxi fuel compared to mission fuel. Long-haul taxi-out reductions are 0.14% and taxi-in reductions are 0.03%.

Table 32: Potential CO_2 emission reductions to be delivered by reduced engine taxi, SH stands for short-haul and LH for long-haul flights

Measure	2030	2040	2050	Remarks
Reduced engine taxi – SH	0.42%/flight	0.42%/flight	0.42%/flight	From taxi-out
Reduced engine taxi – LH	0.14%/flight	0.14%/flight	0.14%/flight	From taxi-out
Reduced engine taxi – SH	0.24%/flight	0.24%/flight	0.24%/flight	Intra-EU+ arrivals only
Reduced engine taxi – LH	0.03%/flight	0.03%/flight	0.03%/flight	Intra-EU+ arrivals only

Electric taxi - Operational towing

Already in 2014, the first commercial flights were operated from Frankfurt Airport with a TaxiBot – a vehicle that carries out operational towing of the aircraft during the taxi phase. In 2020, Amsterdam Airport Schiphol performed trials with a TaxiBot finding fuel savings of 50-65% compared to the standard taxiing procedure (Bresser & Prent, n.d.). Taking advantage of operational towing, the aircraft's engines do not need to be used for taxiing which saves fuel onboard the aircraft. However, an engine-warm up time of a few minutes close to the runway remains necessary. Meanwhile, TaxiBots have been certified by EASA for the Boeing 737 Classic and Next Generation-series, as well as for the Airbus A320 Family (TaxiBot, 2023). The vehicle uses a hybrid combination of electric and diesel engines – and a full electric version is under development. During the taxi-phase, the pilot is in control of the steering of the TaxiBot.

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[90] In the case of an aircraft with three or four engines a subset of them can be turned off during taxiing.

[91] The possible weight savings from the reduction of taxi-in fuel were calculated and are found to be 10kg for short-haul respectively 17kg for long-haul flights. As the weight savings for reduced engine taxiing have not been modelled previously, these low possible savings justify to be of negligible influence.

[92] The 80% limit is set for safety to prevent for example single-engine jet blast.

For operational towing, the additional benefit on top of the reduced engine taxiing is evaluated. For short-haul flights 0.96% taxi-out and 0.72% taxi-in improvements can be achieved by 2035. For long-haul, there is a 0.32% taxi-out and a 0.1% taxi-in improvement. As the taxi-in fuel does not need to be carried, an additional weight saving is modelled using 3.5% cost of weight per block hour. The implementation of operational towing is foreseen to take place between 2025 and 2035, the 2030 value is estimated with half of the improvements.

Table 33: Potential CO_2 emission reductions to be delivered by operational towing, SH stands for short-haul and LH for long-haul flights

Measure	2030	2040	2050	Remarks
Electric taxi / operational towing – SH	0.48%/flight	0.96%/flight	0.96%/flight	From taxi-out
Electric taxi / operational towing – LH	0.16%/flight	0.32%/flight	0.32%/flight	From taxi-out
Electric taxi / operational towing – SH	0.36%/flight + 14.5 kg weight saving	0.72%/flight + 29 kg weight saving	0.72%/flight + 29 kg weight saving	Intra-EU+ arrivals only, weight saving modelled using 3.5% cost of weight per block hour
Electric taxi / operational towing – LH	0.05%/flight + 26 kg weight saving	0.1%/flight + 52 kg weight saving	0.1%/flight + 52 kg weight saving	Intra-EU+ arrivals only, weight saving modelled using 3.5% cost of weight per block hour

> **ELECTRIC FRONT WHEEL**
> Other than the TaxiBot, electric motors in the nose wheels are developed to save fuel during taxiing (SAFRAN, 2023a; SAFRAN, 2023b; WheelTug, 2023). The advantages are an increased manoeuvrability and that no additional towing trucks are driving on the taxiways. But there is a penalty by the additional weight which needs to be carried during the flight leading to a higher in-flight fuel consumption. Therefore, a trade-off in terms of cost- and climate impact needs to be made and it seems like only the implementation on regional aircraft is beneficial due to their relatively long taxi times compared to the total flight time (van der Sman, et al., 2023). Also, the additional complexity and the integration of such a system need to be taken into account. Therefore, and as the TaxiBot seems to be earlier ready for operation, this concept is not considered as an operational measure in DESTINATION 2050.

Stationary power and ventilation

Electricity supply and supply of preconditioned air (PCA) to stationary aircraft can enable a reduced usage of the APU and thus less fuel burn. For other functions such as the engine start, the APU will remain necessary. The necessary infrastructure is already available at several airports[93]. When ground power units (GPUs) with a diesel generator are used, there are still CO_2 emissions released into the air. The use of battery-powered or green hydrogen GPUs reduces these CO_2 emissions[94].

The Regulation for the Deployment of Alternative Fuels Infrastructure (AFIR) (European Council, 2023a) requires the supply of electricity from 2025 on for aircraft at the gate and from 2030 at remote stands. It is also specified that from 2030 on the electricity should come from the grid or should be generated on-site without fossil resources. AFIR does not require the supply of preconditioned air which, depending on local weather and temperature, maintains the reliance on running the APU. The Trans-European Transport Network (TEN-T) (EP & CEU, 2024) includes the obligation for the Member States to ensure that airports of the core network (by end of 2030) and comprehensive network (by end of 2040) with more than four million passengers to provide pre-conditioned air supply (PCA) to stationary aircraft at aircraft contact stands[95].

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[93] In a survey by ACI Europe in 2018 with responses from 51 airports (including half of the busiest airports) 82% of the responding airports provide fixed electrical ground power and 58% of respondents provide pre-conditioned air (EEA, EASA & EUROCONTROL, 2019).

[94] As this energy is directly supplied to the airplane, it is in scope for the DESTINATION 2050 roadmap review.

[95] PCA for remote stands falls under another Article in the TEN-T regulation and has no implementation timeline.

According to the UK Department for Transport (2017), APU fuel burn makes up 1% of the whole mission fuel burn. The provision of external ground power and PCA is found to reduce the emissions by 40% (ATAG, 2015) respectively 47.6% (Padhra, 2018). As several airports already installed the necessary infrastructure[96] and as it is used by airlines, the improvement potential is estimated to be 0.3% per flight. The emission saving depends heavily on the source of the supplied electricity – whether it is from the grid, or in the most optimistic case completely from renewable electricity. This anticipated to be realised before 2030 and this is noted in Table 34.

ICAO LTAG (2022e) states much higher numbers with around 2.2% emission reductions per flight and a slower implementation timeline. For Europe, the 0.3% before 2030 is seen as more realistic as the implementation of electrical ground power and PCA supply is already more advanced.

Table 34: Potential CO_2 emissions reduction to be delivered by stationary power and ventilation

Measure	2030	2040	2050	Remarks
Reduced APU usage	0.3%/flight	0.3%/flight	0.3%/flight	

Expenditure assessment

Compared to the first edition of the DESTINATION 2050 roadmap the traffic is updated. For “Reducing APU usage by providing ground power and pre-conditioned air” the investment needs are updated with the growth factor 0.9% p.a. which was formerly 0.8%. The utilisation efficiency improvement is kept at 0.4%. What changed in the meantime is that the provision of pre-conditioned air and electrical ground power will be mandatory under TEN-T and the AFIR-regulation.

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[96] Around half of the gates and stands are already equipped with ground power facilities and in 2018 around 27% are equipped with PCA infrastructure (Adler, et al., 2023).

4.5 Results and conclusions

Decarbonisation impact

The CO_2 reduction potential of each individual measure either stays constant or increases over time as the measure will be implemented on larger scales and the needed innovations will reach higher maturity levels. In the modelling, the improvements from operations are applied once the demand reduction and the aircraft and engine technology improvements have been subtracted from the baseline scenario CO_2 emissions. This approach follows the logic that new aircraft with lower emissions are first introduced to the market and then operated. Also, flights that do not take place due to demand reduction do not need air traffic management and operations. Applying the improvements from the decarbonisation measures from Section 4.4 to the flights that take place including improvements in aircraft and engine technology, the average CO_2 emission reduction per flight lies at 7.8% in 2030, at 9.5% in 2040 and 11.6% in 2050. In absolute numbers, the CO_2 emissions savings by improvements in operations grow from 14 Mt CO_2 in 2030 to 16.5 Mt CO_2 in 2040 and will be 19 Mt CO_2 in 2050.

To compare the improvement from ATM and operations with the other pillars, the absolute CO_2 emission savings are evaluated for the whole network with respect to the baseline scenario emissions without any improvements. In this case, the improvements in ATM and aircraft operations lead to a CO_2 emission reduction of 6.7% (rounded to 7%) in 2030, 6.6% (rounded to 7%) in 2040 [97] and 6.4% (rounded to 6%) in 2050 which is visualised in Figure 16.

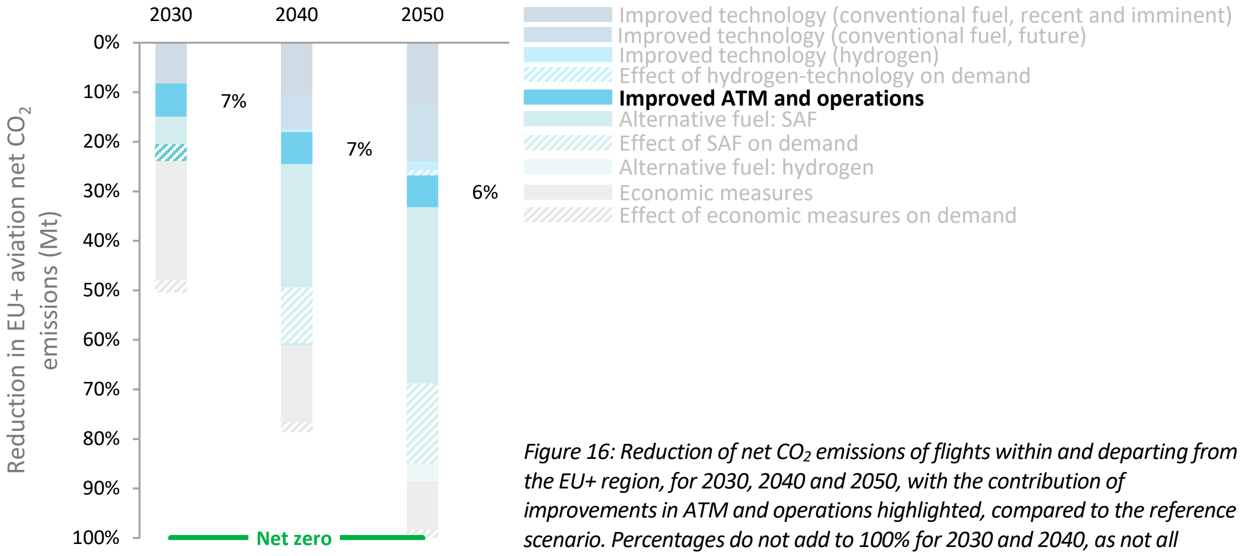

Figure 16: Reduction of net CO_2 emissions of flights within and departing from the EU+ region, for 2030, 2040 and 2050, with the contribution of improvements in ATM and operations highlighted, compared to the reference scenario. Percentages do not add to 100% for 2030 and 2040, as not all emissions are neutralised in these years.

Expenditure impact

The assumption from The Cost of Net Zero (Adler, et al., 2023) that the costs for the airline operations decarbonisation measures can be covered by the cost reductions of fuel burn savings is retained. The costs for the period 2018-2030 of Single European Sky and SESAR costs is scaled by 11/12 to account for the baseline change from 2018 to 2019 leading to €24 bn. The costs for non-European ATM efficiency improvements use the updated improvement potentials (1.5% for non-European ATM efficiency improvement and 5.7% for intra-EU+ SESAR improvements) leading to €6.3 bn until 2050.

For operational towing, the assumptions are kept the same and the traffic is updated. This leads to €4.4 bn for on short-haul flights and €0.8 bn on long-haul flights. For fixed electrical ground power (FEGP) and mobile electrical ground power (e-GPU), the costs are estimated to be €0.7 bn and for pre-conditioned air €1.4 bn.

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[97] The numbers for 2040 were estimated in Section 4.4 but not explicitly modelled as there is no big deviation from a linear interpolation of the 2030 and 2050 numbers.

This leads to total expenditures for improvements in ATM and operations of €37.6 bn. For the proportion between baseline and premium, the same assumptions as in The Cost of Net Zero (Adler, et al., 2023) are used: expenditures for ground operations are counted as premium and 50% of the ATM costs are premium under the assumption that the half of the investments for (SES)AR and non-European efficiency improvements would have to occur anyway. The premium costs are hence €22.5 bn and the baseline costs €15.1 bn.

Conclusions

Currently, improvements in ATM and operations are in full swing with innovations being deployed and research for new innovations being in progress. In comparison to the other pillars, improvements in ATM and operations can be implemented relatively fast. This enables the avoidance of fuel burn and CO_2 emissions on the short-term and has a continuous effect on the long term. In ATM, the optimal trajectory forms a limit for the absolute improvement potential, and no improvements better than that are achievable on a single flight basis, however network effects need to be taken into account. Certain inefficiencies cannot be reduced due to safety, accommodation of traffic growth and capacity constraints.

The largest improvement potential comes from the Single European Sky and the SESAR research programme which investigates and prepares the ATM innovations for tomorrow. A true Single European Sky would further increase possibilities to optimise both each individual flight trajectory and the whole network to minimise the CO_2 emissions. Continued effort beyond 2035 is essential for further decarbonisation.

Many different stakeholders contribute to the advancements in aircraft operations and reduced CO_2 emissions making it a collaborative effort: airlines, ANSPs, airports, technology providers, maintenance companies, researchers, aircraft and engine manufacturers, policy makers etc.; an implementation of available improvements from new technologies or new ideas of operational concepts create the largest benefit when applied industry-wide. New operational strategies and concepts, such as improved North Atlantic flights, wake energy retrieval and operational towing, are or will be enabled by newest technology. These are some of the examples that show where future development and improvement pathways could lead.

4.6 Implications

Solid and sound policies need to support and foster the decarbonisation activities in ATM and operations where the fuel burn reduction with induced cost saving is not enough of a driver. The combined effort of all stakeholders will need financial support to safeguard the ambitious targets of necessary CO_2 reductions.

Implications for airline operations

To minimise the environmental impact of air travel, further development and improvement of flight planning software is necessary, making it available to even more airlines. This software should be utilised by all airlines to fly or at least request optimal, constrained trajectories, reducing fuel consumption and emissions. Reducing CO_2 emissions can be achieved by reducing nominal speeds to long range cruise speed. Rising fuel prices and the associated costs of economic measures help to align fuel burn reductions and cost optimalisation.

Additionally, the practice of economic tankering will be stopped, except in cases justified by ReFuelEU Aviation guidelines, to reduce unnecessary fuel consumption and reduce emissions. Continuous improvement in operational aircraft efficiency is important, where airlines should maintain best practices in weight reduction, airframe condition, and maintenance, and develop new innovative solutions to further minimise the CO_2 emissions.

Implications for airspace and air traffic management (ATM)

The Single European Sky as an ambitious and meaningful airspace reform and the SESAR programme need to be further pursued as they hold a big potential for efficiency improvements from optimum (unconstrained) flight routings, efficiency improvements from the network, mitigating disruptions and significant CO_2 emission reductions. Within the Single European Sky, performance should be consistently addressed across R&D, deployment, performance, and charging schemes. This requires the development of environmental indicators that not only monitor performance improvement per flight but also the total emissions in the network. Further research on performance monitoring should be undertaken to develop better indicators.

The European ATM Master Plan 2025 Edition outlines an expected efficiency improvement of a 9.3% reduction in fuel burn per flight by 2050. To achieve this goal and having benefits on the short term, it is important that all stakeholders work in a collaborative manner to support timely implementation of the ATM Master Plan objectives to enable deployment of identified and future SESAR solutions and enabling technologies. Their effectiveness should be continuously monitored based on real CO_2 emission savings.

The European Union should prioritize continued SESAR funding beyond 2027. Furthermore, ATM efficiency improvements should be supported globally. Continued investment in the development and fast deployment of SESAR solutions, air traffic management systems and flight planning systems is recommended.

An expanded civil-military coordination on a European level would enable military training without compromising on civil airspace users' needs. Airlines should make use of the new flight planning possibilities above the North Atlantic Ocean. Additionally, collaboration should continue to make wake energy retrieval operationally possible, driving sustainable aviation forward.

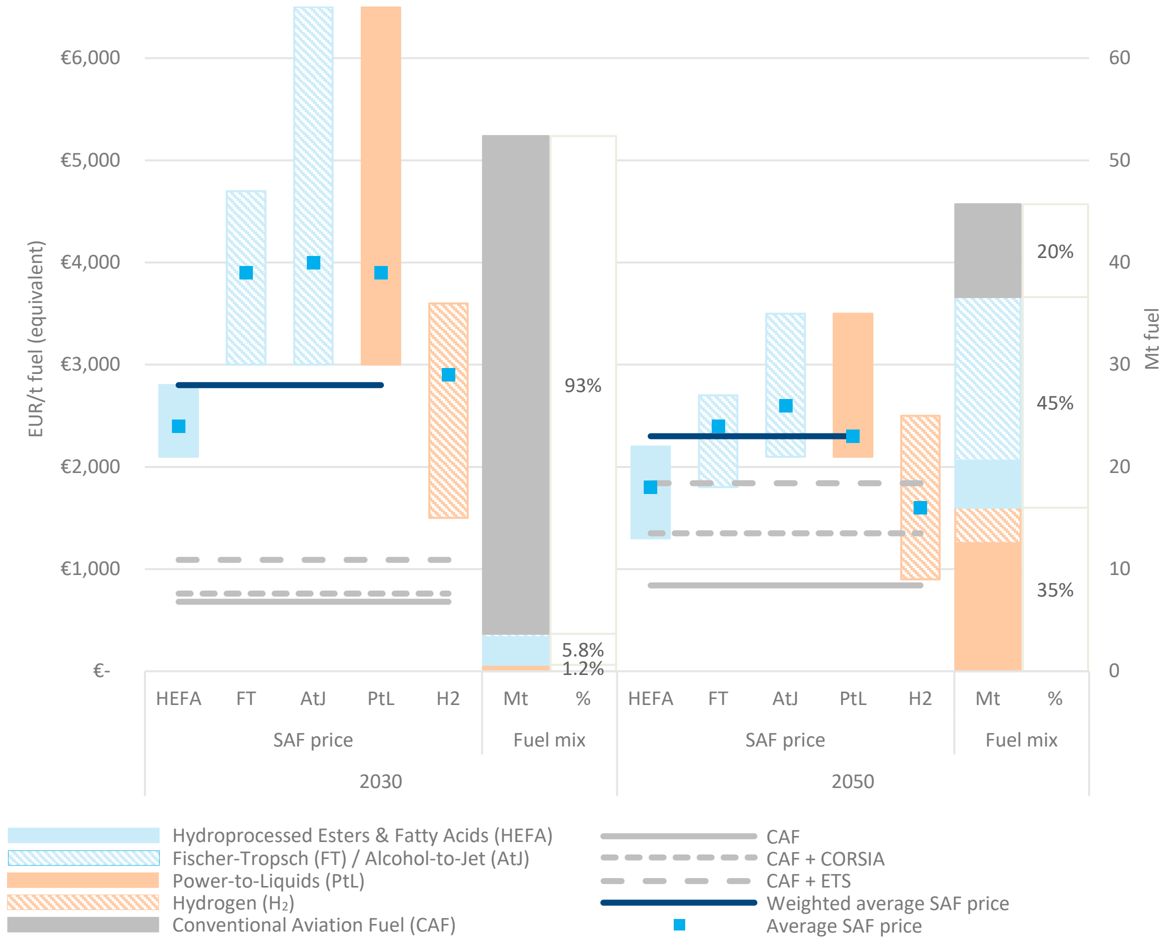
Implications for ground operations at airports

Reduced engine taxiing should be encouraged or even enforced to reduce fuel consumption and emissions of the taxi phase. Additionally, operational towing trucks should be implemented at airports to further decrease fuel burn and emissions. To support the adoption of operational towing, a solid business case should be developed, highlighting the benefits and cost savings of this practice. Moreover, diesel-powered ground power units (GPUs) should be replaced with green hydrogen GPUs or battery-powered GPUs that utilise renewable electricity or, at a minimum, electricity from the grid. The use of pre-conditioned air at airports should be further encouraged, reducing reliance on the APU and promoting a more sustainable and healthier ground handling operation.

5 Alternative fuels and sustainable energy

Using alternative fuels contributes the most to net zero CO$_2$ by 2050

1 The modelled average **price of SAF is projected to go down** over time, while its **uptake increases**



The price ranges reflect the price uncertainty.

2 There is a **high reliance on carbon capture technologies**, for synthetic SAF production and reducing emissions of the combustion from conventional aviation fuel

3 **SAF will remain more expensive; policy support** is therefore crucial for **encouraging its uptake and production,** as well as for **reducing the price gap** compared to the other sustainability measures in the report

Through to 2050 the cumulative premium expenditure for SAF and hydrogen over CAF is estimated at **€786 bn**

To realise net zero CO$_2$ by 2050,
joint actions are needed by industry and government that must be coordinated and decisive

1 **Scale up SAF production and renewable energy deployment**

2 **Further develop carbon-capture technology**

3 **Enhance support to encourage SAF uptake**

The emission reductions shown are compared to a hypothetical scenario with no measures implemented, assuming a 1.4% annual increase in flight movements, and considering the effects of reduced demand due to increased costs.

5.1 Introduction

This chapter presents all alternative fuels and sustainable energy carriers used to decarbonize aviation in the period between 2019 and 2050. The majority of the emission reductions will be obtained by using Sustainable Aviation Fuel (SAF) and hydrogen.

On the next pages, Section 5.2 first discusses notable developments since the first edition of the DESTINATION 2050 roadmap report was published in February 2021. Section 5.3 then outlines the approach taken for the current report, with Section 5.4 and Section 5.5 detailing the approach further. Section 5.6 describes the global SAF uptake, and Section 5.7 details the price developments of aviation fuels from now till 2050. This is followed by Section 5.8, which presents modelling results and conclusions, regarding the contribution of SAF and hydrogen to the overall decarbonisation of European aviation. Closing this chapter, Section 5.9 presents implications regarding alternative fuels and sustainable energy.

Scope and relation to other pillars

This chapter discusses the decarbonisation potential of alternative fuels, the expected SAF and hydrogen supply, the availability of feedstocks, pricing, the current policy measures and potential future developments. The technical challenges associated with using SAF above the current certification limits are treated in Section 7.3.4. The technical and economic aspects of using hydrogen-powered aircraft are addressed in Section 3.4.2.

> **RELEVANCE TO NON-CO_2 CLIMATE IMPACT OF AVIATION**
> The chemical composition of the fuel has an influence on the emissions, in particular the amount of particulate matter, and therefore the non-CO_2 climate effects. Changing the chemical composition by lowering the level of aromatics can have positive effects on contrail formation and air quality around airports. Research is currently ongoing in this field. The industry is currently working on developing a new standard without aromatics. More details are provided in Section 7.3.4.

Definitions

In this edition of DESTINATION 2050, a fuel is considered SAF when it adheres to the following two principles:

1. **Certified Synthetic Blend Component**. The produced fuel is certified according to ASTM D7566, this specification covers the manufacture of aviation turbine fuel that consists of conventional and synthetic blending components (SBCs) (ASTM, 2024a). This specification includes the most widely used production processes (sometimes referred to as ‘pathways’) to produce SBCs, it includes, for example, Hydroprocessed Esters and Fatty Acids (HEFA), Fischer-Tropsch (FT) and Alcohol-to-Jet (AtJ) amongst others. See Appendix D.4.3.1 for an overview of accepted productions processes with their specifications.

> **DROP-IN FUEL**
> Aviation turbine fuel manufactured, certified, and released to all the requirements of specification D7566, meets the requirements of Specification D1655 and shall be regarded as Specification D1655 turbine fuel, which is considered a “drop-in” fuel. Fuel that meets Specification D1655 is considered conventional aviation fuel, e.g., Jet A or Jet A-1 (ASTM, 2024b).

2. **Meets sustainability criteria.** When an SBC is produced from (approved) waste streams and/or renewable feedstocks, it can achieve reductions in greenhouses gas (GHG) emissions over its life-cycle when compared to fossil resources-based aviation fuel. This benefit is achieved through emission reductions upstream in the value chain, i.e., the uptake of CO_2 from the atmosphere during feedstock growth/production. In order to be classified as SAF, SBCs must meet sustainability standards set by CORSIA on a global level, and sustainability standards set by the European Renewable Energy Directive (RED III per 1 January 2025) for use in the EU.

SAF = Synthetic Blend Component (ASTM D7655) + Sustainability Criteria (EU RED III)

Figure 17: Definition of SAF for DESTINATION 2050

In this edition of DESTINATION 2050 the following definitions for aviation fuels are followed:

- Aviation fuel is drop-in fuel manufactured for direct use by conventionally-fuelled aircraft.
    - Conventional aviation fuel (CAF):
        - Fuels produced from fossil non-renewable sources of hydrocarbon fuels;
    - Sustainable aviation fuels (SAF) are:
        - Synthetic SAF:
            - Renewable fuels of non-biological origin, as defined by the RED III. Such as fuels produced from CO_2.
            - Hydrogen shall also be regarded as a synthetic SAF, even though it cannot be used in conventionally-fuelled aircraft, since it can be used to fulfil the synthetic aviation fuel minimum share of the ReFuelEU Aviation regulation.
        - Non-synthetic SAF:
            - Renewable fuels of biological origin, as defined by the RED III (specified as (advanced) biofuels). Such as fuels produced from biomass.

5.2 Developments since the initial roadmap

Since the launch of the first edition of the DESTINATION 2050 roadmap report, the worldwide SAF policy and regulatory landscape has gained momentum, by developing the necessary foundations for long-term investment security in SAF. The EU adopted the ReFuelEU Aviation regulation and the US launched the SAF Grand Challenge. ICAO adopted the long-term aspirational goal of net zero CO_2 emissions by 2050 based on a detailed assessment of measures which include a strong reliance on SAF, as it is currently the only solution for long haul flights. The decarbonisation potential of SAF therefore remains undisputed. In Europe, hydrogen also remains a key enabler for aviation decarbonisation with the inclusion of renewable hydrogen in the ReFuelEU aviation mandate.

To ensure that future SAF supply can reach and exceed the mandated levels, a smooth implementation of ReFuelEU is necessary. The current actions, taken by both the industry and governments in the EU, focus on the actual implementation of national regulations. To prepare for SAF scale up, the industry is undertaking actions to demonstrate the technical feasibility of increasing the blending limit from 50% (for most SAFs) to 100%.

This timeline distinguishes between **developments in government and policy**, **industry progress** and **joint actions**.

02/2021: Launch of the DESTINATION 2050 alliance and the first European Aviation Net-Zero roadmap

09/2021: SAF Grand Challenge (U.S. Department of Energy, 2024)

DOE, DOT, and USDA launching a government-wide Memorandum of Understanding (MOU) to meet the following goals:

- Achieve 3 billion US gallons per year of domestic SAF production that achieve a minimum of a 50% reduction in life-cycle GHG emissions compared to conventional fuel by 2030;
- Supply sufficient SAF to meet 100% of aviation fuel demand by 2050.

11/2021: Airbus A350 flies on 100% SAF (Airbus, 2021c)

In a consortium including Airbus, Rolls-Royce and DLR, an Airbus A350 was operated using 100% SAF (Airbus, 2021c). Emissions measurements taken in flight suggest a positive impact of SAF on non-CO_2 climate impact, as particular matter emissions were reduced.

04/2022: ICAO ACT-SAF (ICAO, 2024c)

The ICAO Assistance, Capacity-building and Training for Sustainable Aviation Fuels programme (ACT-SAF) is an initiative aimed at facilitating ICAO Member States' development and deployment of sustainable fuels. ACT-SAF will incorporate tailored support for States, which may comprise feasibility studies, policy and regulatory developments, and specific SAF implementation projects. ACT-SAF will also provide a targeted platform to encourage knowledge sharing and recognition of all SAF initiatives.

04/2022: ICAO LTAG report (ICAO, 2022e)

CAEP formed the Long-Term global Aspirational Goal Task Group (LTAG-TG) to provide technical analyses of future international aviation CO_2 emission trajectories up to 2070 with the aircraft technologies, operations and alternative fuels associated with varying future scenarios. Publication of the report includes a detailed appendix M5 on fuels. (ICAO, 2022e).

06/2022: RLCF alliance (Directorate-General for Mobility and Transport, 2023)

The Renewable and Low-Carbon Fuels Value Chain Industrial Alliance is a new initiative that focuses on boosting production and supply of renewable and low-carbon fuels in the aviation and waterborne sectors.

08/22 Inflation Reduction Act (IRA) of the Biden administration is signed into law (IRS, 2023)

The IRA aims to curb inflation by investing in domestic energy production while promoting clean energy, amongst other things. The IRA includes an incentive for SAF in the form of a SAF credit, applicable to SAF with at minimum reduction 50% lifecycle GHGs.

10/2022: 41st ICAO Assembly adopts LTAG for international aviation of net zero carbon emissions by 2050

ICAO Member States adopt a collective long-term global aspirational goal (LTAG) of net zero carbon emissions by 2050 (ICAO, 2022). The increased production and deployment of SAF is one of the key measures to achieve this goal.

11/2022: UK RAF's Voyager aircraft flies on 100% SAF (UK Government, 2022)

First 100% SAF flight conducted in the UK with a RAF's Voyager aircraft, using Rolls-Royce Trent 700 engine, performing a 90-minute flight.

03/2023: Airbus A321neo flies on 100% SAF (Airbus, 2023a)

Following the earlier 100% SAF flight of an Airbus A350, Airbus also operated an A321neo on 100% SAF as part of the VOLCAN project. Again, in-flight emission measurements were taken by DLR.

18/04/2023: CBAM

Carbon Border Adjustment Mechanism imposes a levy on certain emission-intensive imports into the EU. This may impact the import of hydrogen and electricity, therefore the import prices.

18/04/2023: EU ETS reform SAF allowances

20 million EU ETS allowances become available from the 1st of January 2024. These allowances can be used to support up to a 100% of the cost difference between SAF and conventional aviation fuel.

10/2023 Final ReFuelEU Aviation Regulation

In 2021, the European Commission presented its first proposal of a draft regulation. After a number of amendments and negotiations, the final act was adopted by the Council on the 9th of October 2023 and signed on the 18th of October 2023.

24/11/2023: ICAO CAAF/3

Global Framework for SAF, LCAF and other Aviation Cleaner Energies. The framework includes a 5% emission reduction target by 2030 through the use of cleaner energy sources. It also contains provisions to avoid double counting of the emission reductions derived from the use of cleaner energies.

11/2023: EU ETS Innovation Fund call open for SAF production support

The 2023 Innovation Fund call for proposals opened with a budget of €4 bn to support the deployment of innovative decarbonisation technologies. The call was funded by revenues from the EU Emissions Trading System (EU ETS). Projects were assessed based on their potential to reduce greenhouse gas emissions, their degree of innovation, maturity, replicability and cost efficiency. The Innovation Fund can cover up to 60% of a project's relevant costs.

22/04/2024: EASA Aviation Fuel Stakeholder Forum (EASA, 2024a)

EASA hosted the first EU Aviation Fuel Stakeholders Forum on April 18-19, 2024. The event marked the launch of a network of European fuel stakeholders to strengthen cooperation in Europe, with the aspiration of optimising the jet fuel composition to respond to environmental challenges.

28/11/2023: World's first commercial airline transatlantic flight on 100% SAF (Brogan, 2023)

The Virgin Atlantic Boeing 787 with Rolls-Royce Trent 1000 engines flew from London Heathrow to New York. This is the first flight to showcase the feasibility of flying on 100% SAF over such a distance.

24/04/2024: IATA Net Zero Roadmap Comparative Review

The study compares 14 leading net zero CO_2 transition roadmaps for aviation. All roadmaps assume that SAF will be responsible for the greatest amount of CO_2 reductions by 2050. The role of SAF varies from 24%-70%, reflecting the uncertainties in scaling up the sector, depending on several aspects.

25/04/2024: UK SAF mandate (UK Department for Transport, 2024)

The government has confirmed new targets to ensure 10% of all jet fuel in flights taking off from the UK comes from sustainable sources by 2030 through its Sustainable aviation fuel mandate.

06/06/2024: ECLIF3 results (Airbus, 2024)

In-flight measurements from an A350 aircraft using 100% sustainable aviation fuel (SAF) show a significant reduction in soot particle emissions and formation of contrail ice crystals compared to using conventional aviation fuel Global model simulations estimate 26% reduction in contrails' climate impact when using 100% SAF.

ReFuelEU Aviation

The ReFuelEU Aviation regulation is a comprehensive policy proposal with the aim to boost the supply and demand for SAF in the EU till 2050. The proposed rules set a mandate for fuel suppliers to gradually increase the share of SAF that they distribute at EU airports, and set an anti-tankering policy for aircraft operators. This section aims to give a brief overview of the most important elements of ReFuelEU Aviation.

Table 35: Minimum share of SAF, including synthetic aviation fuel, according to ReFuelEU Aviation

Fuel mix	**2025**	**2030**	**2035**	**2040**	**2045**	**2050**
SAF (minimum share)	2.0%	6.0%	20.0%	34.0%	42.0%	70.0%
Synthetic aviation fuels (minimum share)	0.0%	1.2%	5.0%	10.0%	15.0%	35.0%
SAF (remainder)	2.0%	4.8%	15.0%	24.0%	27.0%	35.0%
Conventional aviation fuel	98.0%	94.0%	80.0%	66.0%	58.0%	30.0%
Total	**100.0%**	**100.0%**	**100.0%**	**100.0%**	**100.0%**	**100.0%**

- As stated in Article 4 “[..] aviation fuel suppliers shall ensure that all aviation fuel made available to aircraft operators at each Union airport contains the minimum shares of SAF, including the minimum shares of synthetic aviation fuel [..]”. The minimum shares of SAF according to ReFuelEU Aviation shall increase as shown in Table 35.
- As stated in Article 15 “[..] from 1 January 2025 until 31 December 2034, for each reporting period, an aviation fuel supplier may supply the minimum shares of SAF defined in Annex I as a weighted average over all the aviation fuel it supplied across Union airports for that reporting period.”
- As stated in Article 5 “The yearly quantity of aviation fuel uplifted by a given aircraft operator at a given Union airport shall be at least 90 % of the yearly aviation fuel required.” This is notwithstanding fuel safety rules. This prevents that airlines fuel their planes at airports outside of the EU to avoid increased fuel costs due to SAF blending.
- To ensure the SAF blending mandate and the uplifting obligation are met, non-compliance penalties are defined, as stated in Article 12:
  - “[…] any aircraft operator that fails to comply with the obligations laid down in Article 5 is liable to a fine. That fine shall be proportionate and dissuasive and not less than twice as high as the amount resulting from the multiplication of the yearly average price of aviation fuel per tonne by the total yearly non-tanked quantity.”
  - “[…] any aviation fuel supplier that fails to comply with the obligations laid down in Article 4 relating to the minimum shares of SAF is liable to a fine. That fine shall be proportionate and dissuasive and not less than twice as high as the amount resulting from the multiplication of the difference between the yearly average price of conventional aviation fuel and SAF per tonne by the quantity of aviation fuels not complying with the minimum shares [..]”
  - “[…] any aviation fuel supplier which has accumulated a shortfall from the obligation laid down in Article 4 relating to the minimum shares of SAF or of synthetic aviation fuels in a given reporting period, shall supply the market in the subsequent reporting period with a quantity of that respective fuel equal to that shortfall, in addition to their reporting period obligation. “
- As stated in Article 9 “Aircraft operators shall not claim benefits for the use of an identical batch of SAF under more than one greenhouse gas scheme.”, i.e., the environmental benefits can be used either for the EU ETS for intra-EU flights *or* for the Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA) for extra-EU flights.
- As stated in Article 13 “[…] The Agency shall publish every year a technical report [..] That report shall contain at least the following information […] the average total content of aromatics and naphthalenes by percentage volume and of sulphur by percentage mass in aviation fuel supplied [..]” Fuel suppliers will have to report details regarding the composition of the delivered fuel to authorities of Member States. Fuel composition data is useful information for improved understanding and quantification of the non-CO_2 effects, as explained in Chapter 7.

5.3 Approach

The approach for identifying the decarbonisation potential of sustainable fuels is given for the short term, up to 2030, in Section 5.4, and the long term, up to 2050, in Section 5.5. For 2030 the supply of SAF is based on the (announced) production capacity for SAF, as described in Section 5.4.1. To determine the demand for SAF the ReFuelEU Aviation regulation is taken as a basis, but additional SAF uptake is expected based on voluntary SAF targets, as described in Section 5.4.2. Finally, the feasibility of meeting the demand is analysed, according to modelling performed in this edition of DESTINATION 2050, in Section 5.4.3. For 2050 the demand for SAF is initially determined based on the ReFuelEU Aviation regulation, and adjusted based on availability of feedstock, energy requirements and reliance on various technologies (SAF production technologies and carbon removal technologies), as described in Section 5.5.1. This gives a more balanced approach to fulfilling demand, relying on non-synthetic SAF and synthetic SAF in combination with carbon removal technologies. Subsequently various options are explored that could contribute to additional SAF uptake in 2050, above the target share set by the ReFuelEU Aviation regulation, in Section 5.5.2. Finally, the availability of synthetic aviation fuels and hydrogen is analysed in Section 5.5.3.

The global SAF uptake is explored in Section 5.6, and followed by an analysis of 2030 and 2050 (market) pricing of alternative fuels and sustainable energy in Section 5.7.

5.4 2030 decarbonisation potential

On the short term, the aviation sector will rely on drop-in sustainable fuels, as new aircraft types with alternative propulsion systems based on (renewable) hydrogen, or battery-electric, have not yet entered the market, see also Section 3.4.2. Thus, the main contributor to the achieving carbon emissions reductions, and complying with the ReFuelEU Aviation regulation is SAF. This section assesses the supply of SAF for 2030, based on announced European production facilities for the various production technologies, as done by SkyNRG in their SAF Market Outlook and the sub-mandate for synthetic aviation fuels.

The ReFuelEU Aviation regulation mandates a minimum of 6% SAF use in 2030, with a minimum of 1.2% synthetic aviation fuel. Given that the mandate will be leading, and is expressed in percentage of fuel use, this study will also express the share of sustainable fuels in percentages.

5.4.1 SAF availability

According to the SAF Market Outlook (SkyNRG, 2023; SkyNRG, 2024), the total SAF production within Europe, based on announcements, will reach 3.8 Mt by 2030. Since not all production facilities that will be operational in 2030 are announced yet, SkyNRG expects production capacity to grow to 4.0 Mt SAF in 2030, with a majority relying on the HEFA technology, at 2.7 Mt, 0.6 Mt of FT or AtJ-based SAF and 0.6 Mt of PtL-based SAF and 0.1 of co-processing-based SAF. Previous versions of the SAF Market Outlook suggested that the EU+ capacity could grow to 4.5 Mt, with a higher share of FT and AtJ-based SAF. However, it remains uncertain if all SAF produced in Europe will be used in Europe, given that other markets, such as the US, have incentives in place for SAF use.

Argus Media and ICAO have published reports and trackers for (potential) SAF production facilities. Argus Media reports 45 SAF production facilities (planned and operational), summing all known capacities totals 3.4 Mt of SAF

(Argus Media, 2023); for most of co-processing facilities the capacity is not known/specified. Total capacity for HEFA-based SAF would amount to 1.9 Mt, for FT and AtJ-based SAF this would be 0.8 Mt and approximately 0.5 Mt of PtL-based SAF. The remainder is filled with co-processing and other SAF production technologies. However, including all co-processing capacity, the total SAF production capacity is likely higher. The ICAO SAF tracker (ICAO, 2024d) estimates the number of SAF production facilities in Europe to be 100+, as it also includes facilities that could theoretically produce SAF if modifications were made to the existing facility. Many of these facilities produce renewable fuels for road transport, but could be adapted to produce (more) SAF in the future. For most facilities, SAF will only represent a portion of the product slate. According to the ICAO SAF tracker, The Netherlands, Sweden, France, Germany, the UK and Spain combined, represent 75% of (announced) production facilities in Europe. It must however be noted that several SAF production capacity projects under development were recently halted, such as Shell's refinery in Rotterdam and bp's refinery in Germany (Reuters, 2024b; Reuters, 2024a). This might put meeting the ReFuelEU Aviation mandate at risk.

The required amount of synthetic aviation fuel is calculated based on the sub-mandate for synthetic aviation fuels under the ReFuelEU Aviation regulation. Given a 1.2% sub-mandate of the 6% overall mandate, 20% of the mandated SAF will be synthetic aviation fuel in 2030. According to the SkyNRG Market Outlook 2024 (SkyNRG, 2024), to fulfil the sub-mandate, approximately 0.6 Mt of synthetic aviation fuel is necessary. Combining Argus Media and SkyNRG's numbers for PtL-based SAF it is likely that this amount can be met.

LIFE-CYCLE EMISSIONS OF SAF

Life-cycle Analysis

A life-cycle analysis (LCA) evaluates the environmental impact of a product from the initial stage of gathering raw materials to its end use—this is called the "Well-to-Wake" (WtW) approach. The analysis identifies emissions at every stage and attributes them to the product based on specific characteristics, such as energy content.
For aviation fuels, the life-cycle is typically divided into two phases:

- Well-to-Tank (WtT): Covers all steps from raw material gathering to in-tank delivery.
- Tank-to-Wake (TtW): Refers to the combustion (use) of the fuel.

In Europe, the RED III legislation requires that any new renewable fuel facility operational after 2021 must achieve at least 65% GHG savings on a WtW basis (EC, 2018a).

Tank-to-Wake Emissions

Following the methodologies of the Greenhouse Gas Protocol (GHGP), EU ETS, and RED III, as well as guidance from the World Economic Forum (WEF), the emissions from burning sustainable fuels are considered 0 g CO2e/MJ (WEF, 2022; EC, 2018a; EC, 2003; GHGP, 2011). This equates to a 100% emission reduction in the TtW phase. This is because the CO_2 released during combustion equals the CO_2 absorbed by the feedstock during its growth or removed using carbon removal technologies. As a result, these emissions are effectively balanced out and excluded from the life-cycle assessment.

Since this study focuses on TtW emissions in aviation, all Sustainable Aviation Fuels (SAFs) discussed here provide a 100% reduction in TtW emissions.

Well-to-Tank Emissions

Emissions can still occur in the Well-to-Tank (WtT) phase. These emissions may arise during:

- Feedstock collection
- Processing of feedstock into SAF
- Transport of the final product from refinery to the airport

For non-synthetic SAFs, WtT emissions vary greatly depending on the feedstock and technology used. Prussi et al. (2021) highlight a wide range of carbon intensities based on different feedstock-technology combinations in *CORSIA: the first internationally adopted approach for calculating life-cycle GHG emissions for aviation fuels*. (Note: Fuel combustion contributes to the life-cycle assessment only when non-biogenic carbon content is present in the feedstock.)

Since this study focuses on TtW emissions, WtT emissions of SAFs (or conventional aviation fuels, CAFs) are not quantified here. However, producing more sustainable SAFs can reduce WtT emissions, further reducing emissions of the aviation sector. Reductions in WtT emissions could be achieved by integrating SAF production with Carbon Capture and Storage (CCS), and decarbonizing the transport of feedstock and final product. Additionally, decarbonizing the production process of CAF from fossil resources, referred to as Low-carbon Conventional Aviation Fuels (LCAF), can also contribute to further reducing WtT emissions of the aviation sector, in lieu of 100% SAF adoption.

> Future Outlook
> By 2050, it is expected that non-synthetic SAFs will reduce emissions by almost 100% over their complete life-cycle compared to CAF. For synthetic SAF and hydrogen, when produced from renewable energy, a 100% reduction in emissions is assumed. If this is combined with LCAF, for the non-SAF share of the fuel used, the WtT of the aviation sector could be completely reduced.

5.4.2 Additional SAF uptake above the mandate

Airlines which are part of World Economic Forum's (WEF) Clean Skies for Tomorrow Coalition have expressed their ambition to increase the worldwide SAF uptake to 10% in 2030 (WEF, 2021). Additionally, several airlines have voluntarily committed to higher SAF targets in 2030, at 10-30%, see Table 35 for a non-exhaustive list, and have submitted these to Science-Based Targets initiative for verification. These voluntary targets, set at a higher level than the ReFuelEU Aviation regulation, will create additional demand above the mandate. Since airlines operate on a global scale, it does not require them to purchase and uplift SAF within Europe, to meet their targets. In this study, the SAF uptake is increased by 1% above the ReFuelEU Aviation regulation in 2030, which totals to 7% SAF in the energy mix in 2030.

Table 36: Voluntary SAF targets set by airlines for 2030 (non-exhaustive)

Voluntary SAF target	Airline(s)
10%	Aer Lingus (Aer Lingus, 2023) British Airways, Iberia (IAG, 2021) Finnair (Finnair, 2024) Air France (Air France, 2024) KLM (KLM, 2024), Transavia (Transavia, 2024) Vueling (Vueling, 2024)
12.5%	Ryanair (Ryanair, 2024)
30%	DHL (DHL Group, 2024)

5.4.3 Feasibility of fulfilling the SAF demand

Based on the modelling in this edition of DESTINATION 2050, 52.4 Mt of fuel is required in 2030 fulfil the energy demand of the sector, see Section 5.8 for the full results. The equivalent amount of SAF necessary, at a 7% SAF share of the energy mix, is 3.7 Mt, of which 0.6 Mt is synthetic aviation fuel, see Table 37. The required amount of SAF and synthetic aviation fuel, is within range of the expected availability of SAF and synthetic aviation fuel, as estimated by SkyNRG and Argus Media, in 2030. Therefore, a 7% share of SAF in the energy mix in 2030 is considered feasible.

Table 37: Energy demand and fulfilment for 2030 as modelled in DESTINATION 2050

Fuel demand	Unit	2030	Share
Reference scenario	Mt	66.2	
Sustainability scenario	Mt	52.4	
SAF (non-synthetic)	Mt	3.1	5.8%
HEFA	Mt	2.7	
FT	Mt	0.2	
AtJ	Mt	0.2	
SAF (synthetic)	Mt	0.6	1.2%
PtL	Mt	0.6	
H_2	Mt (SAF_{eq})	0	
Conventional aviation fuel	Mt	48.7	93%

5.5 2050 decarbonisation potential

To achieve net zero for the aviation sector in 2050, the remaining fuel consumption post technological and operational improvements, can either be:

- fulfilled by using alternative energy and sustainable fuels, or
- reduced due to demand-related impact of economic measures, or
- reduced via carbon removal technologies, especially relevant for residual emissions of conventional aviation fuel.

The ReFuelEU Aviation regulation ensures a minimum of 70% sustainable fuel use in 2050, and thus a maximum of 30% reliance on carbon removal technologies. Furthermore, ReFuelEU Aviation regulation specifies a minimum of 35% synthetic SAF use in 2050, which can be fulfilled by either synthetic aviation fuel (PtL-based SAF) or renewable or low-carbon hydrogen (for use in hydrogen-based aircraft).

Based on modelling performed in this edition of DESTINATION 2050, including all improvements of other pillars result in emission reduction and their demand-related impacts, 45.7 Mt of aviation fuel is necessary in 2050. Following ReFuelEU Aviation regulation, this would equate to a minimum of 16.0 Mt of synthetic SAF, which includes 3.5 Mt SAF$_{eq}$ H$_2$ (following from the share of hydrogen-based aircraft in operation, see Section 3.4.2) [98], 16 Mt of non-synthetic SAF, and 13.7 Mt CAF. Table 38 breaks down the fuel demand in 2050, and related emission reductions to achieve net zero emissions.

Table 38 (continuous on next page): Comparison between an 80% and theoretical 70% SAF share scenario. Multiple factors influence total fuel use; however, this was modelled for 80% SAF, and based on the outcomes a theoretical 70% SAF scenario was calculated. Emission factor of 3.16 kg CO$_2$/kg aviation fuel is applied to convert fuel use to emission data

70% SAF		
Total fuel use	45.7	Mt aviation fuel
Share of SAF	70%	
Total SAF use	32.0	Mt SAF
Share of synthetic aviation fuel	35%	
Total synthetic aviation fuel	16.0	Mt SAF
Hydrogen use	3.5	Mt SAF$_{eq}$ H$_2$
Total synthetic aviation fuel (ex. H$_2$)	12.5	Mt SAF
Share of SAF (non-synthetic)	35%	
Total SAF (non-synthetic)	16.0	Mt SAF
Share of conventional aviation fuel	30%	
Total conventional aviation fuel	13.7	Mt conventional aviation fuel
Total CO$_2$ emissions (aviation fuel)	144.4	Mt CO$_2$
SAF		
Emission reduction SAF (non-synthetic)	50.6	Mt CO$_2$
Emission reduction SAF (synthetic)	39.6	Mt CO$_2$

80% SAF		
Total fuel use	45.7	Mt aviation fuel
Share of SAF	80%	
Total SAF use	36.6	Mt SAF
Share of synthetic aviation fuel	35%	
Total synthetic aviation fuel	16.0	Mt SAF
Hydrogen use	3.5	Mt SAF$_{eq}$ H$_2$
Total synthetic aviation fuel (ex. H$_2$)	12.5	Mt SAF
Share of SAF (non-synthetic)	45%	
Total SAF (non-synthetic)	20.6	Mt SAF
Share of conventional aviation fuel	20%	
Total conventional aviation fuel	9.1	Mt conventional aviation fuel
Total CO$_2$ emissions (aviation fuel)	144.4	Mt CO$_2$
SAF		
Emission reduction SAF (non-synthetic)	65.2	Mt CO$_2$
Emission reduction SAF (synthetic)	39.6	Mt CO$_2$

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[98] Tonne of SAF equivalent (t SAF$_{eq}$) is used as a unit of energy defined as the amount of energy released by burning one tonne of SAF; for SAF (non-synthetic and synthetic) this is assumed to be 44 MJ/kg, as specified in the RED III (EC, 2018a), and for hydrogen this is assumed to be 120 MJ/kg.

70% SAF		
Emissions avoided due to use of H_2	11.0	Mt CO_2
CAF		
Emissions compensated with DACCS (via economic measures)	43.3	Mt CO_2

80% SAF		
Emissions avoided due to use of H_2	11.0	Mt CO_2
CAF		
Emissions compensated with DACCS (via economic measures)	28.7	Mt CO_2

5.5.1 Non-synthetic SAF availability

According to a recent study performed by Imperial College London (ICL), the amount of biomass for bioenergy purposes from EU feedstocks ranges between 215-366 Mtoe [99] in 2050 (Panoutsou & Maniatis, 2021). The feedstocks considered cover only domestic feedstocks (EU27+UK) which are included in Annex IX of RED II (Part A and B). These feedstocks are of agricultural, forest and waste origin. It should be noted that not all eligible feedstocks under Annex IX Part A & B of RED II are considered in the ICL study. For a full comparison between considered and eligible feedstocks, see Appendix D.4.3.2. This study also indicates that approximately 56 Mtoe of biomass could be imported for bioenergy purposes (mainly agricultural and forestry residues).

The overall bioenergy availability, as presented by ICL, is very similar to ranges estimated by the European Commission (EC) impact assessment, DG RTD and JRC TIMES, see Table 39, which include similar feedstocks. The amount of bioenergy imported according to the EC is lower, at around 5% of total bioenergy usage (EC, 2020b).

Table 39: Biomass potentials (in Mtoe) for bioenergy for 2050

	Imperial College London (Panoutsou & Maniatis, 2021)		**EC Impact assessment (EC, 2021d)**		**DG RTD (EC, 2017)**		**JRC TIMES (Ruiz, et al., 2019)**	
Scenario	Low	High	Low	High	Low	High	Low	High
Biomass potential for bioenergy [Mtoe]	215	366	311	336	224	300	195	497

ICL estimates that, including imports, between 101 and 252 Mtoe of biomass is available for sustainable fuel production in transport (PRIMES was used to estimate demand from power, industry, services and agriculture & residential heat; biomass imports are fully dedicated to fuel production for transport). Finally, they assume an average conversion yield from biomass for energy to the final form bioenergy of 70% in 2050. Resulting in approximately 70 to 176 Mt of sustainable fuels production.

At 70% SAF, with 35% non-synthetic SAF at 16.0 Mt, aviation would use approximately 23% of available biomass for the transport sector in the low biomass scenario, 9% in the high biomass scenario. This is below estimates on the share of aviation in the biomass for transport of the EC at 26% (published before ReFuelEU Aviation regulation was adopted) (EC, 2021d), bp’s Energy Outlook expects the aviation’s share in biomass for transport to be between 50-60% (bp, 2023; bp, 2024) and the Net Zero Roadmap published by the International Energy Agency (IEA) which estimates the non-synthetic fuel volume for aviation to be twice as large as for shipping (IEA, 2023c). Furthermore, the feedstock potential might be higher as the ICL study does not consider all eligible feedstocks mentioned in Annex IX Part A & B of RED II, and discussions are currently ongoing to include more feedstocks in this Annex. This suggests that there is potential for higher non-synthetic SAF production in the EU+ region. Higher feedstock availability would not come without challenges, as additional feedstock supply chains would need to be developed and conversion technologies should be developed further.

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[99] 1.045 Mtoe = 1 Mt non-synthetic SAF.

Following ReFuelEU Aviation regulation's SAF target of 70% in 2050, and assuming that all CO_2 for synthetic aviation fuel production is captured using carbon removal technologies, at least 39.6 Mt CO_2 should be captured to produce synthetic aviation fuel, and an additional 43.3 Mt of CO_2 should be captured and stored using carbon removal technologies, through economic measures to compensate for emissions of CAF. This is equivalent to 62% of the total CO_2 emission reductions needed to achieve net zero in 2050 [100]. This would mean a high reliance on carbon removal technologies, which have yet to be proven at scale. Given high uncertainty on the development of carbon removal technologies, and the higher level TRL of non-synthetic SAF production, increasing the share of non-synthetic SAF would more evenly spread the emission reductions, and associated risk. At 45% non-synthetic SAF, and a total SAF share of 80%, approximately 51% of emission reductions needed to achieve net zero in 2050 would rely on carbon removal technology, see Table 38.

Additionally, with only marginal need for external energy for non-synthetic SAF production, increasing its share would also decrease the need for overall renewable energy. At 2.8 MWh/t CO_2 captured (Babacan, et al., 2020), increasing the non-synthetic SAF share would decrease the energy demand for carbon removal technologies by 40 TWh (from 120 TWh to 80 TWh) in 2050. A more detailed analysis of the electricity demand in 2050 is given in Section 5.5.4.

Finally, the measures outlined in this edition of DESTINATION 2050 regarding the technological, operational and economic pillars, are highly ambitious. Consequently, it is unlikely that these pillars can significantly contribute to decarbonisation beyond presently assumed, by 2050. Achieving 80% SAF in the fuel pool by 2050 is of essential importance to attain the overall goal of net zero CO_2 emissions by 2050. Not reaching that SAF uptake poses a dual risk: compromising the net zero goal and increasing cumulative (net) CO_2 emissions, thereby diminishing the likelihood of adhering to the 1.7 °C carbon budget as described in Section 2.6.2.

5.5.2 Additional SAF uptake above the mandate

To achieve an 80% SAF share in the fuel pool, and meet climate ambitions/targets, this section explores options that could facilitate a higher SAF uptake above the mandate as set forth in the ReFuelEU Aviation regulation, these include:

- Increasing the ReFuelEU Aviation mandate
- Voluntary additional SAF uptake by
    - Voluntary SAF targets by airlines, that exceed the ReFuelEU Aviation regulation
    - Corporate aviation customers flying on 100% SAF
    - Extra consumer uptake
- Incentives to decrease the price gap between SAF and CAF

The above-mentioned options are extrapolated based on the current status quo in the aviation sector and developments seen in the market. Additional economic measures, such as financing initiatives, SAF allowances, airport SAF incentives, etc. are not described in this section, see Chapter 6 for more details on the application and efficacy of economic measures. Increasing the uptake of SAF above the mandate will not come without its challenges: various technologies need to be developed to higher TRL, feedstock supply chains need to be further developed, etc.

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[100] Emissions from the use of H_2 are excluded in the total, as this does not emit CO_2

Increasing the SAF share in the ReFuelEU Aviation regulation

In the adopted ReFuelEU Aviation regulation, fuel suppliers will have to supply at least 70% SAF in 2050, with a minimum share of 35% synthetic fuels (EC, 2023h). The supply obligation combined with the non-compliance penalty, and obligation to supply any shortcomings in the following year, as well as the anti-tankering requirement for aircraft operators, create a solid foundation for a European SAF market.

To reach net zero emissions in 2050, the emissions from the use of CAF should be mitigated by additional measures. This can be achieved by using additional sustainable fuels, e.g., SAF or renewable hydrogen, although constrained the share of hydrogen-powered aircraft in the fleet, or by adopting carbon removal technologies, which would mainly rely on DACCS in this edition of DESTINATION 2050.

During the trilogue discussions the European Commission, European Parliament and European Council proposed various minimum shares of SAF for 2050, with the European Commission and European Council proposing 63% and the European Parliament 85% (Soone, 2023). Increasing the minimum SAF share to 80% in 2050, from 70%, for fuel suppliers, and maintaining the other provisions, would ensure a higher SAF share in the fuel pool, and less reliance on, and associated risk of, carbon removal technologies.

Voluntary additional SAF uptake

VOLUNTARY SAF TARGETS BY AIRLINES, THAT EXCEED THE REFUELEU AVIATION REGULATION

Ahead of the ReFuelEU Aviation regulation, several airlines had committed to minimum SAF targets for 2030, see Table 36 in Section 5.4.2. These targets exceed the minimum SAF share in 2030, as set forth by the ReFuelEU Aviation regulation, at 6% in 2030 (EC, 2023h). Additionally, several airlines, such as Lufthansa, DHL Group and Air France-KLM, have committed themselves to the Science-Based Targets initiative (SBTi), including commitments to using SAF (Lufthansa, 2023a; DHL Group, 2024; Air France-KLM Group, 2022).

The current commitment of airlines to SBTi and voluntary SAF targets for 2030, indicating willingness to go beyond what is regulated, might translate to similar commitments for 2050. However, it must be noted that these targets are usually set at the group level/global scale. Assuming that these airlines not only operate in the EU+ region, SAF could be uplifted in other regions too to meet the target. In a scenario where SAF is more expensive in the EU+ region, due to the mandate, it is likely that SAF will be uplifted in other regions, at a lower price point. Therefore, it is uncertain if these voluntary targets will lead to additional SAF uptake above the minimum SAF share in the EU+ region.

CORPORATE AVIATION CUSTOMERS FLYING ON 100% SAF

Approximately 18% of all flight kilometres in commercial aviation are attributed to business and corporate travellers, according to modelling in this edition of DESTINATION 2050. Since emissions are directly proportional to distance flown, this group is responsible for a similar share – about 18% – of aviation-related emissions.

Under the ReFuelEU Aviation regulation, 70% of these emissions will be reduced through the use of Sustainable Aviation Fuel (SAF) by 2050, translating to a 12.6% reduction in total emissions. The remaining 5.4% will be offset through carbon removal technologies, as part of economic measures. If corporate travellers were to fly exclusively on 100% SAF, this would represent an additional 5.4% SAF uptake, exceeding the minimum SAF share mandated by the ReFuelEU Aviation regulation. However, this report does not explore the feasibility of achieving 100% SAF usage for corporate aviation.

Currently, only one organization, PwC Netherlands (PwC NL, 2021), offsets 100% of its aviation-related business travel emissions by purchasing SAF credits, as it does not directly engage in fuel procurement. Other companies, such as BCG, DHL Express, and Microsoft, are also working to reduce their business travel emissions through SAF credit purchases (BCG, 2024; World Energy, 2023b; World Energy, 2023a).

Regulations, such as the Corporate Sustainability Reporting Directive (CSRD), and the net zero ambitions of certain organizations may incentivize more companies to reduce their business travel emissions. However, the higher cost of SAF compared to conventional aviation fuel is expected to persist in 2050, potentially limiting uptake among organizations.

EXTRA CONSUMER UPTAKE

Consumer awareness of the environmental impact of travel has increased in recent years, driven in part by movements like ‘flygskam’ (flight shame), which gained prominence following Greta Thunberg's advocacy in 2018. Travellers now have several options to offset or reduce the carbon footprint of their air travel, including tools like CHOOOSE and Fly on SAF (CHOOOSE, 2024; Fly on SAF, 2024), as well as integrated options within the booking systems of airlines such as KLM and the Lufthansa Group (KLM, 2024; Lufthansa Group, 2023b). Lufthansa reported that within 100 days of introducing its ‘green fare’ option 200,000 passengers selected this option. A ‘green fare’ compensates the emissions of a flight by partial use of SAF (20%), with the remaining emissions offset through carbon credits (Lufthansa Group, 2023b).

The combination of carbon offsets and SAF offers a lower-cost option for consumers looking to offset the emissions of their flights, as carbon offsets are generally much cheaper than SAF. However, the effectiveness of voluntary carbon offsets has been questioned, as discussed in Chapter 6 on Economic Measures.

Research by the Lufthansa Innovation Hub shows that 78% of travellers are aware of their environmental impact, and 73% express an intention to purchase carbon offsets (TNMT, 2020). Despite these intentions, only 1% actually follow through by purchasing offsets; in this study reforestation-based options were presented, which typically come at lower cost. Similarly, a McKinsey & Company study found that 39% of travellers across all age groups are willing to pay at least 20 USD extra for a carbon-neutral flight on a 1,000 USD ticket (McKinsey & Company, 2022).

Given current and projected SAF prices, however, achieving a carbon-neutral flight for an additional 20 USD on a 1,000 USD ticket is unrealistic. If consumer behaviour remains consistent through 2050, with SAF prices expected to stay significantly higher than those of carbon offsets, substantial uptake of SAF beyond the mandated minimum share is unlikely.

Incentives to reduce the price gap between SAF and CAF

The high price point of SAF is a major barrier to its adoption. Since its inception, SAF prices have been higher than those of CAF. However, it is expected that SAF prices will decline over time (see Section 5.7). Nevertheless, SAF will likely remain more expensive than CAF.

To reduce the cost of SAF for aircraft operators, various incentives have been introduced in recent years. For instance, SAF has been granted a zero-emission rating under the EU ETS, exempting aircraft operators from submitting emission allowances and effectively reducing their operational expenses (EC, 2023e). Additionally, London's Heathrow Airport and Amsterdam Schiphol Airport have both introduced SAF incentives that reduce the cost of SAF for aircraft operators that uplift SAF at those airports (Heathrow, 2024; Schiphol Airport, 2024). Furthermore, SAF Allowances were introduced under the EU ETS that can cover part of the price premium of SAF compared to CAF (see Section 5.7 for more information).

These incentives contribute to decreasing the price gap between SAF and CAF, which could facilitate higher SAF uplift. If such incentives were available in 2050, it is possible that additional SAF uptake above the mandate could be realized. Since the demand effect of SAF is determined by the price, SAF prices below the ones modelled in the report would (ceteris paribus) need to be compensated through additional measures such as an even higher SAF uptake.

Another way to reduce SAF prices is through financial support during the investment phase of a production capacity project. This support can take the form of loan guarantees from European or national governments or the availability of governmental funds, such as is available up to 2030 through the European Innovation Fund (EC, 2024b). Alternatively, governments can offer contracts for difference to provide aircraft operators with long-term expense certainty. By offering these forms of support, governments can help reduce the price gap between SAF and CAF.

5.5.3 Synthetic SAF availability

Synthetic aviation fuels require renewable electricity to produce green hydrogen, and CO_2 either from point sources or from carbon capture technologies. In this section, the amount of green hydrogen production in the EU and imports is assessed.

Overall renewable electricity demand in the EU will increase significantly towards 2050. In particular, in the transport sector, renewable electricity demand is expected to increase considerably due to the electrification of road transport. Electricity demand is expected to double towards 2050 compared to 2015 levels in many of the policy scenarios investigated by the European Commission in the analysis “Clean Planet for all”. These policy scenarios expect the installed renewable electricity capacity to range between 1600 GW up to nearly 3000 GW (EC, 2018b). Policy scenarios that assume a high demand of Power-to-X fuels and hydrogen, require the largest amounts of installed capacity. However, a recent study by the International Renewable Energy Agency (IRENA) show that the EU is currently not on track in achieving those ambitious scenarios (IRENA, 2020). According to IRENA, the EU is headed towards 828 GW of installed capacity, compared to the 1655 GW that would be required in the IRENA Transforming Energy Scenario[101], a scenario comparable to the pathway presented in this edition of DESTINATION 2050. These publications highlight that the actual amount of installed capacity by 2050 remains highly uncertain. This illustrates that the production of green hydrogen and synthetic aviation fuels in the EU is therefore also very uncertain.

Hydrogen availability for aviation in 2050

Hydrogen availability in the EU is highly dependent on the renewable electricity capacity. The RED III includes the *additionality* principle that ensures that the supplies of renewable hydrogen, which are due to come on online by 2030, are connected to new, rather than existing, renewable energy production. The aim is to incentivise an increase of the renewable energy capacity in the EU. This means that dedicated installed capacity needs to be built for the production of renewable hydrogen.

Table 40 summarizes the literature estimates for production volumes of renewable hydrogen in the EU and the amount of renewable imports.

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[101] “The “Transforming Energy Scenario (TES)” describes an ambitious, yet realistic, energy transformation pathway based largely on renewable energy sources and steadily improved energy efficiency (though not limited exclusively to these technologies). This would set the energy system on the path needed to keep the rise in global temperatures to well below 2 degrees Celsius (°C) and towards 1.5°C during this century.” (IRENA, 2020)

Table 40: Literature estimates for EU green hydrogen production and imports.
** 10 Mt of 30Mt import is renewable, according to figure 11, p. 32; ** approximately 30% of total imports is renewable, according to figure on p. 7*

	WEC (World Energy Council, 2021)	**EC (Blanco Reano, Nijs, Ruf, & Faaij, 2018)**	**Deloitte (Villavicencio, 2021)**
EU production	30 Mt	20-120 Mt	42-77 Mt
Imports	10 Mt *	Not considered	4 Mt **

The import amounts shown in Table 40 only consider the renewable portion of the imported hydrogen, which in both cases is approximately 30% of the imports, the overall hydrogen imports are expected to the larger. The average values from the reviewed literature were used to estimate a total renewable hydrogen supply of 57 Mt in the EU, consisting of 50 Mt from domestic production and 7 Mt from imports.

The amount of hydrogen used by the transport sector in 2050 will depend on both the demand from other sectors and the production capacity installed by that time. According to the European Commission's 1.5TECH scenario[102], 40% of the total hydrogen supply is projected to be allocated to transport (EC, 2018b). Many sources in the literature highlight strong competition for renewable hydrogen within the transport sector, particularly between aviation, maritime, and heavy-duty road transport. Maritime fuels, such as ammonia, methanol, and liquefied hydrogen, all rely on hydrogen as a key component, intensifying the competition.

Given these dynamics, the aviation sector's share of the available hydrogen within transport is estimated at 25%, translating to 10% of the total hydrogen supply in Europe, or approximately 5.7 Mt. However, the extent of competition for hydrogen across sectors remains highly uncertain and will need to be closely monitored in the coming years.

Hydrogen use in aviation in 2050

In 2050, non-synthetic SAF production, via HEFA, AtJ and FT pathways, will demand approximately 0.6 Mt of hydrogen[103], with hydrogen-powered aircraft needing approximately 1.3 Mt of hydrogen (3.5 Mt of SAF-equivalent hydrogen), based on the modelling in this edition of DESTINATION 2050 (see Chapter 3 for more information on hydrogen-powered aircraft). This leaves roughly 3.8 Mt of hydrogen for the production of synthetic SAF. At an average requirement of 0.5 kg of hydrogen per kg of synthetic aviation fuel[104] (Concawe, 2022), this 3.8 Mt would translate to approximately 7.6 Mt of synthetic aviation fuel.

To fulfil the sub-mandate for synthetic aviation fuel, at 35% in 2050, 16.0 Mt of synthetic aviation fuel is needed. 3.5 Mt of that need is fulfilled by hydrogen use in hydrogen-based aircraft and approximately 7.6 Mt of synthetic aviation fuel produced from the remaining available hydrogen. This leaves a need for approximately 5.0 Mt of synthetic aviation fuel, which needs to be fulfilled with imports.

If less hydrogen is available, more synthetic aviation fuel will need to be imported from outside the EU. Lower availability of hydrogen, would mean more imports of synthetic SAF, and this this may also risk the introduction of hydrogen-powered aircraft. Importing renewable hydrogen could be challenging due to infrastructure needs. To overcome these challenges, investment in either pipelines or conversion facilities need to happen.

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[102] The 1.5TECH scenario “aims to further increase the contribution of all the technology options, and relies more heavily on the deployment of biomass associated with significant amounts of carbon capture and storage (BECCS) in order to reach net zero emissions in 2050.” Taken from “Clean Planet for All”

[103] HEFA hydrogen need: 0.08 kg of hydrogen per kg of HEFA-based SAF; AtJ hydrogen need: 0.03 kg of hydrogen per kg of AtJ-based SAF; FT hydrogen need: n.a.

[104] Figure 82, p169, of Concawe, 2022, to produce 0.0232 kg synthetic kerosene, 0.0117 kg of hydrogen is necessary, this yields approximately 0.5 kg synthetic kerosene/kg hydrogen.

5.5.4 Feasibility of fulfilling the SAF demand

Based on the modelling in this edition of DESTINATION 2050, 45.7 Mt of aviation fuel is required in 2050 fulfil the energy demand of the sector, see Section 5.8 for the full results. The equivalent amount of SAF necessary, at an 80% SAF share of the energy mix, is 36.6 Mt, of which 16.0 Mt is synthetic aviation fuel, see Table 41. Given today's low production volumes, SAF production must be rapidly scaled up to 2050. This is achievable with coordinated, collective effort of governments, aircraft operators and industry.

Table 41: Energy demand and fulfilment for 2050 as modelled in DESTINATION 2050

Fuel demand	Unit	2050	Share
Reference scenario	Mt	93.2	
Sustainability scenario	Mt	45.7	
SAF (non-synthetic)	Mt	20.6	45%
HEFA	Mt	4.6	
FT	Mt	8.0	
AtJ	Mt	8.0	
SAF (synthetic)	Mt	16.0	35%
PtL	Mt	12.5	
H_2	Mt (SAF_{eq})	3.5	
Conventional	Mt	9.1	20%

5.5.5 Electricity demand

In order to fulfil the energy demand of aviation in terms of fuel, the rapid deployment of renewable electricity, dedicated to the production of alternative energy and sustainable fuels, is crucial. Non-synthetic SAFs, i.e., HEFA, AtJ and FT-based SAF, require significantly less energy for their production than synthetic SAF (PtL-based) and hydrogen, or carbon removal technologies require. The electricity requirements for the various SAF production pathways, and hydrogen and carbon removal technology are given in Table 42.

Table 42: Electricity requirement per SAF production pathway, hydrogen and carbon capture technology

Process	Electricity requirement	Unit	Note	Source
HEFA	6.5	MWh/t SAF	Includes electricity demand for H_2 requirement in the HEFA process, at 0.08 t H_2/t SAF	(Pipitone, Zoppi, Pirone, & Bensaid, 2023)
FT	0	MWh/t SAF	Does not require external electricity due to exothermic nature of the process	(Tanzil, Brandt, Wolcott, Zhang, & Garcia-Perez, 2021)
AtJ	2.3	MWh/t SAF	Includes electricity demand for H_2 requirement in the AtJ process, at 0.03 t H_2/t SAF	(Bedin, 2024)
H_2	76.3	MWh/t H_2	At 50% efficiency	(The Royal Society, 2023)
PtL	42.9	MWh/t SAF		(Drünert, Neuling, Zitscher, & Kaltschmitt, 2020)
Carbon removal technologies	2.8	MWh/t CO_2		(Babacan, et al., 2020)

Table 43 shows the total electricity requirement for the production of various SAFs and H_2, as well as the energy requirement for the necessary carbon removal to compensate for the combustion of conventional aviation fuel (CAF). For the production of 20.6 Mt non-synthetic SAF, approximately 48 TWh of renewable electricity is required. For the production of 16 Mt synthetic SAF (equivalent), approximately 635 TWh of renewable electricity is needed. To capture the CO_2 emissions of 9.1 Mt CAF [105], approximately 80 TWh of renewable electricity is needed. It must be noted that (hybrid-)electric aircraft also require renewable electricity, however in 2050 this is limited to 2.33 GWh, which is negligible compared to the demand for SAF and hydrogen production, and carbon removal technologies.

Table 43: Electricity demand in 2050 for the production of SAF, H_2 and DACCS (to reduce emissions of conventional aviation fuel (CAF) in TWh.
** Includes the electricity demand for the production of hydrogen required in the process.*
*** 1 t CAF = 3.16 t CO_2*

	Fuel	Unit	Electricity requirement	Unit	Total electricity demand	Unit
SAF (non-synthetic)						
HEFA *	4.6	Mt SAF	6.5	MWh/t SAF	**30**	TWh
FT	8.0	Mt SAF	0	MWh/t SAF	**0**	TWh
AtJ *	8.0	Mt SAF	2.3	MWh/t SAF	**18**	TWh
SAF (synthetic)						
H_2	1.27	Mt H2	76.3	MWh/t H_2	**97**	TWh
PtL *	12.5	Mt PtL SAF	42.9	MWh/t SAF	**538**	TWh
CAF **	9.1	Mt CAF	2.8	MWh/t CO_2	**80**	TWh
Total	**45.7**	**Mt CAF equivalent**			**762**	**TWh**

At 762 TWh, a significant amount of renewable electricity must be deployed between now and 2050. In 2022 Europe produced 2,641 TWh of electricity, of which 39.4% was generated from renewable sources (wind (15.9%), hydro (11.3%), solar (7.6%), biomass (4.0%) and geothermal (0.2%)), resulting in 1,040 TWh of renewable electricity (European Council, 2024). Assuming that only a small fraction of the currently deployed renewable electricity is used for SAF and/or hydrogen production and carbon removal technologies, the total amount of renewable electricity for alternative fuel production in 2050 must still be deployed. This is in addition to substituting current non-renewable electricity demand of all other sectors, as well as the growth of electricity demand of those sectors from now till 2050. If renewable electricity is not sufficiently available, other low-carbon sources of energy must be explored to fulfil the energy demand.

5.6 Global SAF supply

Within the ICAO LTAG report (ICAO, 2022e), three scenarios have been developed for fuels (F1, F2 and F3), representing varying levels of introduction of both drop-in and non-drop-in fuels that could reduce the life-cycle GHG emissions from aviation (ICAO CAEP, 2022). F1 represents the low end of potential GHG reductions from fuels using mainly mature production technologies. F2 depicts “middle readiness/attainability and middle aspiration”. When applied to fuels, this leads to the middle of the range of potential GHG reductions from fuels, combined with medium attainability and readiness of fuel production technologies and certification processes. F3 represents the high end of potential GHG reductions from fuels using advanced fuel production technologies.

In this report, the global SAF uptake is aligned with scenario F2 from the ICAO LTAG report. This scenario assumes that the global policy framework incentivises SAF in the same manner as road transport. The policy framework favours SAF types which lead to the best carbon abatement costs. From a sector-wide perspective, it assumes that electrification of ground transportation leads to increased availability of SAF, as ground transport uses more electricity and less sustainable fuels.

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[105] 9.1 Mt CAF = 28.8 Mt of CO_2

Technology evolution enables the production of SAF from waste gases, increases feedstock availability, facilitates the use of blue/green hydrogen for fuel production and enables the use of Carbon Capture Utilization and Storage (CCUS). This scenario assumes that ASTM will approve the use of drop-in SAF up to 100% in the 2050 timeframe.

The SAF uptake (excluding low carbon aviation fuels) estimated under scenario F2 for a middle traffic forecast results in 25 Mt of SAF by 2030, 200 Mt by 2040 [106] and 415 Mt by 2050. Resulting in 8% SAF uptake by 2030, 44% in 2040 and 72% in 2050. An overview of the modelling assumptions for global SAF uptake is given in Appendix 4.4.3.3.The 2030 share of 8% SAF, with an on average 70% emission reduction, results in 5.6% reduction of emission, which is in line with the CAAF/3 emission reduction target of 5% by 2030 through the use of cleaner energy sources.

The SAF uptake is not anticipated to be consistent across all world regions due to differences in market dynamics. In particular, countries or regions with favourable low GHG fuel policies may attract greater volumes of these fuels. Other differences may occur due to regional availability of feedstock resources (biomass, solid/liquid wastes and waste CO_2). The European SAF assumptions outlined in this roadmap differ from the global SAF assumptions defined in F2 mainly due to the increased share of SAF by 2050. The higher ambition level presented in the DESTINATION 2050 report aligns with elements of scenario F3 of the ICAO LTAG report.

5.7 Sustainable fuels market prices

In the first edition of the DESTINATION 2050 roadmap report, minimum fuel selling prices (MFSP) for SAF were investigated. These MFSPs reflect the production costs of SAF excluding profit and risk margins associated with running the first production facilities. Moreover, they do not reflect the effect of market dynamics, such as the effect of scarcity of the product. Many factors may influence the market price, such as increased risks associated with running the first production facilities in Europe, market power of suppliers, lack of price transparency and an immature market. There is limited data publicly available for the market price of SAF. Therefore, a *market factor* was developed, based on MFSPs given in literature and available market pricing for HEFA-based SAF in 2022 and 2023. The market factor can be applied to MFSPs to estimate market pricing for the shorter term, up to 2030. The market factor for 2050 was developed by taking the average of the market factor for 2030 and the estimate by the EC, that in 2050 SAF will be sold with a 10% premium (EC, 2021d). The used market factors to convert MFSP data to market pricing is 1.63 for 2030, and 1.36 for 2050. The same market factors are applied for hydrogen for use in hydrogen-powered aircraft.

ETS allowances for SAF

The possibility to use EU ETS (SAF) allowances to decrease the price gap between SAF and CAF is not considered for 2030. This is due to anticipated depletion of the 20M allowances before the policy ends by 2030 [107].
Hydrogen-powered aircraft are not yet operational before 2030, thus ETS allowances can’t be used to decrease hydrogen prices.

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[106] Values for 2040 result from a linear interpolation between given values for 2035 and 2050, from Table 4.6 in Annex M5.

[107] Fuel demand in the period 2025-2029 is modelled at approximately 52.4 Mt aviation fuel in this edition DESTINATION 2050 (growth of the sector is offset by technological and operational improvements, resulting in the net same fuel demand), with a 2% SAF mandate applicable in that period, this equals approximately 1 Mt of SAF per year. Following the example calculation presented in the SAF allowances box (page XX), using HEFA-based SAF, this equals approximately 9.5 M SAF allowances per year in that period, depleting the allowances by 2028 at the latest. Other SAF types (such as AtJ and FT-based SAF) that come at a higher price point and receive more support, deplete SAF allowances quicker.

SAF ALLOWANCES

Fundamentals

SAF allowances are designed to reduce the financial burden on aircraft operators that choose to use SAFs, which are currently more expensive than CAF. These allowances are intended to offset the higher costs of SAFs by reducing aircraft operators' compliance costs under the EU Emission Trading Scheme (ETS). Reducing the cost of SAF intends to promote its uptake at the early stages of SAF blending.

Under the EU ETS, airlines are required to purchase carbon allowances to cover their CO_2 emissions from aviation activities within the European Economic Area (EEA). For each ton of CO_2 emitted, airlines must surrender an equivalent number of allowances (known as EU Allowances or EUAs).

SAF allowances will provide aircraft operators with free allowances proportional to (a share) of the price difference between CAF and the type of SAF used. This will lower the need for airlines to purchase EUAs, effectively compensating them for the higher cost of SAF compared to CAF.

There are 20 million EU ETS allowances available, which support up to 100% of the cost difference for eligible fuels uplifted from 01/01/2024. All operators (EEA and non-EEA) can request support for all commercial flights that are subject to EU ETS surrender requirements.

Below details regarding SAF allowances are based on *"ETS allowances for SAF"* as presented by DG CLIMA B.4 and the European Commission in November 2023 (EC, 2023f).

Support

Allowances cover up to the following percentage of the price difference between eligible fuels* and CAF:

- 70% for eligible fuels that are considered 'advanced biofuels' compliant with Article 25 of Directive (EU) 2018/2001, and renewable hydrogen
- 95% for eligible fuels that are considered 'renewable fuels of non-biological origin (RFNBOs) compliant with Article 25 of Directive (EU) 2018/2001
- 100% for SAFs uplifted at airports at small islands, at airports not classified as Union airports in the context of the ReFuelEU Aviation regulation, and at airports in an outermost region
- 50% for SAF not derived from fossil resources, that are not referred to in above points. These include for example SAFs made from UCO and animal fats

* Eligible fuels include SAF and other aviation fuels that are not derived from fossil resources, identified in the ReFuelEU Aviation Regulation.

Example calculation for SAF allowances, prices taken from this edition of DESTINATION 2050 for 2025:

- *CAF price of 600 €/t CAF*
- *SAF (UCO-based) price of 2,800 €/t SAF*
- *ETS Allowance price of 100 €/t* CO_2

Avoided costs for CAF: 3.16 t CO_2*/t CAF * 100 €/t* CO_2 *= 316 €/t CAF*
Price difference = 2,800 €/t SAF – 600 €/t CAF – 316 €/t CAF avoided carbon cost = €1,884.
*Eligible SAF allowances: 50% * €1,884 / 100 €/allowance = ~9.5 ETS allowances per tonne of SAF*

Timeline for SAF allowances

1. Aircraft operator uplifts fuel on eligible route (during the year, e.g., 2024)
2. Aircraft operator reports uplifts for given year (start of next year, e.g., 2025)
3. Aircraft operator applies for the SAF allowances (e.g., 2025)
4. EU Commission publishes annual average prices for previous year (e.g., 2024 prices published in 2025.
5. Competent authority determines free allocation of allowances (e.g., 2025)
6. Aircraft operator receives free ETS allowances (e.g., 2025)

Hence, there is a delay between the use of SAF and free allocation of EU ETS allowances.

Effects of SAF allowances

SAF allowances have an indetermined impact on CO_2 emissions depending on if the long-term benefits to SAF production capacity and price transparency are outweighed by the short-term higher levels of CO_2 emissions from free allowances, lower EU ETS prices and lower SAF prices. The reduction in SAF price will reduce the demand-related impact of SAF uptake in the short-term until SAF allowances run out.

2030 onwards

By 1 January 2028 the European Commission will carry out an evaluation of the support scheme and may propose to allocate an additional capped number of allowances up until 2034, in particular for the uplift of RFNBOs.

Market prices for SAF are developed for three types of non-synthetic SAF, namely HEFA-based SAF, FT-based SAF and AtJ-based SAF, for one type of synthetic SAF, namely PtL-based SAF, and for hydrogen, for the use in hydrogen-powered aircraft. Prices are determined for 2030 and 2050 based on literature. The weighted average SAF price is determined based on the (sub-)mandate set by the ReFuelEU Aviation regulation and the availability of the various types of SAF. The required amounts of SAF, per type, as given in Section 5.4.3 for 2030 and in Section 5.5.4 for 2050 to fulfil the (sub)mandate, are used to determine the weighted average prices. The average SAF price is determined for non-synthetic SAFs, synthetic SAF and hydrogen separately, as well as for all SAF types combined.

The price for CAF was taken from the ICAO LTAG report (ICAO, 2022a), with carbon pricing for EU ETS and CORSIA according to the assumptions given in Chapter 6. All pricing information for the various types of SAF, the weighted average and the comparison to conventional aviation fuel (with carbon pricing) is shown in Figure 19. The weighted average SAF price is determined based on the composition of the aviation fuel mix, as given in Table 45. The pricing data used for modelling is also given in Table 46. Full pricing data, including referenced sources for SAF prices, is presented in Appendix D.4.3.4, Appendix D.4.3.5, and Appendix D.4.3.6.

Given that SAFs will remain more expensive than CAF, including carbon pricing, it is expected that this will create a demand impact, especially in 2050, with a share of alternative energy of 80%.

Uncertainty in pricing

The MFSP of SAF and hydrogen exhibits a notable spread across the gathered data, see Table 44 for the minimum and maximum found MFSPs and Appendix D.4.3.4 and Appendix D.4.3.6 for the full data set. This spread in MFSP values underscores the inherent uncertainty associated with the production cost of SAF and hydrogen. The application of a market factor introduces additional uncertainty due to the limited availability of publicly accessible data. Consequently, the combined uncertainty is reflected in the substantial price ranges observed for AtJ, FT, and PtL-based SAF. That effect is even more pronounced for hydrogen when expressing the data per tonne of hydrogen, rather than per tonne of SAF-equivalent.

The MFSP of SAF and hydrogen is dependent on a variety of factors. Several factors could contribute to high(er) MSFPs and the eventual market prices of SAF, such as:

- High feedstock costs due to limited availability of sustainable biomass, resulting from poor supply chain development or high competition with other sectors, such as road transport in case of limited electrification.
- Limited improvements in the overall energy efficiency of SAF and hydrogen production processes and/or limited development of novel SAF production processes, stemming from insufficient investment in R&D activities.
- A concentrated market with a limited number of SAF suppliers, potentially leading to reduced competition.
- High cost of renewable energy, particularly relevant for PtL-based SAF and hydrogen production, due to limited availability and/or deployment of renewable energy for the aviation sector.
- Insufficient investment in new European SAF production facilities, hindering domestic production capacity and leading to reliance on imports.

In contrast, development of several factors could contribute to low(er) MFSPs and eventual market prices of SAF, such as:

- Low feedstock costs due to optimized supply chains, increased availability of biomass and/or expansion of eligible feedstocks, or reduced competition with other sectors, such as road transport in case of rapid electrification.
- Development of novel SAF production process, possibly allowing for novel feedstocks to be used, and significant improvements in the overall energy efficiency of SAF and hydrogen production processes, resulting from substantial investment in R&D activities.
- A diverse market with a large number of SAF suppliers, potentially leading to increased competition.
- Decreased costs of renewable energy, driven by advancements in technology, economies of scale, or increased deployment, for the aviation sector.
- Robust investment in new European SAF production facilities, enabling increased domestic production capacity.

The approach taken in DESTINATION 2050 considers only a single scenario to reach net zero, and the impact of aforementioned factors that contribute to MFSPs and market prices of SAF and hydrogen are not quantified. However, it is likely that an increase in the price gap between SAF and CAF would likely amplify the demand-related impact. Conversely, a decrease in the price gap would likely diminish the demand-related impact. In case of price parity between SAF and CAF, it is likely that the demand impact is negligible, and that SAF would be the preferred fuel option due to its environmental benefits when compared to CAF. This would also further facilitate the scale-up of the SAF sector.

Table 44: Spread in Minimal Fuel Selling Prices (MFSPs) found in literature in €/t of fuel, for SAF and hydrogen. Prices are converted to €/t of fuel form the original data

	2030			2050			
	Min.	**Average**	**Max**	**Min.**	**Average**	**Max.**	**Unit**
HEFA	1,275	1,473	1,697	983	1,318	1,608	€/t SAF
AtJ	1,827	2,446	4,018	1,563	1,916	2,563	€/t SAF
FT	1,875	2,387	2,877	1,340	1,774	2,007	€/t SAF
PtL	2,013	2,418	3,004	1,225	1,654	2,750	€/t SAF
H_2	2,563	4,793	6,109	1,800	3,171	4,909	€/t H_2

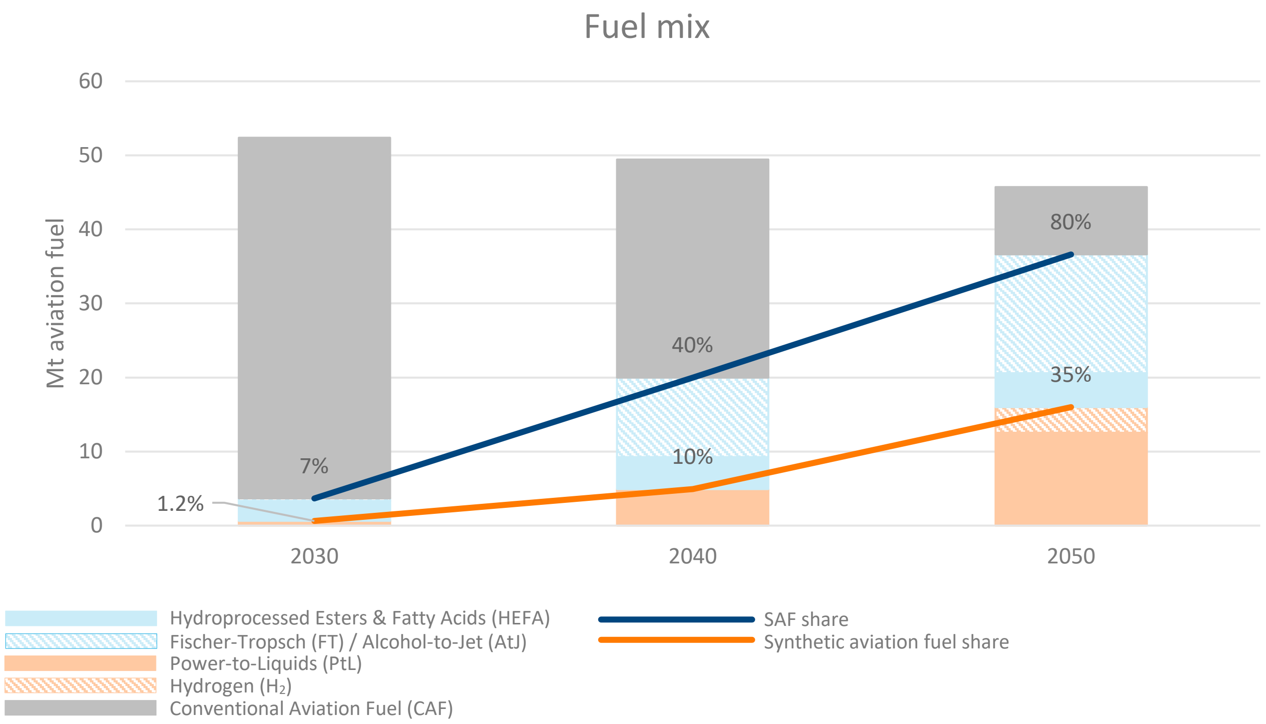

Figure 18: Composition of the aviation fuel mix given for 2030, 2040 and 2050, based on ReFuelEU Aviation and the availability of the various types of SAF and need for hydrogen

Table 45: Composition of the aviation fuel mix for 2030 and 2050, based on ReFuelEU Aviation and the availability of various types of SAF and the need for hydrogen.

	Unit	Syn. SAF	H_2	HEFA	FT/AtJ	CAF	Total
2030	Mt aviation fuel equivalent	0.6	0	2.7	0.3	48.7	**52.4**
2050	Mt aviation fuel equivalent	12.5	3.5	4.6	16.0	9.1	**45.7**

Table 46: Assumptions used in modelling for market prices of fuels (and carbon pricing) for 2030 and 2050, based on the weighted average market price of the various types of SAF and composition of the aviation fuel mix (Table 45).

	Unit	SAF	H_2 (in SAF_{eq})	CAF	CAF + ETS	CAF + CORSIA
2030	€/t aviation fuel equivalent	2,800	2,900	680	1,090	760
2050	€/t aviation fuel equivalent	2,300	1,600	840	1,840	1,350

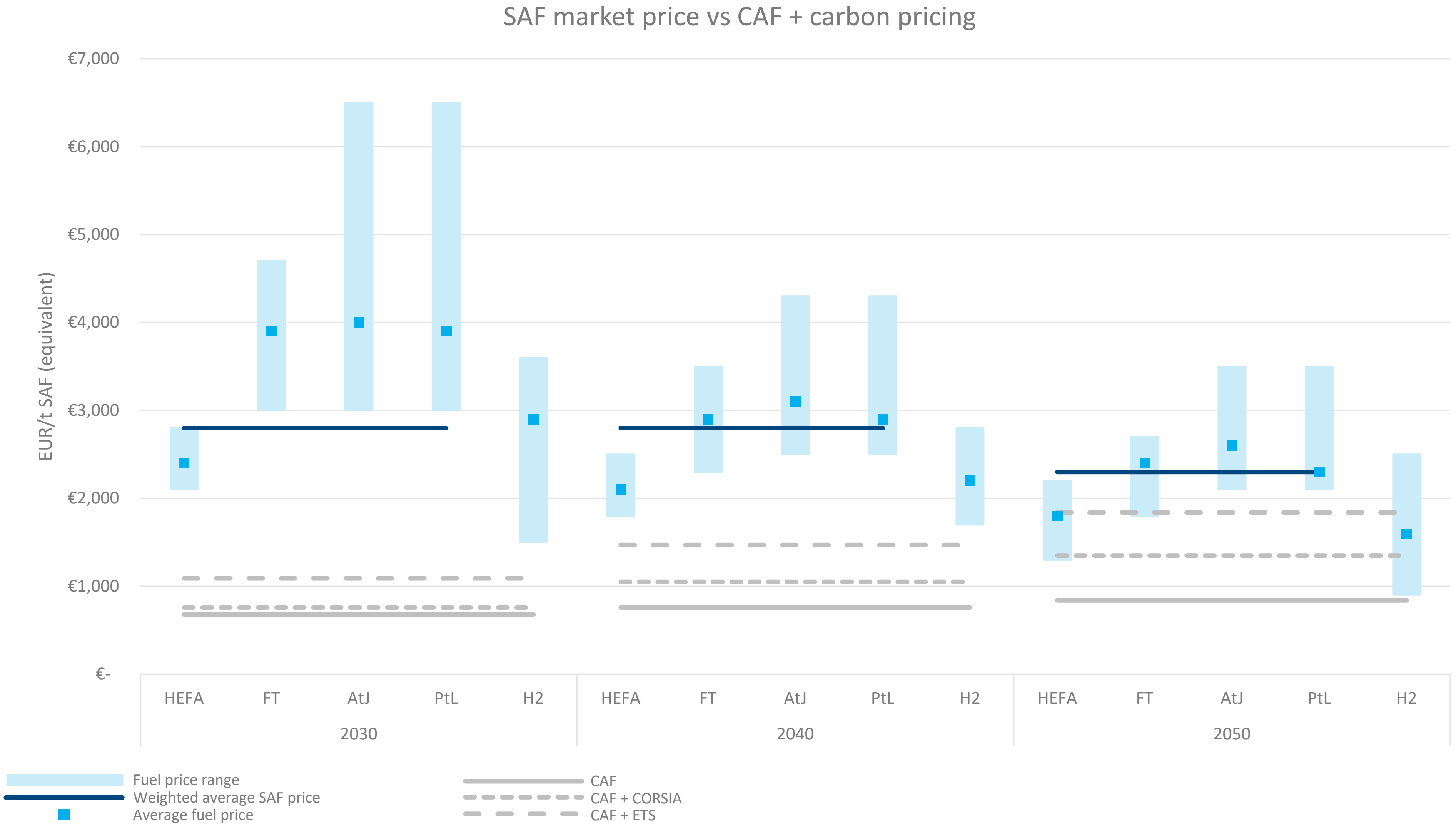

Figure 19: Market pricing of various SAF types and hydrogen, and the weighted average SAF market price (excl. hydrogen) based on demand and availability of various types of SAF in 2030, 2040 and 2050. This is compared to the price of conventional aviation fuel with ETS and CORSIA carbon pricing in 2030, 2040 and 2050. Light blue bars indicate the price range based on data found in literature. Underlying data points are given in Appendix D.4.3.5 and Appendix D.4.3.6

5.8 Results and conclusions

Decarbonisation impact

The use of sustainable fuels and hydrogen will lead to a CO_2 reduction of 9% in 2030, 35% in 2040 and 56% in 2050, all including the demand impact of using sustainable fuels, compared to the reference scenario, which is visualised in Figure 20. The CO_2 reductions, both in relative and absolute terms, drastically increase over time as the share of sustainable fuels in the fuel pool will increase from 7% in 2030 to 80% in 2050. In terms of absolute reductions, alternative fuels reduce CO_2 emissions, compared to the reference scenario, by 19 Mt in 2030, 90 Mt in 2040 and 163 Mt in 2050, including demand-related impact. In order to achieve these reductions, approximately 12-29% of available sustainable biomass feedstock in Europe needs to be allocated towards energy production for the aviation sector[108]. Exceeding the ReFuelEU Aviation regulation by 10% in 2050, with additional non-synthetic SAF, the reliance on carbon removal technology is approximately equal to the reliance on non-synthetic SAF. Additionally, a high share of alternative fuels, produced in Europe, in the energy mix aids in achieving Europe's energy independence goals.

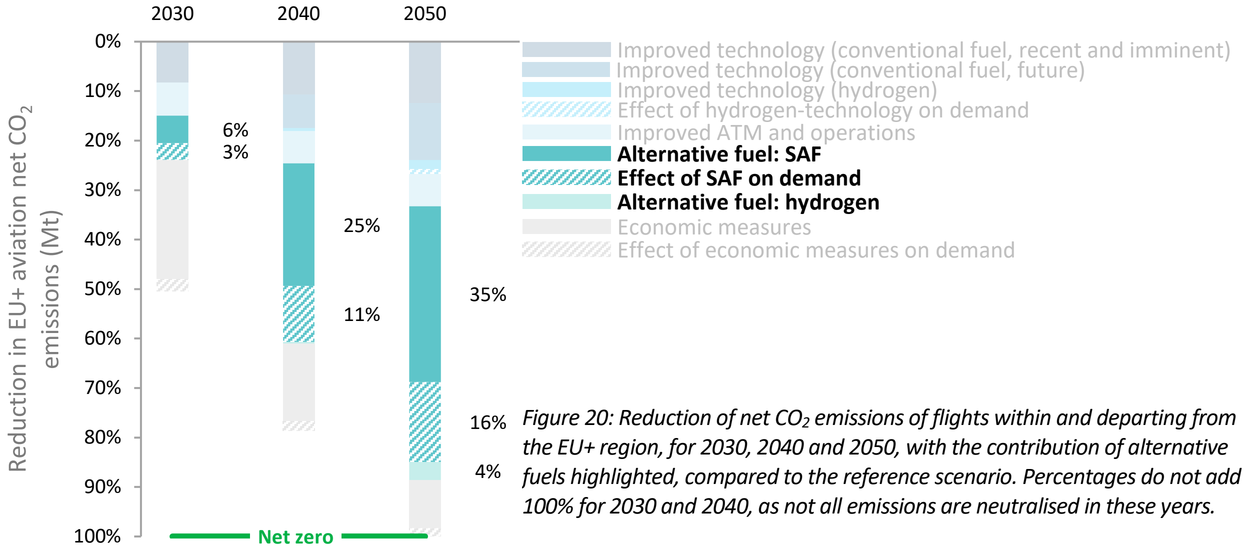

Figure 20: Reduction of net CO_2 emissions of flights within and departing from the EU+ region, for 2030, 2040 and 2050, with the contribution of alternative fuels highlighted, compared to the reference scenario. Percentages do not add to 100% for 2030 and 2040, as not all emissions are neutralised in these years.

SAF will remain at a higher price than conventional aviation fuel, including carbon pricing via ETS or CORSIA, but the price gap will decrease between now and 2050. Further reducing the price gap could facilitate higher uptake of SAF. Since the demand effect of SAF is determined by the price, SAF prices below the ones modelled in the report would (ceteris paribus) need to be compensated through additional measures such as an even higher SAF uptake. Given that SAF remains at a higher cost than conventional aviation fuel, and the use of alternative fuels increases over time, the relative CO_2 reduction due to the demand-related impact is also seen to increase over time, from 3% in 2030 to 16% in 2050. In terms of absolute reductions, the demand-related impact reduces emissions, compared to the reference scenario, by 7 Mt in 2030, 29 Mt in 2040 and 47 Mt in 2050.

In 2050, 45.7 Mt of conventional aviation fuel equivalents will be required: 36.6 Mt of sustainable fuels and 9.1 Mt of conventional aviation fuel. The sustainable fuels consist of 1.3 Mt of renewable hydrogen (3.5 Mt of SAF equivalents), 12.5 Mt synthetic SAF and 20.6 Mt of non-synthetic SAF. It is likely that synthetic SAF needs to be imported, due to the limited availability of renewable hydrogen in Europe, to achieve the mandated minimum share of synthetic aviation fuels.

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[108] 29% in low biomass availability scenario, 12% in high biomass availability scenario

Compared to the first edition of DESTINATION 2050, alternative fuels and sustainable energy in total contribute more CO_2 reductions. The use of hydrogen contributes less to achieving net zero in this iteration, due to hydrogen-powered aircraft replacing less flights compared to the first iteration.

Expenditures impact

The costs associated with the aforementioned are comprised of the price premium of alternative fuels compared to CAF. Based on presented price developments of alternative fuels the total cost of the price premium in 2030 is €7.8 bn. For 2040 this increases to €40.2 bn, and for 2050 this increases further to €48 bn. Cumulatively between 2019 and 2050 the price premium of alternative energy[109] is €786 bn. This cost is additional to the base fuel cost (at the cost of conventional aviation fuel), which between 2019 and 2050 is equivalent to €324 bn.

5.9 Implications

In order to realise the modelled CO_2 emission reductions from alternative fuels and sustainable energy and, a number of steps are deemed required.

Firstly, to realise the modelled quantities of alternative fuels and sustainable energy, its production capacity in Europe needs to increase rapidly. This could be achieved by the development of, for example, a SAF industrial strategy in Europe, that goes beyond ReFuelEU aviation. Hereto governmental support can play a crucial role in de-risking investments, by providing low-interest loans or loan guarantees to investors, as well as making investment funds available, like the European Innovation Fund. Public-private partnerships will be key to develop alternative fuel and sustainable energy quantities necessary to achieve climate goals.

Secondly, the aviation sector needs access to sufficient sustainable feedstocks for non-synthetic SAF production. Hereto further research must be done to the availability of these feedstocks, as well as an exploration of expanding the scope of feedstocks while adhering to defined sustainability criteria. This can be further supported by research and development for the pre-treatment of these feedstocks, to increase overall efficiency of SAF production from these feedstocks. Support in the development and introduction of novel SAF production technologies could also help in widening the feedstock base, as well as increase the competitive landscape for SAF production, helping reduce price and risk.

Thirdly, to allow for rapid scaling of synthetic SAF and hydrogen production, several foundational technologies must rapidly be deployed in the coming years, namely i) electrolyser capacity for the production of hydrogen as a fuel and as a feedstock, ii) carbon removal technologies for fulfil the demand for carbon in synthetic SAF production, and iii) renewable energy production, to fulfil the energy requirement of electrolysers, carbon removal technologies and synthetic SAF production. Furthermore, R&D activities must be carried out to improve efficiencies of aforementioned technologies, to reducing the total renewable energy demand for the aviation sector.

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[109] This includes the price premium of hydrogen as alternative fuel, but excludes the capital investment in new aircraft. This is considered in Chapter 3.

Fourthly, to facilitate the uptake of SAF, it is essential to address the regulatory framework. The ASTM requirements for SAF blends above 50% need to be established, and new SAF production technologies must be approved. Additionally, advocating for global emission and technology standards would harmonize national and regional regulations on emission accounting and sustainable technologies, avoiding fragmentation in aviation markets. Global harmonization of SAF uptake would facilitate an equal playing field and prevent SAF from being exported to countries with less stringent regulations.

Fifthly, the ReFuelEU Aviation regulation targets 70% SAF uptake by 2050; however, based on the work presented in this edition of DESTINATION 2050, higher blending rates, of at least 80%, are necessary to achieve climate goals. Therefore, it is recommended to further explore how SAF blends of at least 80% can be achieved. This should be accompanied by further R&D activities for infrastructure requirements for SAF and hydrogen, such as storage, blending, and transport, to allow for these blends to be used.

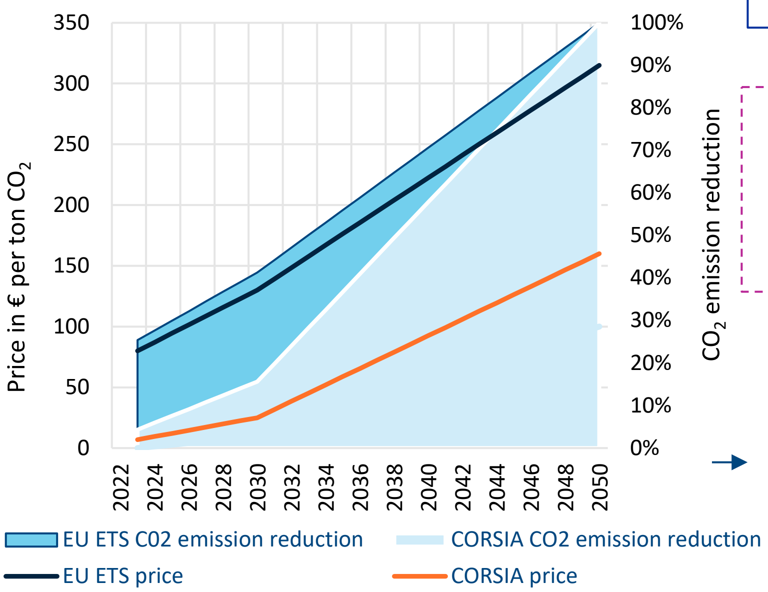
Finally, given that SAF will remain more expensive than conventional aviation fuel, including carbon pricing via EU ETS or CORSIA, enhanced policy support is necessary to increase SAF uptake. SAF allowances may also provide a beneficial mechanism to support SAF uptake between now and 2030; however, further investigation in the coming years is required to determine their effectiveness.

By addressing these points, the aviation sector can work towards achieving significant emissions reductions and realizing the modelled alternative fuels and sustainable energy scenario.

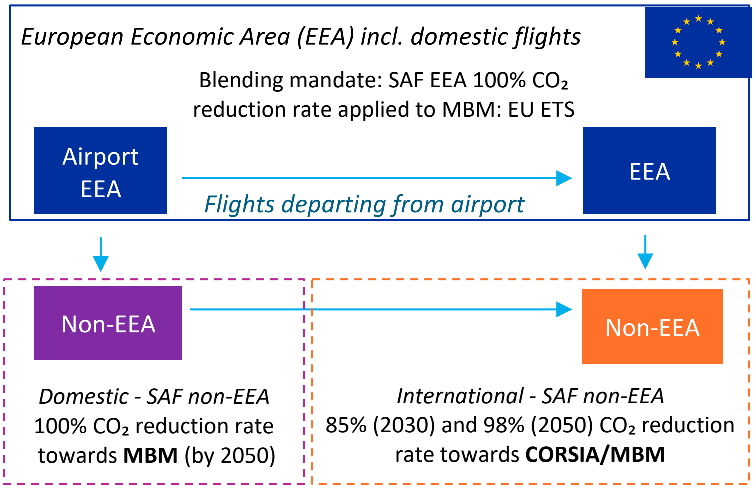
6 Economic measures

Market-based measures incentivise in-sector decarbonisation

	EU ETS	CORSIA
Market-based Measure (MBM)	Cap and trade	Offsetting
Instrument	Emissions allowances	Carbon credits



Scope and framework for modelling assumptions



European Economic Area (EEA) incl. domestic flights

Blending mandate: SAF EEA 100% CO_2 reduction rate applied to MBM: EU ETS

Domestic - SAF non-EEA
100% CO_2 reduction rate towards **MBM** (by 2050)

International - SAF non-EEA
85% (2030) and 98% (2050) CO_2 reduction rate towards **CORSIA/MBM**

Crucial assumptions

- Market-based Measures increase in their CO_2 emissions reduction and price over time
- Relative importance of MBMs decreases over time as other CO_2 emission reduction pillars expand

Limitations and uncertainties

- CORSIA regulation of carbon neutral growth is not aligned with net zero CO_2 emissions goal
- Future of CORSIA is uncertain for flights leaving the EEA and beyond 2035
- Direct Air Carbon Capture and Storage (DACCS) is required for net zero CO_2 emissions goal in 2050 but neither part of EU ETS nor demonstrated at industrial scale
- UK alignment with EU ETS is uncertain
- Role of SAF allowances with respect to EU ETS beyond 2030 is uncertain
- Regulation in non-EEA domestic markets is uncertain

Implications

- Ensure CORSIA/MBM for flights leaving EEA that are aligned with the net zero goal
- Monitor MBM instrument alignment with the Paris Agreement
- Earmark EU ETS auctioned allowances revenues for climate sustainability ambitions
- Monitor and regulate DACCS
- Monitor impact of SAF allowances on the net zero goal if extended beyond 2030
- Support implementation of market-based measures on all non-EEA domestic aviation markets

The cumulative cost of economic measures up to 2050 is **€220 bn**

6.1 Introduction

Economic measures assign a price to CO_2 emissions to ensure that airlines take climate costs explicitly into account in their business decisions. This internalisation of climate costs is increasingly recognised as a key mechanism to reduce emissions. To ensure cost-effectiveness, economic measures must be market-based where emissions can be priced through emission trading and offsetting schemes. These schemes are currently favoured over direct levies on CO_2 emissions which would be another form of internalization. The two former measures have proven to be politically more feasible which makes them preferable over levies since the use of as few measures as possible ensures efficiency and the earmarking of revenues towards decarbonisation ensure effectiveness.

Emissions trading schemes such as EU ETS rely on the cap-and-trade system wherein a cap is put on the amount of emissions allowed and allowances are traded between entities on the market. An offsetting scheme such as CORSIA allows for emissions to be compensated by investing in carbon removal projects. Concerns regarding the quality of carbon offsets are considerable and addressed in the sections below.

The European Emission Trading Scheme (EU ETS) is the mechanism that is implemented in Europe while ICAO's Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA) is applied to international flights outside the European Economic Area. Together, they aim to incentivise aviation decarbonisation and bridge the gap until breakthrough technologies and SAFs become widely available. Through this and because of their regulatory interdependencies, market-based measures are linked to all other measures generally and in particular to SAF (allowances), see below.

> LINK TO OTHER PILLARS
>
> **SAF applicability to EU ETS and CORSIA**
>
> Since 2012, biofuels used on EU ETS flights benefit from zero emission factor. This equals to an EU ETS carbon price incentive for SAF use at about €250/ tonne fuel depending on the EU ETS price per tonne of CO_2. For CORSIA, SAF lowers the offsetting requirement according to the lifecycle emission savings.
>
> **SAF allowances**
>
> SAF allowances in support of additional SAF uptake can affect the quantity and price of EU ETS certificates, in particular when available beyond 2030 which is not envisioned in this DESTINATION 2050 update. This SAF price incentive is additional to the CO_2 emission reduction applicability of SAF to EU ETS and CORSIA above, see s Section 5.7.
>
> RELEVANCE TO NON-CO_2 CLIMATE IMPACT OF AVIATION
>
> Non-CO_2 GHG effects are under consideration by the EU including the connection to the EU ETS cost.

Economic measures may result in in-sector and out-of-sector emission reduction. In-sector reductions are described in the other DESTINATION 2050 pillars. Out-of-sector reductions are achieved through investing in other sectors. This should be a measure of last resort since, financing in-sector sustainability measures yields substantially lower risks than realizing the same emission savings through out-of-sector carbon reduction (see for more detailed information on DACCS and other carbon removal alternatives, i.e. Negative Emission Technologies (NETs) in the price of Net Zero (Adler et al., 2023).

Over time, breakthrough technologies and the use of SAF reduce the role of economic measures. The price of allowances and carbon credits will increase as the most cost-effective decarbonisation measures are taken first. Marginal abatement costs for decarbonisation are expected to rise, and this will eventually lead to a price whereby carbon removal projects become economically attractive to investors. In 2050, all remaining emissions need to be balanced by *carbon removal projects*, which are assumed to lead to the issuance of additional carbon emission allowances and carbon credits. Direct Air Capture and Carbon Storage (DACCS) is seen as an important enabling technology for deployment in the medium term in order to create high quality carbon allowances and credits.

> **CARBON DIOXIDE REMOVAL FOR AVIATION IN THE EU: THE CASE OF DIRECT AIR CAPTURE AND CARBON STORAGE (DACCS))**
> Carbon dioxide removals, also known as carbon removal projects or greenhouse gas removal projects, refer to the physical removal of carbon dioxide from the atmosphere via nature-based solutions[110] and technology-based solutions[111]. Carbon removals are required to achieve net zero CO_2 emissions at a global level as well as to meet the EU Green Deal objective of climate neutrality by 2050, as stated by both the Intergovernmental Panel on Climate Change (IPCC) and the International Energy Agency (IEA). These organisations also highlight the key role of neutralizing residual emissions from hard-to-abate sectors, including aviation.
>
> The DESTINATION 2050 roadmap estimates that 29 Mt CO_2 of aviation's residual emissions will need to be abated with carbon dioxide removal projects in the EU in 2050. Other industry scenarios developed by the International Civil Aviation Organization, the Air Transport Action Group (ATAG) and the International Air Transport Association (IATA) (ICAO, 2022c) also find carbon dioxide removal to be necessary to reach net zero aviation emissions.
>
> Carbon removal through Direct Air Capture and Carbon Storage (DACCS) captures the emitted CO_2 directly from the air. To achieve net zero CO_2 from aviation in 2050, high quality carbon removal technologies such as DACCS are crucial. DACCS promises higher quality carbon removal as it is expected to achieve permanent carbon removal at lower collateral environmental cost than other carbon removal technologies (Adler, et al., 2023). All economic measures in scope for DESTINATION 2050 rely heavily on DACCS in their assumptions as well as their ability to ensure net zero CO_2 emissions by 2050.

Currently, DACCS has not been demonstrated at large scale which is required to accommodate the aviation sector's residual emission. DACCS is likely to require substantial amounts of green energy, storage facilities and finances (see also Chapter 5). Since by 2050, the CO_2 reductions from economic measures (i.e. EU ETS and CORSIA) are assumed to be DACCS, it can also be assumed that the price for an avoided tonne of CO_2 is identical to the price of a tonne CO_2 capture by DACCs. This assumed price equality is the basis of the efficient price assumption defining the price of EU ETS and CORSIA in the year 2050. The chapter is structured as follows. Section 6.2 presents the developments since the release of the first edition of the DESTINATION 2050 roadmap report published in February 2021. Section 6.3 gives insight to the approach used, based on which Section 6.4 presents the decarbonisation and expenditure impact of the measures. Section 6.5 provides implications to further strengthen the measures' legislations and ensure their effectiveness.

Scope

This study focuses on two supranational legislations which determine the market-based measures of interest; an emissions trading scheme in the form of the EU ETS and an offsetting scheme in the form of CORSIA. Since 2012, EU ETS covers emissions from intra-EEA flights with a temporary derogation for extra-EEA flights. CORSIA has a global reach and was introduced in 2021 for international flights. The schemes differ in approach, geographical coverage, applicability and ambition level. It is yet unclear how both measures will develop and co-exist in the future. One global measure, or coordinated measures, would be more efficient, (in most cases) lower market distortion and carbon leakage, but should also be ambitious enough to indeed sufficiently contribute to emissions reduction and climate goals. However, it is currently considered likely that multiple schemes remain in place for the time being.

The scope of this study does not expand to national legislations such as taxes, or to other charges such as ticket surcharges or supply cap measures such as a CO_2 ceiling. Indeed, the existing market-based measures, in particular EU ETS, would make additional measures that address the same externality, i.e. CO_2 price market failure, inefficient The Tinbergen Rule (Tinbergen, 1952), applied to the EU ETS, suggests that each environmental policy goal—such as reducing carbon emissions—requires a distinct instrument, like the cap-and-trade system, to effectively target and manage that specific objective.

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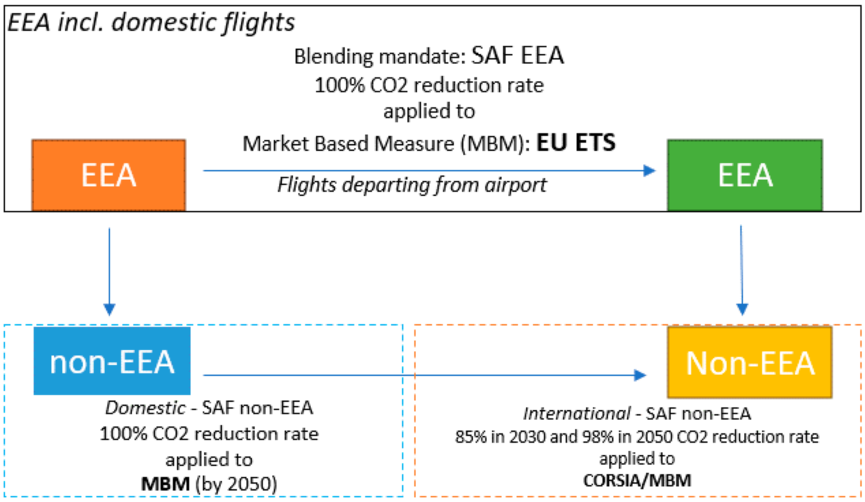
[110] For example, afforestation, reforestation, ocean-based removals, biochar.
[111] For example, bioenergy with carbon capture and storage, direct air carbon capture, ocean-based carbon capture.

The geographical applicability of market-based measures (MBM) as envisioned by this DESTINATION 2050 update and as depicted in Figure 21 is derived from the review of both measures as well as their expected evolution and interactions. For flights within the EEA, EU ETS applies. For flights leaving the EEA, CORSIA applies or an MBM that provides credible, high quality off-sets leading to net zero CO_2 in 2050. This is a critical and strong assumption about flights leaving the EEA that is not consistent with current legislation. For both economic measures, the interaction between SAF blending mandates and market-based measures is captured through assumed CO_2 reduction percentages. More details providing foundations for this figure can be found in the following sections.



Note: CORSIA extends in its planning until 2035 and the assumption made towards 2050 is agnostic to what MBM that applies to international flights departing from the EEA, CORSIA or other. For international travel between non-EEA countries, the price effect from sustainability measures is in scope while the C02 emissions are not counted towards EEA emission targets of DESTINATION 2050.

Figure 21: Market Based Measures: EU ETS and CORSIA

6.2 Developments since the initial roadmap

The European Green Deal, approved in 2020, is a set of policy initiatives by the European Commission with the overarching aim of making the European Union (EU) climate neutral in 2050. In 2021, the European Climate Law was passed, which legislated that greenhouse gas emissions should be 55% lower in 2030 compared to 1990. The Fit for 55 package, proposed by the European commission in 2021, is a large set of proposed legislation detailing how the European Union plans to reach this target. This package included a revision of the European Union Emissions Trading System (EU ETS) and a revision of the EU ETS for aviation. While both revisions have now been adopted, subsequent implementing and/or delegated acts, reports and evaluations, and/or revisions are expected in the coming months and years. Significant upcoming developments include the potential introduction of EU ETS for flights from and to countries not applying CORSIA in 2027, the discussions about a possible EU ETS scope extension, as well as the decision regarding the future of SAF allowances in 2028. The timeline below (not exhaustively) summarises the notable developments that have taken place in the past three years as well as the expected upcoming developments. It distinguishes between developments in government and policy, industry progress and joint actions.

02/2021: Launch of the DESTINATION 2050 alliance and the first European Aviation Net-Zero roadmap

DESTINATION 2050

10/2022: 41st ICAO assembly

Assembly lowers the base line emissions for the scheme period between 2024-2035 to 85% of 2019 emissions

05/2023: Reforms to the European Union Emissions Trading System (EU ETS)

Reforms were published in the Official Journal of the European Union (EC, 2023g; Ruiz P. , 2023)

05/2023: Directive 2023/958

revising the EU-ETS for aviation adopted by EU Parliament and the Council

10/2023: SAF Allowances (EU) 2023/2122

Commission Implementing Regulation, Revision of the Monitoring and Reporting Regulation (EC, 2023d)

07/2023: CORSIA Second Edition of Annex 16, Volume IV in effect

01/2024: 126 states have announced their participation in CORSIA

CORSIA Second Edition of Annex 16, Volume IV applies (ICAO, 2024b)

01/2024: EU ETS SAF allowances start

Q1 2024: SAF Allowances

Revision of the Accreditation and Verification Regulation

04/2024: Carbon Removals and Carbon Farming Regulation

European Parliament adopted the provisional agreement on the Carbon Removals and Carbon Farming (CRCF) Regulation

Q3 2024: SAF Allowances

Commission delegated regulation establishing of the detailed rules for the yearly calculation of the cost difference and for the allocation of allowances for uplifting of eligible fuels

2025: SAF Allowances

Annual publication of the average cost difference between conventional aviation fuel and the eligible sustainable aviation fuels (adjusted) from 2025

2026: EU Commission re-evaluates CORSIA

01/2027: EU ETS for flights to/from countries not applying CORSIA (and not LDC or SIDS).

All EU ETS allowances are now either auctioned or bought from other sectors due to the end of free allowances

Q1 2028: SAF Allowances,

the Commission will carry out an evaluation of the support scheme and may propose to allocate an additional capped number of allowances up until 2034, in particular for the uplift of RFNBOs

6.3 Approach to economic measures

To assess the effectiveness and efficiency of economics measures, the approach of the first edition of the DESTINATION 2050 roadmap is replicated here. The current and upcoming legislation regarding economic measures in scope are reviewed based on the literature and regulation. Building on these sources, assumptions on price levels and volumes are formulated for the implementation in the forecasts to arrive at prospective travel demand and CO_2 emissions.

The quality of EU ETS and carbon credits is measured in their effectiveness to reduce CO_2 emissions. Since CO_2 emissions reductions are traded on a global marketplace, price differences largely reflect quality characteristics such as credibility and emission reduction effectiveness. One major update of this DESTINATION 2050 report is the joint consideration of quantity, quality and prices of market-based measures using the Efficient Market Hypothesis (EMH) [112]. The necessary assumption for the EMH to apply is that EU ETS and carbon credits are tradable assets and therefore their long-term average price contains all information known to the market participants. This is further supported in the case of EU ETS by a recent article from Sattarhoff & Gronwald (2022) that finds that the EU ETS is more efficient than the US stock market due to the lower exposure to external price shocks.

6.3.1 EU ETS: European Union Emissions Trading System

The European Union Emissions Trading System is a key element of the European Climate ambitions further strengthened in the Fit for 55 revision.

Current status

The European Parliament and the Council adopted Directive 2023/958 on 10 May 2023, therein increasing ambitions of the European Climate Law. Contained therein, Article 3c(5) states that the total quantity of aviation allowances should be fixed at the current levels, and that the general ETS linear reduction factor is applied, as per Commission Decision (EU) 2023/2440 of 27 October 2023. The phase out of free allocations is set to occur faster than previously anticipated, with the last free allowances available until 2026. Additionally, under the Transparency Rule defined in Article 14(6), the Commission intends to publish information on aviation emission information per airport and airline within the EEA, departing the EEA, incoming to the EEA and between third countries. Emissions will also be published per aircraft operator detailing the volume of alternative fuel used (and supported by) the EU ETS as well as the amounts and type of credits used for CORSIA offsetting. In general, the Commission implements international CORSIA regulation into EU regulation. This might allow the Commission to determine the future quality of carbon credits, see later explanations regarding CORSIA quality in this chapter and Figure 24.

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[112] Efficient Market Hypothesis (EMH). The EMH was pioneered by Eugene Fama and Paul Samuelson for which they received the Nobel prize. While the concept has roots in the early 20th century, Eugene Fama is often credited with formalizing and popularizing the Efficient Market Hypothesis in his seminal paper titled "Random Walks in Stock Market Prices," published in the Journal of Business in 1965.

Assumptions

The total quantity of allowances on the EU ETS market is composed of allowances which are free, auctioned or bought from other sectors, including DACCS at a later stage. As depicted in Figure 22, all aviation emissions decrease over time until net emissions reach zero in 2050 [113], i.e. the quantity of residual emissions is matched by negative emissions. DACCS is expected to provide negative emissions from 2042 onwards (van der Sman, Peerlings, Kos, Lieshout, & Boonekamp, 2021). The purchase of allowances from other sectors remains necessary until DACCs provides sufficient negative emissions by 2050.

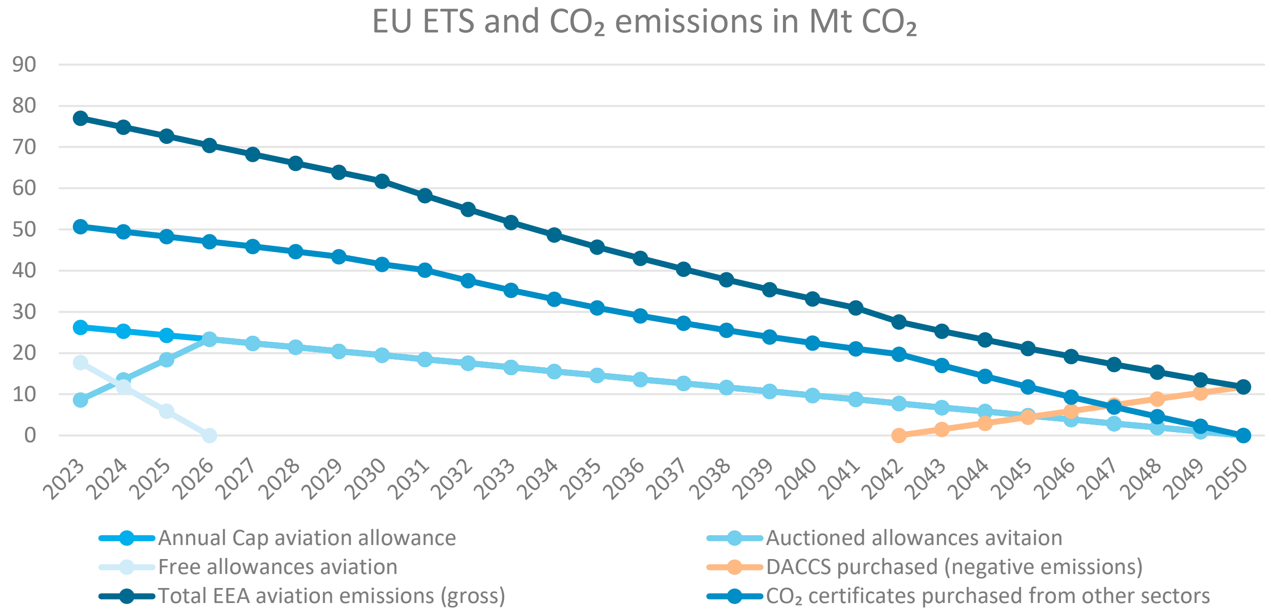

Figure 22: EU ETS emissions and allowances schemes. Note: The auctioned UK ETS allowances are not included in this figure whereas total EEA emissions (gross) does include UK emissions

The price of an EU ETS allowance in 2030 is assumed to be €130 per tonne of CO_2 in line with predictions by Morgan Stanley (2022) , BofA (2021), and Pietzcker et al. (2021), as also shown in Table 47. Approximately 19.5 Mt CO_2 will be available from auctioned allowances whereas an additional 41.4 Mt CO_2 will be required for the forecasted traffic scenario, see for more detailed model description of the net zero pathway Chapter 2. Allowances bought from other sectors, i.e. out-of-sector allowances, are modelled to be equivalent to emissions reductions in the aviation sector. By 2050 their price is assumed to be €315 per tonne of CO_2 emission. Since there will be no more auctioned allowances by then it is necessary to assume that these are from DACCS carbon removal projects. However, the use of carbon removal projects in this context is currently not in line with EU legislation. According to model predictions about 10.5 Mt CO_2 will be necessary for flights within the EEA by the year 2050. Therefore, carbon removal projects are assumed to lead to the issuance of additional allowances and the price is equivalent to their production, cf. the *efficient price assumption* in the first edition of the DESTINATION 2050 roadmap (van der Sman, Peerlings, Kos, Lieshout, & Boonekamp, 2021, p. 131) and in the Price of Net Zero (Adler, et al., 2023, Sec. 3.4.2). In other words, under an efficient trading scheme the allowance prices cannot exceed the price of the most cost-effective (set of) measure(s) to achieve a specific goal. The assumed price developments of EU ETS can be followed in Figure 23.

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[113] It is beyond the scope of this report to assess the availability and the quantity of EU ETS to support this transition in the long-term. There is emerging evidence that EU ETS supply might approach zero before the DESTINATION 2050 end period in 2050 which would have a strong effect on available certificates and prices, see (Pahle, Quemin, Osorio,, Günther, & & Pietzcker, 2023). Furthermore, if sectors outside aviation do not reduce emissions on time, the required emission certificates to be purchased from other sectors might not be available in sufficient quantity, see (Appunn & Wettengel, 2024).

> **THE ROLE OF THE UK IN EU ETS**
>
> The auctioned UK ETS allowances are not included in the total amount of allowances available even though UK emissions are included in the total EEA emissions. While in the previous DESTINATION 2050 model, the UK emissions were part of the EEA emissions, the recent aviation allowances calculations by the Commission appear to exclude any emissions certificates necessary for the UK. As of July 2024, the adjustments to the UK ETS are ongoing and as such there is currently no clarity to the allocation of UK ETS towards UK aviation by 2030 and beyond. Furthermore, due to the structural differences between the UK and EU ETS, non-negligible price differences cannot be ruled out in the future. However, within the DESTINATION 2050 roadmap, generally and therefore also for EU ETS, the United Kingdom is assumed to have full regulatory compliance with the EEA, therefore also in terms of ETS prices and ETS allowances volumes. In 2030, the total share of aviation emissions from the UK in the EEA+UK emissions is 21%, 32 Mt CO_2 out of 154 Mt CO_2 emissions. Of those, the UK aviation will be responsible for 7.4 Mt CO_2 emissions that are subject to the ETS (23% of the EEA+UK total emissions). In summary, the status of the substantial CO_2 emission from the UK aviation sector remains uncertain and a concern with respect to the net zero aim of DESTINATION 2050.

Since a lower price of EU ETS allowances in another sector would motivate the aviation sector to buy these before bidding for sector specific allowances, it is assumed that there is a price equivalence between auctioned allowances and out-of-sector allowances. The main difference is that out-of-sector allowances are considered to be 100% emissions reductions while the auctioned allowances are considered to reduce emissions depending on the quality of the investment taken with the auction revenues.

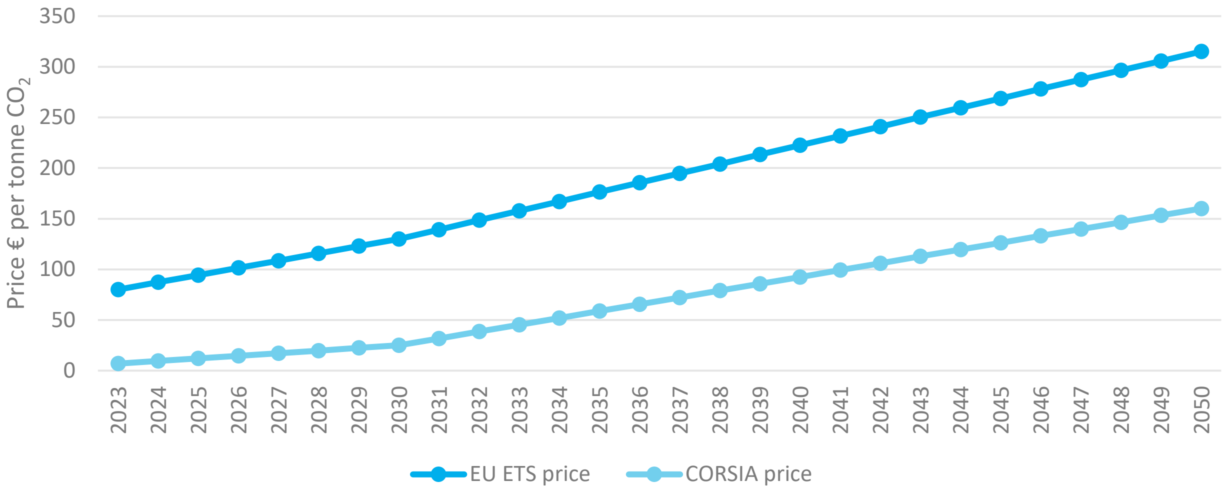

Figure 23: EU ETS and CORSIA prices over time. Note: Expressed in € prices of the year 2019. Price forecast based on literature see Table 47 and Table 48. Potential UK ETS price differences from EU ETS are not included here

As an update to the previous DESTINATION 2050, the calculation of the CO_2 emission reduction potential from CORSIA and EU ETS is now based on the current price in relation to the price of DACCS in 2050 which serves as an indication of the CO_2 emission reduction quality. Implicit is the Efficient Market Hypothesis (EMH) assumption that average, long-term prices reflect the underlying characteristics of technologies available and the information of stakeholders on rules and regulations. Stakeholders would make use of the most cost-efficient technologies available at that time. EU ETS emission reduction from auctioned allowances in 2030 would then be about 40% (vs 50% previously) and 15% for CORSIA (vs 100% previously), as illustrated in Figure 24. By 2050, both measures lead to 100% emission reduction but the price difference between EU and global DACCS remains, since the latter is assumed to be more affordable in comparison to the former supported by the analysis in the previous DESTINATION 2050 roadmap. This figures also highlights that regulation that controls acceptable carbon removal technologies can change the emission reduction pathway as long as the supply of these technologies is sufficiently scalable.

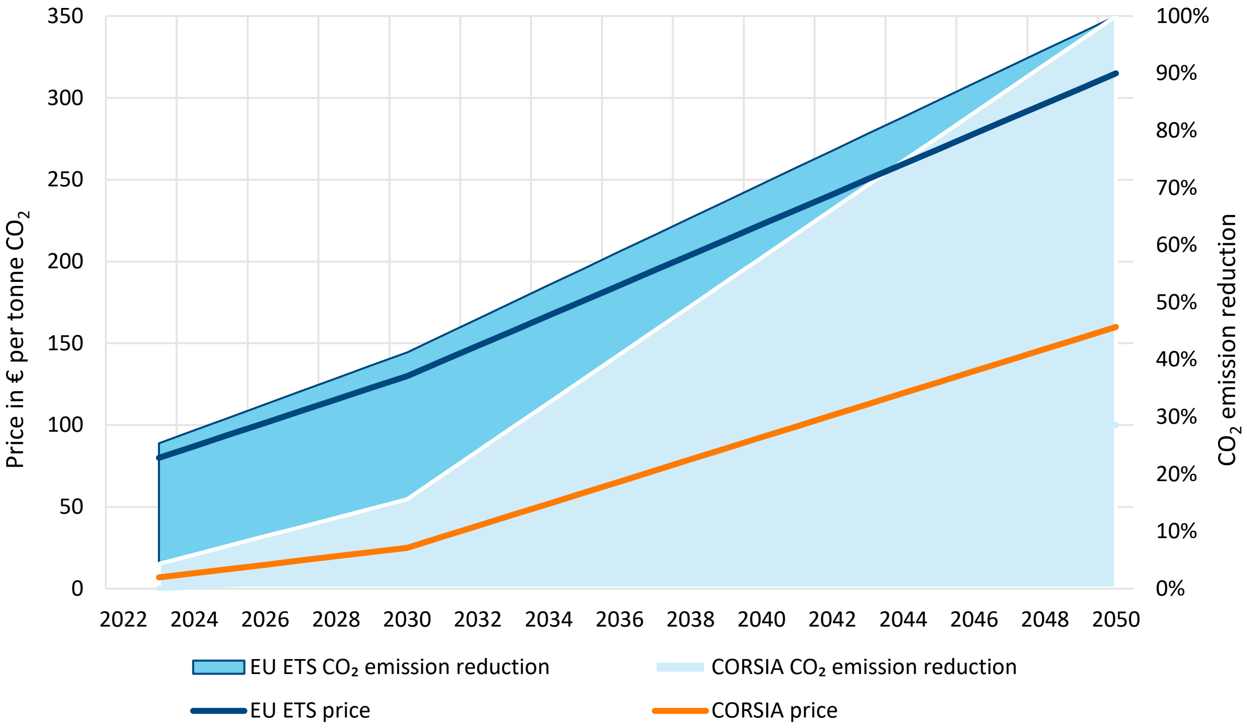

Figure 24: Expected price and CO_2 emission reduction for EU ETS and CORSIA between 2023 and 2050

The quality of the investments made from the revenues from auctioned allowances should be reflected in the price of the EU ETS allowances according to the Efficient Market Hypothesis. Such investments can for instance be in the form of the EU ETS Innovation Fund which was established by Article 10a(8) of Directive 2003/87/EC to support across all Member States innovation in low-carbon technologies and processes. The source of the funding comes from EU ETS auctioning and funded programs should involve innovative technologies that strive for climate neutrality. Funding occurs through Grants and Actions towards deployment of net zero and innovative technologies. This can be in the form of support to manufacturing, production and use in energy intensive industries, renewables, energy storage, carbon capture use and storage, net zero mobility and buildings. Therefore, the innovation fund can also contribute to aviation sustainability funding. Discussions on the possible establishment of an aviation-specific part of funding (ringfencing EU ETS revenues from aviation) are still ongoing as of July 2024. Figure 25 shows how the Innovation Fund fits into the broader set of climate finance of the EU; Adler et al. (2023, Chapter 5) provides further discussion on public support mechanisms.

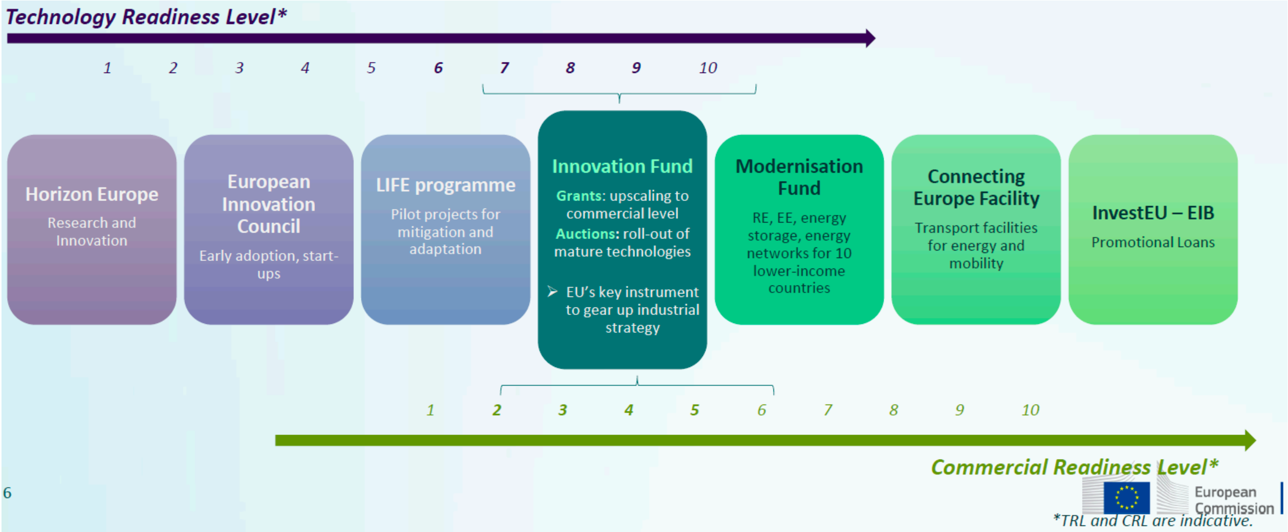

Figure 25: Innovation fund within the wider public finance support system (DG CLIMA, 2024)

Potential impact

From all pillars considered, the EU ETS is expected to have the highest share of CO_2 emissions reduction by 2030. First, the 19.5 Mt CO_2 of auctioned EU ETS allowances are assumed to reduce emissions by about 40% through their use in investment and innovation toward climate neutral technologies and programme, and therefore to be equivalent to 7.9 Mt CO_2 emission reduction. Second, EU ETS allowances bought out-of-sector from industries that are able to abate more cost efficiently are assumed to account for 100% emission reductions, equivalent to 41.4 Mt CO_2. By 2050, EU ETS emission reductions are assumed to be in the form of DACCS amounting to 10.5 Mt CO_2 and resulting in carbon neutrality at this point in time due to the offsetting of the remaining emissions not covered by the other pillars.

Table 47: EU ETS amounts, prices and CO_2 emission reductions

Year	Type of measure	Amount (Mt CO_2)	Price (2019 €)	CO_2 reduction	Note on price assumptions
2030	EU-ETS; auctioned allowances	19.5	€130	40%	Predictions by Morgan Stanley (2022), BofA (2021), and Pietzcker et al. (2021)
	EU-ETS allowances bought from other sectors	41.4	€130	100%	Market price equivalence with auctioned allowances due to trading
2050	EU-ETS allowances bought from other sectors	10.5	€315	100%	Price based on cost of carbon removal projects DACCS within the EEA, see more information in Adler et al. (2023)

Assessment and implications

EU ETS policy developments which guarantee a market based, cost-efficient approach to CO_2 emission reductions are commendable. More specifically, transparency in emission accounting and regulation as well as its steady implementation suggest EU ETS will be an effective measure. When compared to other measures such as the Energy Tax Directive (ETD), the earmarking and reinvestment from funds of EU ETS auctioning provides a higher sustainable efficiency compared to funds without specific allocation, see (SEO & NLR, 2022). Nevertheless, there should be scrutiny regarding the extent to which the EU Innovation Fund and other earmarked funding translate into actual CO_2 emission reductions. Fully ringfencing the entirety of the EU ETS revenues towards a net zero aim could further improve its effectiveness. Note that earmarking and ringfencing of revenues has a distributional effect and the efficiency, effectiveness, optimality, political and stakeholder support of such a policy decision should be investigated prior to such a decision.

As the DESTINATION 2050 roadmap pathway will still have unabated in-sector CO_2 emissions by 2050 which require off-setting to achieve carbon neutrality, credible, high quality greenhouse gas removal projects such as DACCS are required to be included as eligible out-of-sector source of allowances. This is further supported by the attestation that only out-of-sector allowances lead to 100% CO_2 emission reductions while only a share of EU ETS allowances that is auctioned translates into actual emission reductions.

With regards to SAF, the EU ETS 100% SAF CO_2 emissions reduction certification by 2030 overstates the true associated reduction of SAF blended fuels available at this stage. This one-to-one accounting has been introduced in the context of promoting higher SAF production and uptake in the early stages, as the CO_2 accounting of SAF in terms of the EU ETS increases the value of SAF itself. This approach should be re-evaluated in international comparison s since there are otherwise net-negative emissions by covering the price differential.

6.3.2 CORSIA: Carbon Offsetting and Reduction Scheme for International Aviation

Offsetting is an action by a company or individual to compensate for their emissions by financing a reduction in emissions elsewhere. Offsetting and carbon markets are fundamental components of global, regional, and national emissions reduction policies.

In 2016, the International Civil Aviation Organization (ICAO) adopted the Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA) to address CO_2 emissions from international aviation. Offsetting is an action by a company or individual to compensate for their emissions by financing a reduction in emissions elsewhere. Offsetting and carbon markets are fundamental components of global, regional, and national emissions reduction policies.

In 2021, airlines committed to reaching net zero carbon emissions by 2050. Governments followed suit at ICAO's 41st Assembly by adopting a Long-Term Aspirational Goal for aviation. On 27 June 2018, ICAO adopted the international Standards and Recommended Practices (SARPs) for CORSIA as Annex 16, volume IV, to the Chicago Convention. On the 1st of January 2024, the Second Edition of Annex 16, Volume IV became applicable on which updates the following section is based.

Current status – International Perspective

As of 1 January 2024, 126 States have announced their intention to participate in CORSIA, as shown in Figure 26 (ICAO, 2022d) [114]. Considering their special circumstances and respective capabilities, ICAO member states agreed to implement CORSIA offsetting requirements in phases. Between 2021 and 2026, only flights between States which volunteer to participate in CORSIA are subject to offsetting requirements. This first phase is divided in two parts, the pilot phase between 2021 and 2024, and the first application phase between 2024 and 2026. Then, from 2027 onwards, all international flights will be subject to offsetting requirements. However, flights to and from Least Developed Countries, Small Island Developing States, Landlocked Developing Countries and States which represented less than 0.5% of the global international revenue tonne per kilometre (RTK) in 2018 will be exempt from offsetting requirements unless these States participate on a voluntary basis.

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[114] 11 more States (Antigua and Barbuda, Bahrain, Ecuador, Kuwait, Samoa, Seychelles, Sierra Leone, Solomon Islands, Mauritius, Malawi, and Haiti) announced their intention to participate in CORSIA from 1 January 2024, which would bring the total number of participating States to 126.

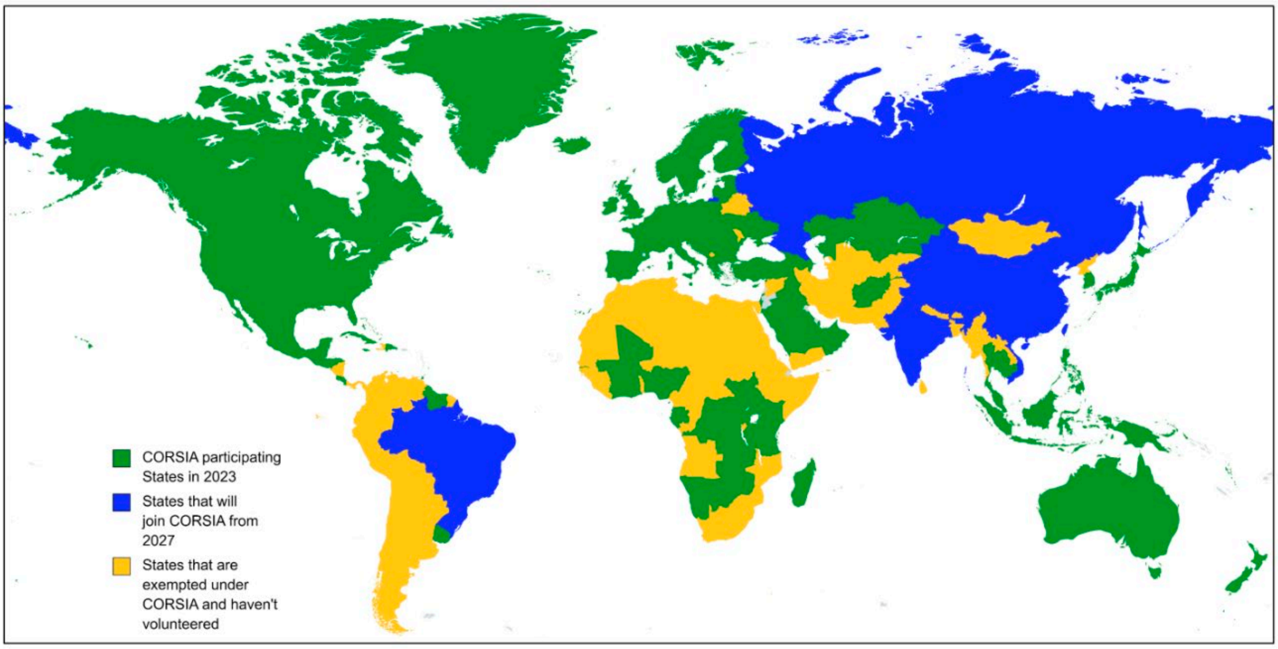
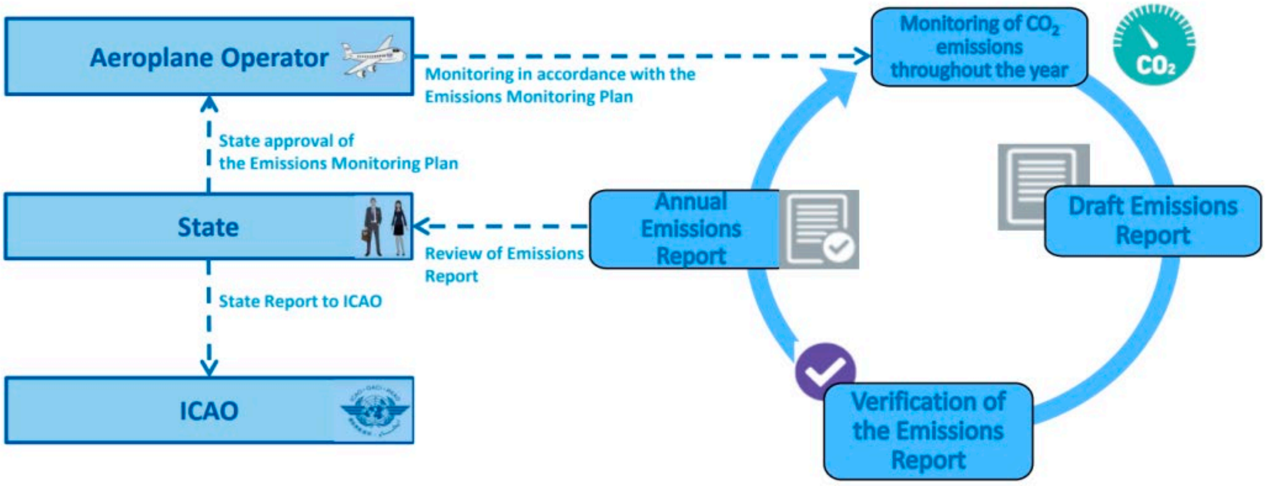


Figure 26: ICAO CORSIA members (IATA, 2024a)

Upon completion of each 3-year compliance period, operators will have to demonstrate that they have met their offsetting requirements by cancelling the appropriate number of emissions units. More precisely, the CORSIA process, detailed in Figure 27, has airline operators monitor and report their CO_2 emissions to states. These verify emission reports and compile annual information for ICAO.



Source: ICAO Secretariat, "CORSIA MRV System: Monitoring of CO2 Emissions" report

Figure 27: ICAO CORSIA MRV PROCESS

Current status – EEA Perspective

As the regional scope of CORSIA includes the EEA region, it overlaps with the countries to which EU ETS is applied. Therefore, the EU Commission has amended **Council Decision (EU) 2020/954** to implement both CORSIA and EU ETS regulations accordingly. First, the Commission redefines in Article 25a the overall regional scope to which either EU ETS or CORSIA is applied. The article also defines which routes are exempted from complying to CORSIA. Second, Article 11a(8) defines which credits are eligible for CORSIA off-setting; credits in accordance with Article 6 of the Paris Agreement as well as units from crediting programs approved by ICAO. Article 12(6) lays down the detailed rules for calculating CORSIA related off-setting. These provide ground for EU based airlines operating extra-EEA flights towards a destination participating to CORSIA to be authorized to use eligible international emission credits to comply with CORSIA. As per Article 11a(3), double counting for the use of credits must be prevented. This is consistent with the amendment of Regulation (EU) 2019/1603 to include requirements for reporting unit cancellation as well as the use of CORSIA eligible fuels, so as to ensure proper monitoring, reporting and verification of activities falling under the scope of CORSIA.

> **THE QUALITY OF CARBON CREDITS**
>
> The quality claims made by some of carbon offsetting projects have received persistent criticism in the media (Lakhani, 2019; Song, 2019) and in academia (Cavanagh & Benjaminsen, 2014; Battocletti, Enriques, & Romano, 2023). Critiques towards the use of carbon credits revolve around various concerns and challenges associated with their effectiveness, transparency, and overall impact on addressing climate change. Here are some common points of criticism:
>
> 1. **Effectiveness, additionality and insufficiency**: Critics argue that carbon credits may not always result in genuine emissions reductions. The concept of "additionality" is crucial; it questions whether the emissions reductions claimed through carbon credits would have occurred even without the financial incentive provided by the credit system. Within this context, some may argue in favor of a more comprehensive carbon pricing mechanism to drive significant and sustained emissions reduction. The price per tonne at below €7 in summer of 2024 suggests low quality of and/or low demand for carbon credits, also reflected through the use of EMH here.
>
> 2. **Offsetting versus reduction, dependency and short-term focus:** Carbon credits are often criticized for allowing companies to offset their emissions rather than making genuine efforts to reduce their carbon footprint. Offsetting may create a false sense of environmental responsibility, leading to a lack of motivation for companies to invest in sustainable practices and technologies, therefore delaying the implementation of necessary changes. This is worsened by the fact that this system encourages a short-term focus, potentially neglecting more long term and systemic changes necessary to address climate change effectively thereby creating an unnecessary dependency on off-sets.
>
> 3. **Quality of projects and external effects:** Concerns exist about the quality and environmental integrity of projects that generate carbon credits. Some argue that certain projects, particularly in the forestry and land-use sectors, may have unintended consequences such as land grabbing, displacement of local communities, or unsustainable practices. This brings forward the question of environmental and social justice in the implementation of carbon removal projects.
>
> 4. **Lack of global standards, double counting and leakage:** The absence of consistent and universally accepted standards for carbon credit verification and certification is a significant criticism. The lack of a standardized approach makes it difficult to compare and assess the credibility of different carbon credit programs. It may also accentuate the risks of double counting, leading to an overestimation of the overall impact. Additionally, the concept of "leakage" involves the possibility that emissions reductions in one location may be offset by increased emissions in another area.
>
> 5. **Financial speculation:** The carbon market has been criticized for attracting financial speculation, potentially leading to market manipulation and price volatility. Critics argue that this financial focus could divert attention from actual emissions reduction efforts. A counterargument is that the use of EU ETS on the financial markets has provided wider benefits and is more efficient than the US stock market due to the lower exposure to shocks (Sattarhoff & Gronwald, 2022).
>
> The quality of carbon credits could, under the right circumstances increase over time under the following four arguments: First, the effort of the Commission to ensure the quality of carbon credits by setting minimum requirements, see above. Second, the threat of an EU ETS scope expansion. Third, evidence that voluntary carbon market participants appear to favour higher quality carbon credits that are nature based, have co-benefits and align with Sustainable Development Goals (Forest Trends Association, 2023; Ecosystem Marketplace, 2023). Fourth, the Core Carbon Principles as defined by the Integrity Council for the Voluntary Carbon Markets (ICVCM) and the Voluntary Carbon Market Initiative (VCMI) to strengthen the integrity of voluntary carbon markets.

Domestic aviation markets outside the EEA are not covered by CORISA. As of January 2024, there are 29 emission trading schemes active, 11 under consideration and 8 under development, as shown in Figure 28. Of those only the EEA, UK, China and Korea have an ETS that addresses aviation emissions.

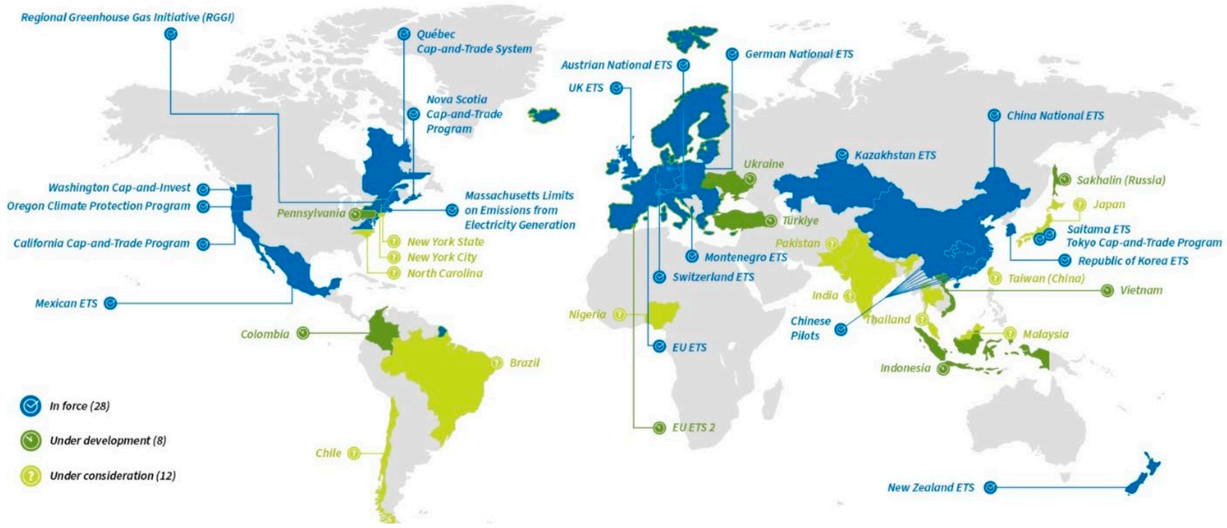


Figure 28: Domestic emission trading schemes, globally for all industries (ICAP, 2023)

Assumptions

Several strong assumptions are made regarding CORSIA and its implementation. First, all relevant countries are assumed to participate by 2030. Second, CORSIA is considered to cover CO_2 emissions from all extra EU+ flights. Under this assumption, airlines should offset emissions above 85% of the 2019 threshold between 2021 and 2035 [115]. Then, between 2035 and 2050, the threshold is gradually decreased to zero. However, since domestic markets are exempt under CORSIA, the internal market of the EU, EFTA and of the UK are excluded from CORSIA and the EU ETS applies instead. Third, it is assumed that CORSIA will be extended beyond 2035 until 2050 by putting into place regulations ensuring climate neutrality is reached by that date[116]. This is coherent with the recently updated ICAO. Fourth, a market-based measure is assumed to be implemented by 2050 which applies to domestic markets outside the EEA with carbon prices equivalent to carbon credits on international flights. This implies that there will be climate legislation for flights within countries such as China, the USA or India. These four assumptions are necessary for aviation to stay within the Paris climate accords, even though these predominantly affect aviation outside the EEA, highlighting the global nature of the issue.

The current price of a carbon credit of CORSIA is around €7 per tonne CO_2. There are aspirations for voluntary improvements in carbon credits by purchasers which would translate into higher quality voluntary carbon market prices. Compared to the first edition of the DESTINATION 2050, carbon credit prices are now modelled at a price of €25 instead of €60 by 2030 (see Table 48). Consequently, while in the previous model carbon credits were considered as 100% CO_2 reduction, only a 15% reduction is applied here since lower prices indicate low quality of carbon credits as explained by the EMH (Section 6.3). The attribution of a 15% rate for CO_2 emissions off-set from CORSIA carbon credits reflects the necessary improvement in carbon credits (an increase of 10 percentage points) in the six years from now until 2030. Similarly, efforts by national regulators to prevent greenwashing might reduce the legality and therefore availability of low quality off-sets.

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[115] In October 2022, at ICAO 41st Assembly, the CORSIA for the year 2024 until 2035 was set to 85% of 2019 emissions, a more ambitious goal than the previous 100% target since it requires carbon off-sets for additional 15% of 2019 emissions.

[116] Climate neutrality covers all GHGs, while net zero primarily targets CO_2.

Finally, carbon removal projects are assumed to lead to the issuance of additional carbon credits by 2050, similar to EU ETS. The assumed price is identical to the one modelled in the first edition of the DESTINATION 2050, namely €160 per tonne CO_2. This is equivalent to the lower cost of DACCS in the world compared with Europe, see also the Price of Net Zero (Adler, et al., 2023). The implicit assumption for large increase in carbon off-setting projects comes from the assumed availability of negative emission technologies (NET) at the required scale and price to maintain net zero CO_2 emissions 2050.

Table 48: CORISA amounts, prices and CO_2 emission reductions

Year	Type of measure	Amount (Mt CO_2)	Price (2019 €)	CO_2 reduction	Note
2030	CORSIA eligible carbon credits	Applies to 6.0 Reduces 1.0	€25	15%	(van der Sman, Peerlings, Kos, Lieshout, & Boonekamp, 2021); (Trove Research, 2021); (ICAO, n.d. - a)
2050	CORSIA eligible carbon credits	18.2	€160	100%	Price based on cost of carbon removal projects DACCS globally, see Adler et al. (2023)

Potential impact

By 2030, CORSIA covers 6.0 Mt CO_2 from flights departing the EEA. Indeed, in 2030 CORSIA only applies to emissions exceeding 92 Mt CO_2, equivalent to 85% of emissions level in 2019. Expected emissions in 2030 by extra-EEA flights are around 98 Mt CO_2 and therefore only 6 Mt CO_2 are covered by CORSIA. Additionally, since the effectiveness of CORSIA in 2030 is assumed to be of 15% in emission reduction, the assumed CO_2 emission reduction from CORSIA amounts to 1 Mt CO_2. The 1 MT CO_2 is more than in the first edition of the DESTINATION 2050 roadmap, due to the increase in ambition level and despite the lower price and effectiveness of carbon credits. Until 2030, CORSIA can be further strengthened by therefore increasing the CO_2 emissions subject to the off-set requirement (above the target of 85% of 2019 emissions) and by improving the CO_2 emission reduction quality of carbon credits.

For the 2050 outlook, the CORSIA price and scope for international flights remain identical to the first roadmap and cover 18.2 Mt CO_2. However, since market-based measures are subsequent to other pillars and we assume more stringent measures globally, the importance of economic measures is (counterintuitively) reduced somewhat. This reduction of importance is based on the assumed international SAF blending obligation and the economic measures in domestic markets The assumed market-based measures in domestic markets outside the EEA decrease aviation demand growth, and thereby cumulative and absolute CO_2 emissions in 2050 also within the EEA.

Implications

CORSIA can be further strengthened by including all countries as well as their domestic markets, or by having an equivalent measure at the national level. Indeed, while domestic net zero CO_2 aviation strategies outside of the EEA do not factor into CO_2 emission savings of this Roadmap, they remain vital to achieving the Paris Agreement.

Carbon credits should also be strengthened to reach credible carbon off-sets by 2030. More specifically, a transition from carbon off-setting of residual emissions to high durability carbon removals would enable to achieve the required long term, credible off-setting on international flights. Additionally, multilateral approaches which avoid both double counting of emissions, carbon leakages and competitive distortions should be the preferred market-based approaches. Such approaches should also have sufficiently high ambitions to safeguard the net zero targets. In 2050, the commitment to carbon off-setting can be further enhanced in the form of DACCS. Upcoming research about the off-setting potential should also be considered while accounting for their price, feasibility, and their secondary, unintended consequences.

At this stage, it is unknown what system will replace CORSIA after the end of the current phase in 2035. Additionally, the current scope of EU ETS excludes international flights leaving the EEA due to a stay order regarding the application to these flights.

6.4 Results and conclusions

Decarbonisation impact

By 2030, the main CO_2 emissions reduction effect comes from market based economic measures, thereby highlighting their significance. 24% of the reduction is attributable to MBM, excluding a 2% demand effect from the MBM. These results are visualised in Figure 29. Auctioned EU ETS aviation allowances cover 19.5 Mt CO_2, 41.4 Mt CO_2 need to be purchased out-of-sector. 6.0 Mt CO_2 of CORSIA carbon credits are necessary in 2030 which reduce CO_2 emissions by 1 Mt CO_2 according to their effectiveness.

By 2050, 10% of the total contribution to net zero CO_2 is attributable to MBM, excluding 2% from the demand effect of MBM. This is equivalent to the combined total of 10.5 Mt CO_2 and 18.2 Mt CO_2 of DACCS which are necessary for flights within the EEA and flights leaving the EEA, respectively, see Table 55.

Concrete regulations and potential exceptions such as SAF allowances are important in determining cumulative emissions and annual emissions levels in 2030, 2040, and 2050. While their importance decreases over time, economic measures combined still constitute 12% of total reduction in 2050 (including demand impact); then compensated for in the form of DACCS.

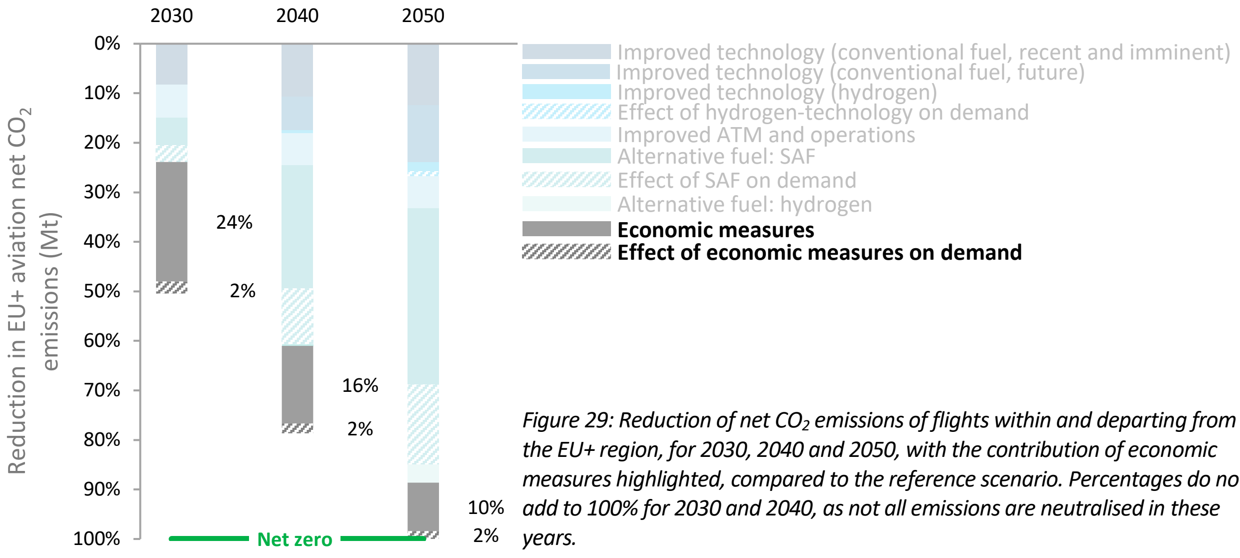


Figure 29: Reduction of net CO_2 emissions of flights within and departing from the EU+ region, for 2030, 2040 and 2050, with the contribution of economic measures highlighted, compared to the reference scenario. Percentages do not add to 100% for 2030 and 2040, as not all emissions are neutralised in these years.

Expenditures impact

For 2050, the price difference between EU ETS and CORSIA is assumed to still exist, as global Negative Emission Technologies (NETs) such as DACCS are currently not part of the EU ETS, and as it is unclear to what extent foreign DACCS would be eligible. Since advanced economies have higher prices and EEA regulations aim at leadership in quality of carbon removal measures, cost divergence is actually expected.

Calculations based on the updated assumptions presented in this report, the cumulative cost of EU ETS over the period between 2019 and 2050 will be €200 bn, where about €190 bn out of those occur from 2024 onwards. Total cost of market-based measures is approximately €225 bn, where €215 bn of those occur from 2024 onwards. These costs are the partial internalization of the external cost of aviation.

6.5 Implications

This chapter evaluates the economic measures available to regulate the emissions of the aviation sector. The EU ETS, a cap-and-trade system, and CORSIA, a carbon offsetting scheme are considered. As such, both measures are expected to reduce the net CO_2 emissions by 24% in 2030 compared to the reference scenario. Eventually, the role of economic measures will decrease as breakthrough technologies are developed and the use of SAF is increased.

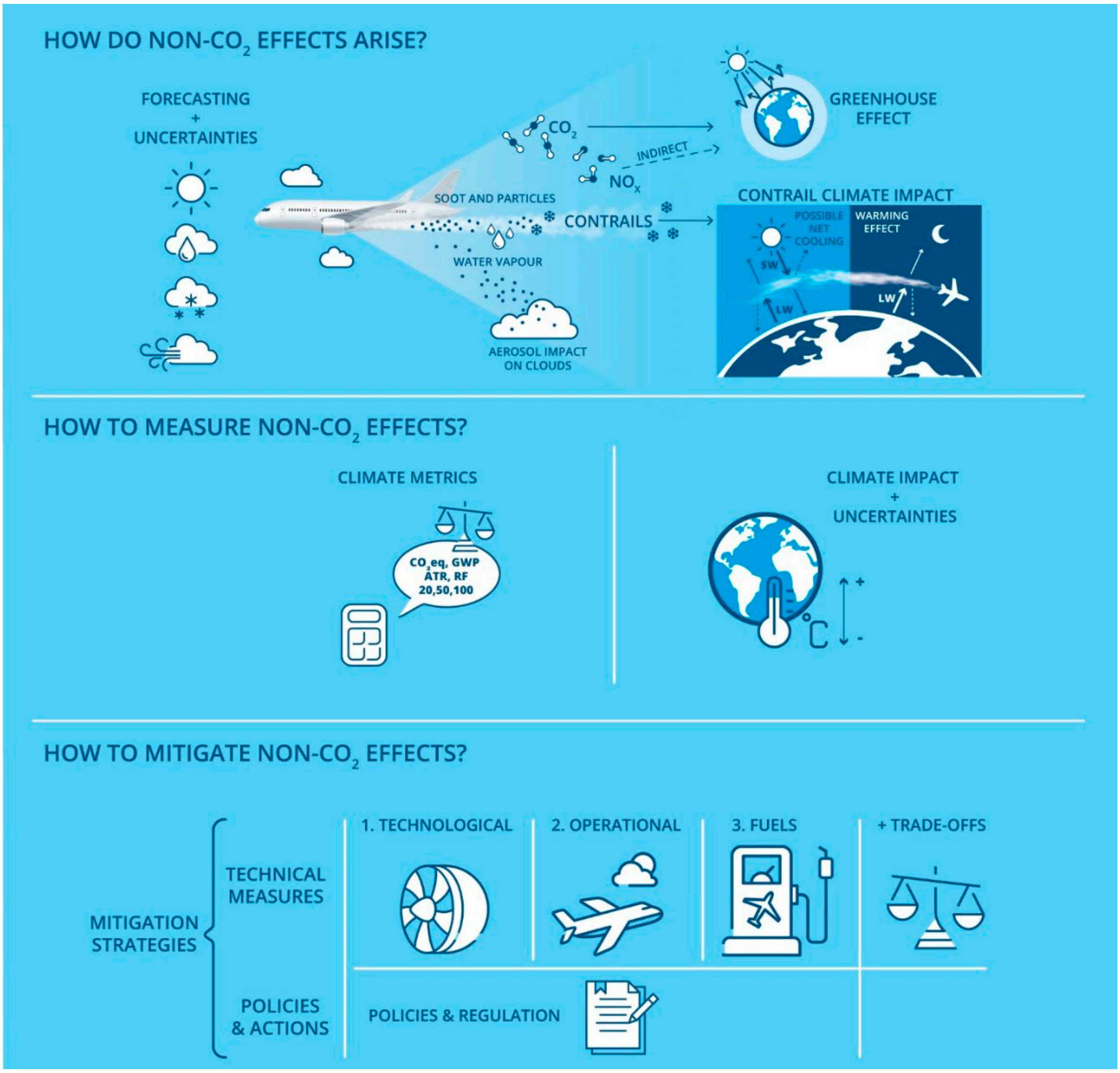
For the upcoming years, the expected process will need to lead to the strengthening of carbon credits in the form of, for instance, more stringent criteria. Additionally, support for economic measures in non-EEA countries domestic markets aiming at net zero by 2050 is observed, suggesting an evolution towards the implementation of such measures. Their exact nature remains undetermined, but our findings highlight the importance of international regulations and cooperation with respect to climate policies. Uncertainty remains around the effect of EU guidelines towards CORSIA implementation and the quality of CORSIA credits.

The introduction of other forms of economic measures beyond the aforementioned should be carefully considered as it may lead to regulatory diversion, thereby increasing the chance for competition distortion. Aviation is currently not included in the Carbon Boarder Adjustment Mechanism to avoid potential competition effects from such regulatory divergence on the international level.

The price and quantity of green energy inputs as well as the lack of credible DACCS at scale may however undermine the credibility of economic measures in the long run. More specifically, there exists large risk associated with and controversial viewpoints on DACCs and its long-term viability in helping reach CO_2 neutrality. Such views point to the long-term character of removal, underappreciation of negative secondary effects, low technological readiness and low financial feasibility of projects. Under the assumptions that CORSIA relies fully on off-setting instead of using additional supporting pillars, a perceived weakness of carbon credits may encourage a potential scope expansion of the EU ETS even at a later stage of the NetZero process. These challenges should be addressed in order to prevent any public distrust which could negatively impact the achievement of DESTINATION 2050, but also wider sustainable policies.

Guaranteeing the quality (i.e. effectiveness) of carbon credits through both industry action and policy intervention is key to realising these necessary reductions in CO_2. Implementing the global economic measure CORSIA is crucial to keeping international aviation on track to reduce emissions and contribute to the net zero ambition globally. For EU ETS in particular but also generally, earmarking of revenues ensures the economic measures fully contribute to the development of aviation decarbonisation solutions. A global approach to market-based measures is critical to prevent market distortion and carbon leakage. Similarly, sound EU regulations regarding the use of DACCS that ensure effectiveness and a level playing field will be necessary in the foreseeable future.

7 Non-CO$_2$ climate effects of aviation



7.1 Introduction

Besides aviation's effect on global warming by increasing the concentration of CO_2 in the atmosphere, so-called non-CO_2 climate effects further contribute to climate change. Since the publication of the IPCC Special Report in 1999 by Penner et al. (1999), many research activities have been undertaken to advance the underlying science of these effects. One of the seminal publications by Lee et al. (2021) contains a reassessment of aviation's full climate impact of the years 1940-2018. Despite therein remaining considerable uncertainties[117], the publication shows a substantial contribution of the non-CO_2 effects to climate change. This led to an increased interest from society, industry and policymakers regarding the non-CO_2 topic. The European Commission selected EASA to write a report (2020) which describes the state of science, and proposes possible mitigation measures and related policy options.

The following chapter aims to provide an overview about aviation's non-CO_2 emissions and effects, based on the triple-diamond structure shown in Figure 30 [118]. The horizontal axis of the figure reads as a timeline, which discerns between three phases:

- Understanding the problem and developing models and metrics reflecting that understanding, for example with respect to the atmospheric processes through which non-CO_2 climate effects have an impact.
- Developing solutions or mitigation measures and validating these.
- Implementing these solutions and reducing non-CO_2 climate effects of aviation.

Each of the diamonds can be seen to consist of a diverging and a converging element, representing the more exploratory and investigative phase at the start of each phase, which is followed by the application of the insights gathered that way. The arrows represent the iterative process.

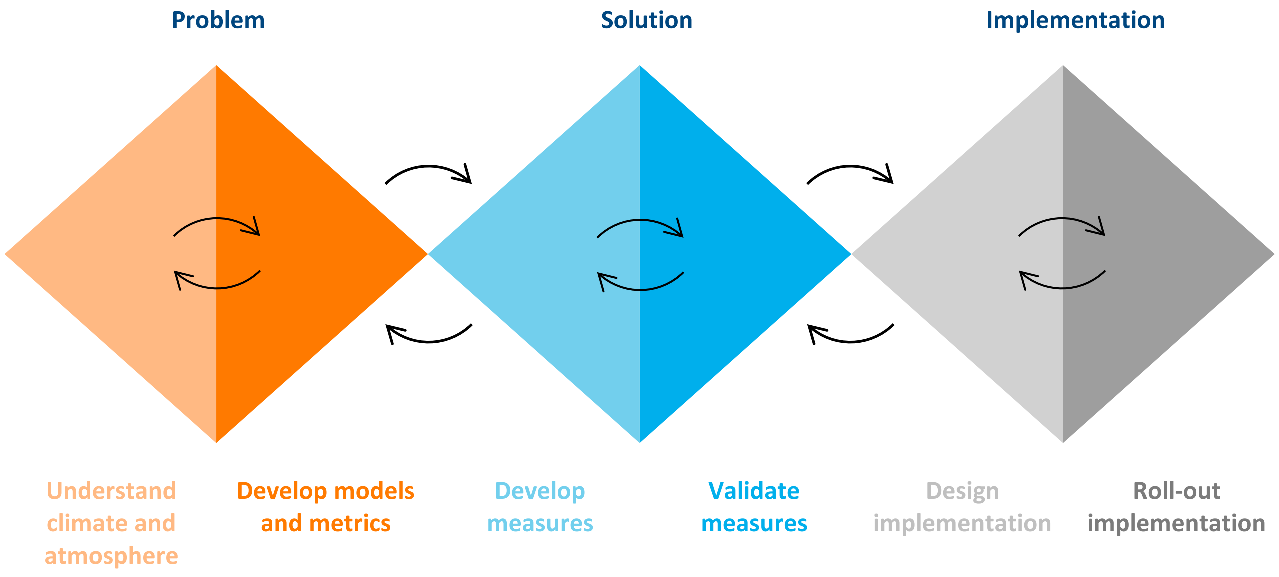


Figure 30: Three strands of activity with respect to non-CO_2 climate effects of aviation, visualised in a triple-diamond model

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[117] The uncertainties are summarised and further explained in (Lee, et al., 2023).

[118] This structure is based on the Double Diamond method (Design Council, n.d.).

The subsequent sections each cover one of the diamonds. Section 7.2 discusses the understanding of the problem, Section 7.3 is concerned with possible solutions or mitigation measures and Section 7.4 treats implementation of solutions and possible policy options to support that. Lastly, Section 7.5 shows a more graphical overview of past and ongoing research and industry efforts, and identifies the gap between these efforts and what is necessary to realise reductions in the non-CO_2 climate effects of aviation.

> **NON-CO_2 EMISSIONS VERSUS NON-CO_2 CLIMATE EFFECTS**
> This report strictly distinguishes between non-CO_2 emissions and non-CO_2 climate effects. Non-CO_2 emissions are, for example, water vapour and soot particulates. Non-CO_2 climate effects are the effects of these emissions on the climate. Non-CO_2 emissions affect physical and chemical atmospheric properties which cause the non-CO_2 climate effects.

7.2 Understanding the problem

While the climate effect of CO_2 emission is well understood, the climate impact of non-CO_2 effects of aviation is still intensively researched and subject to uncertainties. Lee et al. (2023) for example note that non-CO_2 terms contribute eight times more than CO_2 to the uncertainty in determining the climate impact of aviation. There are a few other key differences between CO_2 and non-CO_2 effects:

- Direction or sign: CO_2 emissions are always warming, whereas individual non-CO_2 climate effects can – in certain conditions – have a cooling effect. Overall, however, the net effect of the non-CO_2 climate impacts is estimated to be warming.
- Magnitude: each tonne of CO_2 has the same effect, regardless of where it is emitted. Emissions that lead to non-CO_2 effects can have a very different impact based on the location (latitude, longitude and altitude), time of the day, background concentrations and local atmospheric conditions.
- Lifetime: CO_2 molecules remain in the atmosphere for hundreds of years. Non-CO_2 climate effects of aviation are typically ‘short-lived’ ranging from minutes to a few years.

Due to these differences, quantifying the size of non-CO_2 effects and comparing them with CO_2-effects is challenging. It requires an accurate understanding of atmospheric sciences, and the availability of input data of sufficient quality (e.g. humidity in the upper troposphere) in combination with the ability to model individual flights in actual weather conditions. Non-CO_2 effects have, generally speaking, a climate effect which is more short-term than the impact of CO_2. Reducing non-CO_2 effects would therefore have an immediate positive effect and help to achieve climate benefits within this generation.

The upcoming sections deal with the first of the diamonds introduced in Section 7.1 focused on understanding the problem of non-CO_2 climate impact of aviation. The first three sections are concerned with the diverging part of the diamond and explore non-CO_2 emissions (Section 7.2.1) and non-CO_2 climate effects (Section 7.2.2), and how the one leads to the other (Section 7.2.3). The last three sections capture the convergent phase of the diamond, ultimately focused on quantifying the size of non-CO_2 effects. This is done by discussing CO_2 equivalence metrics (Section 7.2.4) and calculation methods (Section 7.2.5), before assessing the relative contribution of non-CO_2 effects to the total climate impact of aviation (Section 7.2.6).

7.2.1 Non-CO_2 emissions

When burning conventional aviation fuel, aircraft engines produce various emissions: carbon dioxide (CO_2), water vapour (H_2O), nitrogen oxides (NO_X) [119], sulphur dioxide (SO_2), carbon monoxide (CO), hydrocarbons (HC) and particulate matter (PM) which includes soot. Figure 31 graphically illustrates these combustion emissions. CO_2 and water vapour (H_2O) are direct reaction products of (stoichiometric) hydrocarbon combustion. NO_X is emitted by aircraft engines and forms when nitrogen (N_2) and oxygen (O_2) in the air react to form NO_X. This happens if temperatures are high, such as in an aircraft combustion chamber. Generally, there is a trade-off in engine design between fuel burn (and resulting CO_2 emissions, reduced with higher combustion temperatures) and NO_X emissions which increase with higher combustion temperatures (Lefebvre & Ballal, 2010). Sulphur dioxide (SO_2) forms when sulphur contained in the fuel oxidises. If there is a lack of oxygen to allow the fuel to react to CO_2 and water vapour, incomplete combustion occurs which leads to the formation of CO, HC and particulate matter. Soot, a subset of particulate matter, is primarily generated through incomplete combustion of fuels that contain aromatic compounds, such as naphthalene[120]. Quantifying CO_2 emissions is straightforward, as CO_2 is directly correlated to fuel burn. Quantifying non-CO_2 emissions is more complicated, as it depends on various parameters, such as engine type, fuel composition and atmospheric conditions.

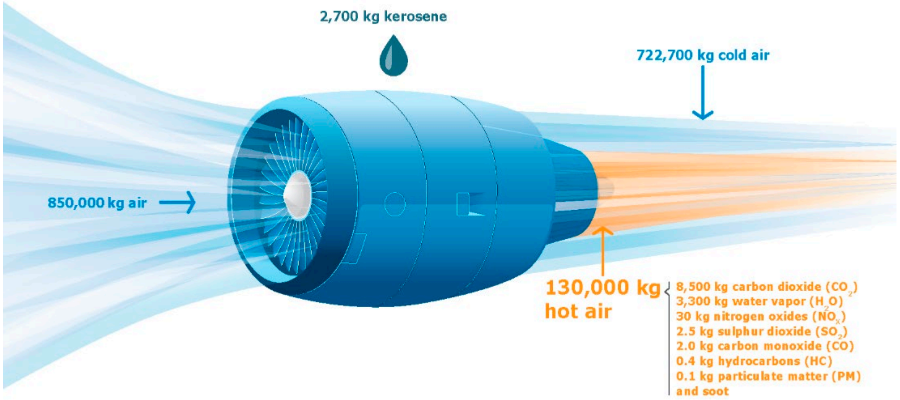

Figure 31: Aircraft engine emissions, quantified for a typical two-engine jet aircraft with 150 passengers flying one hour (FOCA, from EEA, EASA & EUROCONTROL, 2019, p. 22)

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[119] Nitrogen oxides or oxides of nitrogen (NO_X) are very different from nitrous oxide (N_2O). Although NO_X is a non-CO_2 emission that has a non-CO_2 climate effect, NO_X itself is not a greenhouse gas. N_2O, on the other hand, is a greenhouse gas. N_2O is not produced by aircraft or their engines (EEA, n.d. - a).

[120] Aromatic compounds are characterised by a molecular structure that includes (one or more) benzene ring(s). Such molecular bonds are difficult to break, which is what would otherwise happen during combustion. Within the group of aromatics, naphthalene is even more difficult to combust, as it is a polycyclic (rather than a monocyclic) aromatic hydrocarbon.

7.2.2 Non-CO_2 climate effects

This section discusses non-CO_2 climate effects and, specifically, how non-CO_2 emissions affect atmospheric physical and chemical properties which cause the non-CO_2 climate effects and non-CO_2 impacts. These causations are illustrated in Figure 32.

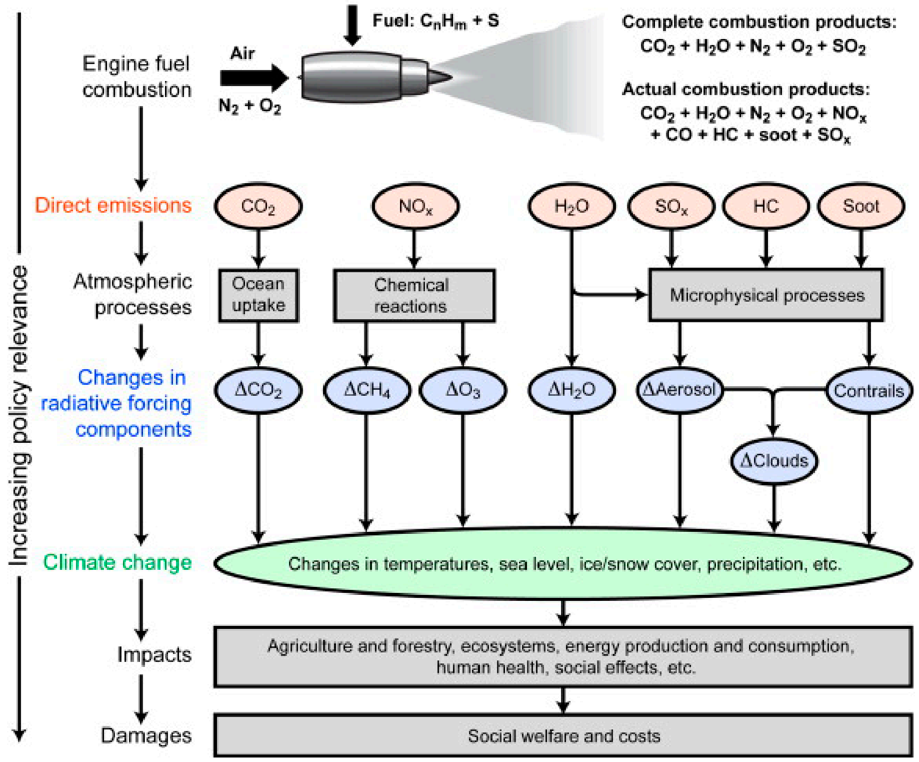

Figure 32: Emissions from aircraft operations and atmospheric processes leading to changes in radiative forcing and climate change (Lee D. , et al., 2009)

Figure 32 starts with the emissions directly resulting from fuel combustion, shown in orange. These emissions have an influence on atmospheric processes (black), which cause changes in radiative forcing components (blue). Radiative forcing is a measure of the change in the Earth's energy balance; radiative forcing components are elements that affect that balance. Next, these changes in radiative forcing components contribute to overall climate change (green), such as changes in temperatures, sea level, ice/snow cover and precipitation[121]. This is what in this report is referred to as the non-CO_2 climate effect. Subsequently, climate change has impacts and causes damages. As the relation between climate change to impacts and damages is independent of a particular contributor of climate change (i.e., not different for aviation-induced climate change compared to other human activities), these last two levels are not further addressed in this chapter.

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[121] The discussion on how best to convert radiative forcing (RF) of aviation emissions into temperature changes and other climate change indicators is still ongoing. In the past, a linear relationship between the RF (respectively ERF taking into account the efficacy of the climate forcing term) and the equilibrium change in global mean surface temperature ΔT_{surf} was often assumed with a climate sensitivity parameter λ (EASA, 2020; Ponater, Bickel, Bock, & Burkhardt, 2021; Lee, et al., 2023).

Besides showing causes and effects, Figure 32 shows that whereas CO_2 emissions have a rather straightforward impact on climate change, the relation between non-CO_2 emissions and non-CO_2 climate effects is more complicated. A few clusters can be identified:

- NO_X emissions affect the chemical cycles of methane (CH_4) and ozone (O_3) in the atmosphere resulting in methane depletion (cooling) and ozone generation (warming). The latter represents the greater effect.
- Water vapour emissions increase the concentration of water vapour in the atmosphere, which has a warming impact. It is, however, a small impact, as the lifetime is very short (Niklaß, et al., 2020).
- Sulphur, hydrocarbon and particulate emissions, which contribute under certain atmospheric conditions to formation and persistence of contrails and contrail-induced cirrus clouds that have an overall warming impact.

Due to these interactions and microphysical processes, the non-CO_2 climate effects of aviation's non-CO_2 emissions strongly depend on the time and position of the emission, on actual weather conditions (atmospheric processes, transport pathways, temperature, humidity) and on the background concentrations (of, for example, methane and ozone). The exact relations are still subject to ongoing research, and many of the uncertainties with respect to the non-CO_2 climate effects of aviation originate from a non-perfect understanding of atmospheric processes and the inaccuracy of key input data.

> **OTHER NON-CO_2 EFFECTS**
> Besides an effect on climate, non-CO_2 emissions can also have other (environmental) effects. Examples are the impact of NO_X on local air quality and local soil quality (the latter through so-called nitrogen deposition), or the health effects of particulate matter (ICAO, 2022b). Given the focus of this report on climate change, these other non-CO_2 effects are not addressed further.

7.2.3 Characteristics of various non-CO_2 effects

Following the introduction to the various non-CO_2 emissions and associated climate effects in Section 7.2.2, this section discusses the characteristics of three main groups of non-CO_2 climate effects[122], ordered from larger to smaller influence on climate:

- Contrails and aviation-induced cloudiness
- NO_X effects
- Other effects

These groups of effects are shown in Figure 33.

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[122] The groups used here are clustered somewhat differently than those in Section 7.2.2 but span the same set of non-CO_2 effects. This list is however more effect-focused, whereas the grouping in Section 7.2.2 starts from the perspective of non-CO_2 emissions.

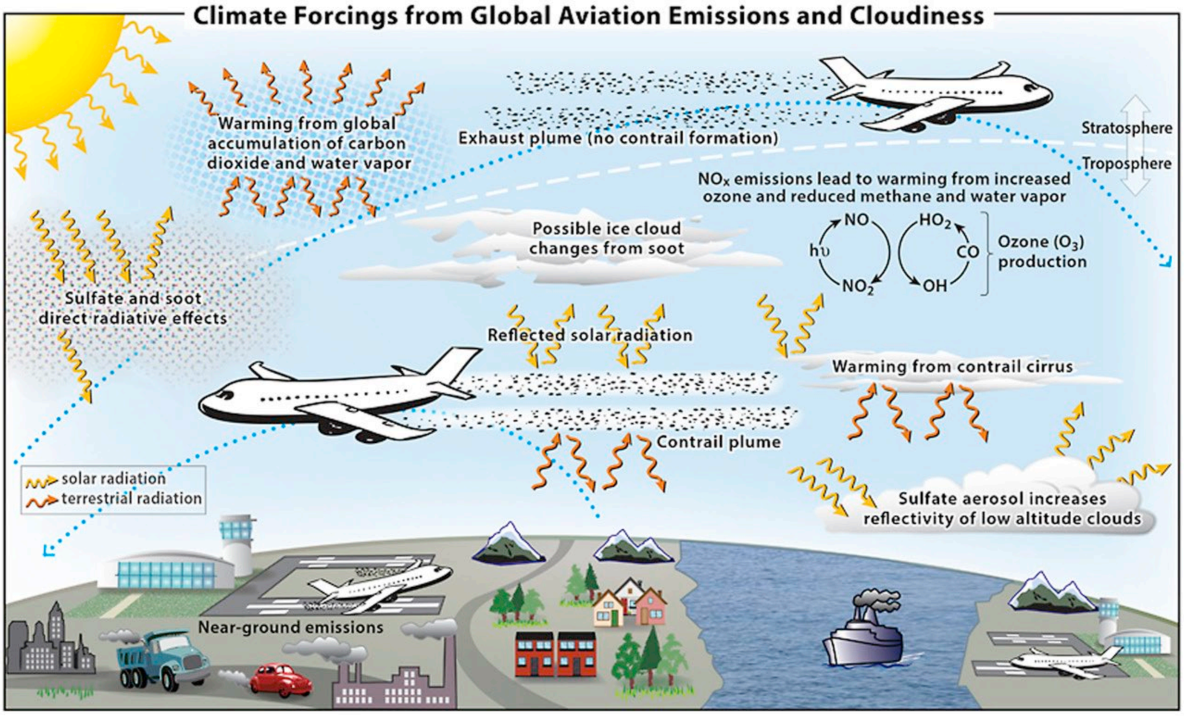

Figure 33: Schematic overview of the processes by which aviation emissions and increased cirrus cloudiness affect the climate system (adapted from Lee, et al., 2021)

(Persistent) contrails and contrail-induced cirrus clouds

Condensation trails, or contrails for short, are the line-shaped clouds that can form behind aircraft under certain atmospheric conditions. Contrails primarily consist of ice crystals. Whether contrails form or not is determined by the Schmidt-Appleman criterion, which describes how contrail formation depends on the ambient temperature, pressure, relative humidity, specific fuel energy content, specific emission of water vapour and the overall propulsive efficiency[123]. Furthermore, the availability of particles – such as soot – on which water vapour can crystallise affects contrail formation and the amount of soot has an impact on the ice crystal size and thus on the contrail properties (Kärcher, 2018).

For the persistence of contrails which depends on the ambient conditions, typically three categories are distinguished:

- Non-persistent contrails, which disappear within minutes, and as such have a negligible climate effect.
- Persistent contrails, which exist for a longer period of time (minutes to hours). These have a larger climate effect than non-persistent contrails, simply because the 'exposure time' is longer. Contrails only persist if the surrounding air is supersaturated with respect to ice. Regions where that condition is met are known as ice-supersaturated regions (ISSRs). Once ice crystals form, they can grow until there is no supersaturation anymore or they fall due to their weight to lower atmospheric layers where they evaporate (Gierens, Lim, & Eleftheratos, 2008).
- Contrail-induced cirrus clouds, in which persistent contrails spread out over an area much larger than the original contrail due to wind shear. Stemming from persistent contrails, contrail-induced cirrus also persists. These have the largest climate effect.

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[123] The Schmidt-Appleman criterion states that if the mixture of the engine exhaust gases and the ambient air reach saturation with respect to water, contrails form. The formation process is thus a purely thermodynamic process (Gierens, Lim, & Eleftheratos, 2008). More efficient engines release less heat to the environment, such that water droplets more easily freeze.

The latter two are jointly referred to as ‘aviation-induced cloudiness’ (AIC), of which contrail cirrus accounts for 80% of the radiative forcing (Kärcher, 2018).

Once generated, contrails affect the climate in various ways:

- First, contrails reflect part of the outgoing (thermal) long-wave radiation from the earth to outer space. This has a warming effect, as heat that would have otherwise radiated out to space, is now trapped.
- Second, contrails influence incoming (solar) short-wave radiation from the sun to the earth, through changing the local albedo (reflectivity) of the earth. This can go in two ways[124]:
    - If contrails form above a body of land or water that is less reflective (generally speaking: darker in colour), the contrail increases the albedo and thereby decreases the amount of solar radiation that reaches the earth surface. In this case, a contrail has a cooling effect.
    - If, instead, contrails form above a body of land or water that is more reflective than the contrail (e.g. snow-covered areas), the reverse happens. In this case, a contrail has a warming effect.

The majority of contrails are of the warming type and also the sum of the contrail impact is warming. As there is no incoming sunlight during the night, night contrails are always warming (Lee, et al., 2021). All the aforementioned differences make that some contrails have a bigger climate effect than others. In a study of the North Atlantic flight corridor from 2016 to 2021 based on model calculations, it was found that 12% of all the flights in this region cause 80% of the annual contrail energy forcing[125] (Teoh, et al., 2022). A more recent study for all flights from 2019 to 2021 suggests that 14% of the flights formed contrails with a net warming effect while only 2% of all flights account for 80% of the annual contrail energy forcing as shown in Figure 34 (Teoh, et al., 2024). These especially strong contrails are called “Big Hits”. The fact that the climate effects of contrails vary widely also means that aiming to prevent a rather limited amount of contrails (and thus: flights) could have a disproportionately positive effect on contrail climate effects. The challenge is to identify these flights based on the given meteorological information and their uncertainties.

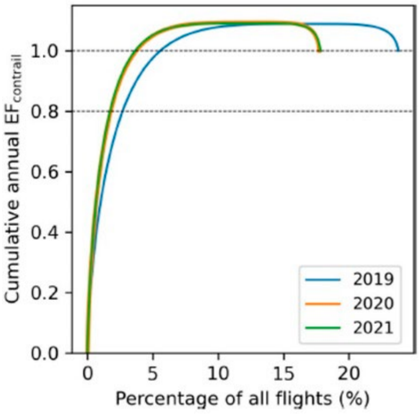

Figure 34: Percentage of all flights that accounted for the energy forcing (EF) of contrails. The cumulative density function exceeds and returns to 1 because of cooling contrails. (adapted from (Teoh, et al., 2024))

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[124] If the backscattering of terrestrial radiation by the contrail’s ice crystals is more effective than the reflection of solar radiation, the net positive radiative forcing leads to a warming tendency of the atmosphere (Kärcher, 2018).

[125] Energy forcing is the integration of net radiative forcing times the length and width of the contrail over the contrail lifetime.

NO_X

Emissions of nitrogen oxides contribute to climate change through several chemical reactions resulting in two predominant effects, which act in different timescales:

- Ozone acts a greenhouse gas and has a warming effect. Additional nitrogen oxides alter chemical reaction sequences involving ozone to lead to the formation of ozone in the upper troposphere and lower stratosphere, at an altitude of approximately between 8 to 12 kilometres altitude (flight level 240 to 380). Ozone formation has a short-term effect.
- Destruction of methane, that previously originated from natural, agricultural, waste and industrial sources. Methane is a greenhouse gas and the destruction of it has a cooling effect on the climate. Unlike ozone formation, methane destruction is a longer-term effect. As second-order (and longer-term) effects, the destruction of methane results in a reduction in ozone (cooling) and a reduction in water vapour in the stratosphere (cooling).

The net effect of aviation NO_X is likely warming but there are large uncertainties associated with this result (Skowron, Lee, Rodriquez de Leon, Lim, & Owen, 2021). The initial warming and the longer time cooling effect of the NO_X emissions from a fleet-sized pulse are depicted in Figure 35.

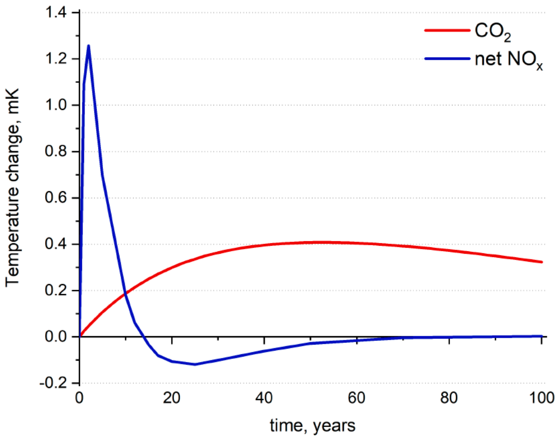

Figure 35: Temperature change due to CO_2 (red) and the net NO_X effect (blue) from a fleet-sized pulse (Skowron, Lee, Rodriquez de Leon, Lim, & Owen, 2021) (Supplementary material)

Annual aviation NO_X emissions are significantly smaller than NO_X emissions from other anthropogenic sources on the ground or natural sources such as lightning but aviation NO_x emissions can be better quantified. EASA (2020) notes that it appears that the NO_X emitted at cruise altitude has a larger radiative forcing than NO_X emitted on the ground. However, there are still uncertainties of scaling ground-level NO_X emissions to cruise level emission indices and a dependency on the background emissions (EASA, 2020; Skowron, Lee, Rodriquez de Leon, Lim, & Owen, 2021).

Other climate forcers

Besides contrails and NO_X, there are a few other ways in which non-CO_2 emissions can have non-CO_2 climate effects (Figure 32 and Figure 33):

- Water vapour accumulation, following from the water vapour emissions that are a direct consequence of the combustion of the hydrocarbon fuels. The amount of water vapour emitted can be computed based on the fuel composition. At flight levels where commercial aviation currently takes place, the (warming) climate impact is relatively small (Niklaß, et al., 2020). If supersonic commercial flights in the lower stratosphere were re-introduced, the emitted water vapour would have a larger climate impact (EASA, 2020).
- Sulphur dioxide[126] direct radiative effect (cooling) and soot direct radiative effects (warming).
- Aerosol-cloud interactions[127] both with low and high-level clouds. The effect is subject to high uncertainties, depends on background aerosol and cannot be estimated reliably (Lee, et al., 2023), requiring further research (Dahlmann K. , 2023).

7.2.4 CO_2-equivalent metrics and time horizons

Whereas previous sections explored non-CO_2 emissions (Section 7.2.1), non-CO_2 climate effects (Section 7.2.2) and some key characteristics of three main groups of non-CO_2 climate effects (Section 7.2.3), this and the following sections turn to the challenge of quantifying the impact of (aviation) non-CO_2 effects relative to the climate impact of (aviation) CO_2.

With a CO_2 equivalent (CO_2eq), the impact of a climate forcer is expressed in terms of the amount of CO_2 that would create the same value for a certain metric[128] (e.g. amount of warming) in a given time period. The CO_2 equivalent value is thus metric dependent and the pure use of a CO_2 equivalent does not yet imply which metric is chosen. The intention of the CO_2 equivalent is that the total climate effect of various climate forcers can be expressed on a single scale, such as tonnes or megatonnes of CO_2 equivalent (t CO_2eq or Mt CO_2eq). As CO_2 is used as a reference climate forcer, the CO_2 equivalent of CO_2 is always 1.

> **CO_2 EQUIVALENCE IN OTHER SECTORS**
> Converting one type of climate effect into another is not unique to aviation: CO_2 equivalence ratios exist in other sectors as well. Methane, for example, is often expressed to have 27 times the climate impact of CO_2. Hence, one tonne of methane emissions is – in terms of warming effect as quantified using the metric GWP100 – identical to 27 tonnes of CO_2, such that the warming effect can be expressed as 27 tCO_2eq. This conversion takes into account the fact that, compared to CO_2, methane has a shorter lifetime (about a decade, compared to centuries for CO_2), but has a much higher radiative efficiency. In terms of GWP20, hence over a time of 20 years, the warming effect is 84 times higher ('more potent') than for CO_2.

Existing climate metrics for aviation

Climate effects of aviation are commonly expressed in physical climate metrics based on radiative forcing or temperature change. For assessing and comparing the climate impact, a climate metric[129] including a time horizon and an emission scenario need to be chosen.

The climate metric value per climate forcer can be expressed as an absolute value with a physical unit such as W/m^2 or Kelvin. The relative climate metric (dimensionless) is obtained by dividing the absolute climate metric value of the climate forcer by the absolute value of CO_2.

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[126] Referred to as sulfates in Figure 33.

[127] Sulphur based emissions and soot together are referred to as aerosols.

[128] In reference to Figure 32, a metric quantifies the direct and indirect effects of aviation emissions on climate change, or 'translates' the emissions to the corresponding climate effect.

[129] Strictly speaking, a climate metric consists of a climate indicator (e.g. RF, GWP, ATR), a time horizon (e.g. 20, 50, 100 years) and an emission scenario (e.g. pulse, sustained, fleet emissions).

RADIATIVE FORCING BASED CLIMATE METRICS

Radiative Forcing (RF) is a metric which measures the change in the Earth's energy balance due to a climate forcer in the unit metre squared. It does not take into account the lifetime of CO_2 and non-CO_2 effects, rather, it solely depends on the instantaneous change in radiative forcing that a CO_2 or non-CO_2 emission causes. RF is often used to quantify the change between two points in time, such as present day compared to pre-industrial, or can be used as the value due to changes in emissions (Niklaß, et al., 2020). Radiative forcing (RF) represents the initial change in the energy balance of the Earth due to external factors such as greenhouse gases or contrail-cirrus. Effective radiative forcing (ERF) also measures the energy balance and accounts for adjustments in the Earth's radiation budget. This takes feedbacks, and responses within the climate system into account but maintains sea surface temperatures constant. A positive RF (or ERF) means a warming effect and a negative RF (or ERF) implies a cooling effect.

Global Warming Potential (GWP) is a widely used metric that does take into account the lifetime of non-CO_2 effects. It is the time integral of radiative forcing corresponding to the cumulative energy that is imposed on the Earth's energy balance. Determining this also requires a time horizon to be specified, such as 100 years for GWP100. In that case, the CO_2 equivalent of a non-CO_2 climate effect can be understood as the amount of CO_2 that, over a period of 100 years, has the same warming effect as the non-CO_2 effect that is to be translated. GWP100 is the agreed metric for reporting under the Kyoto Protocol as well as the Paris Agreement, and is in general the metric of choice for the IPCC to compare long-lived, well mixed greenhouse gases. However, the IPCC (1999) criticises the use of GWP for aviation as non-CO_2 effects do not rely on emissions alone (e.g. contrails) and are dependent on time and location of the emission.

Another RF based time-integrated metric is GWP* (Allen, et al., 2018), a "flow-based" method introduced to represent both short-lived and long-lived climate forcers as warming-equivalent emissions having approximately the same impact on the global average surface temperature on long time-scales. Instead of providing single values over specific time horizons, the GWP* provides a CO_2 equivalent value as a function of time to relate changes in the rate of short-lived climate forcers (such as contrails) to pulses of CO_2. While some sources use GWP* to quantify aviation's climate impact, e.g. Lee et al. (2021), others claim that GWP* is essentially a micro climate model and not a metric (Meinshausen & Nicholls, GWP* is a model, not a metric, 2022).

Megill et al. (2024) have proposed a weighting with the efficacy of the GWP and the GWP* called EGWP and EGWP* to match more closely with temperature-based metrics. The efficacy takes into account how the climate sensitivity parameter differs for different climate forcers (see next paragraph).

TEMPERATURE BASED CLIMATE METRICS

Temperature based metrics go one step further in the cause effect chain in Figure 28 [130] and assess the temperature change as an indicator for climate change. For homogenous distributed emissions like CO_2, a linear relationship between the RF and the equilibrium change in global mean surface temperature $\Delta \mathrm{T}_{surf}$ can be assumed using λ, the climate sensitivity parameter: $\Delta \mathrm{T}_{surf} = \lambda * \mathrm{RF}$. For inhomogeneous emissions (such as several non-CO_2 emissions) the climate sensitivity parameter varies and an efficacy can be defined per climate species compared to the climate sensitivity parameter of CO_2 to take the feedbacks and responses of the climate system into account (EASA, 2020; Ponater, Bickel, Bock, & Burkhardt, 2021; Lee, et al., 2023).

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[130] More physical processes, such as feedback mechanisms (e.g. carbon-cycle, cloud and albedo feedbacks) are thus included. RF-based metrics do not take feedbacks into account (except of those weighted by efficacy).

The GTP (Global Temperature change Potential) is defined as the change in global mean surface temperature at a given time horizon (Shine, Fuglestvedt, Hailemariam, & Stuber, 2005). RF is used to calculate a temperature response of the climate forcer, usually from a simplified climate model. The metric GTP is an end-point metric, which means that the final temperature value is evaluated and no integration over the time takes place such as intermediate temperature changes are unassessed. Integrating the GTP over the time horizon leads to iGTP and by taking the mean (integration and division by the time horizon) of the temperature evolution the ATR (Average Temperature Response) can be defined (Dallara, Kroo, & Waitz, 2011). Table 49 gives a non-exhaustive overview of the presented metrics.

Table 49: Non-exhaustive overview of climate metrics for aviation

	RF-based	**RF-based with efficacy**	**ΔT-based**
Endpoint metric	RF, ERF		GTP
Integrated metric	GWP	EGWP	iGTP, ATR
Flow-based metric	GWP*	EGWP*	

TIME HORIZON

The time horizon determines the length of time over which the climate effects evolve, before they are evaluated. Generally non-CO_2 climate effects of aviation are shorter-lived than the climate effect of CO_2, which is visualised in Figure 36 for a single flight. Selecting a longer time horizon reduces the relevance of non-CO_2 (in this case the contrail impact) compared to total aviation-caused climate change.

The choice of the time horizon depends on the goal and is a trade-off between short- and long-term priorities of mitigation and warming targets. To reduce climate change and temperature peaks in the near future short time horizons may be more appropriate while long-term sustainable aviation goals would imply using long time horizons. As the thermal inertia of the atmosphere and ocean delays the peak in temperature change by about 30 years (Grewe & Dahlmann, 2012), these adjustments would be more accurately covered, especially for temperature-based metrics, by using a longer time horizon. Typical values for the time horizon are 20 years, 50 years and 100 years.

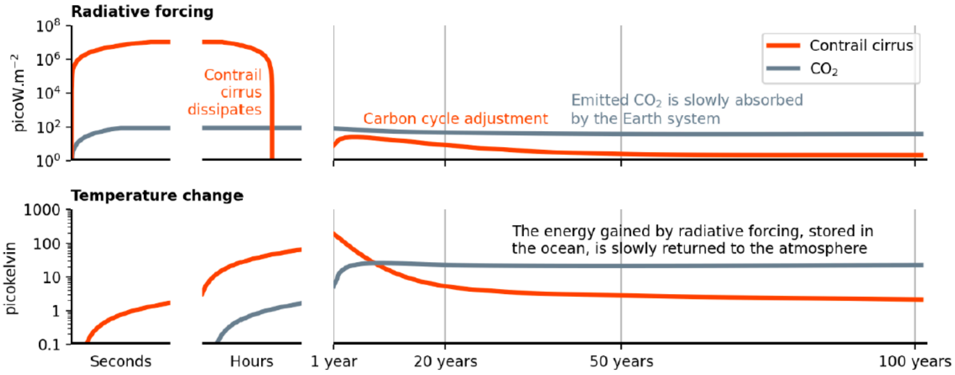

Figure 36: Development of the radiative forcing and global surface temperature change for one flight that emits CO_2 and creates a contrail (Borella, et al., 2024)Emission scenario

Besides the choice of a time horizon, an assumption on the temporal development of the emissions needs to be made, which is again dependent on the goal. If a single flight should be evaluated, a pulse emission should be used. To assess for example technology changes, sustained emissions where the pulse is repeated each year up to the defined time horizon, are more useful. (Evolving) scenario emissions cover variable emissions over time, for example, when a fleet of a new aircraft is phased in and out over time or when a scenario with a constant growth of aviation emissions should be evaluated.

Selecting a suitable metric

The choices of the metric, the time horizon and the emission scenario lead to different combinations. The goal and the use case[131] should determine the choice. Neither one of these metrics is scientifically 'better' or even in general 'correct', as each one was developed with a particular purpose in mind, and each one as such has its own qualities[132]. Nevertheless, various metrics show notably different results, such that different metrics cannot be used interchangeably and a well-considered selection must be made. Examples of differences in resulting CO_2 equivalent values per selected metric and time horizon are given in Table 50, which shows GWP to yield highest CO_2eq/CO_2, followed by GWP* and GTP, and that with longer time horizons, CO_2eq/CO_2 reduces as focus shifts from short lived climate forcers to long lived climate forcers like CO_2 (Lee, et al., 2021).

Table 50: Ratio of total aviation climate impact compared to the climate impact of aviation CO_2 alone, illustrating the differences in outcome with metric and time horizon, adapted from (Lee, et al., 2021)

	GWP			GTP			GWP*
Time horizon (years)	20	50	100	20	50	100	100
Total CO_2**eq/**CO_2	4.0	2.3	1.7	1.3	1.0	1.1	3.0

In an attempt to break the impasse[133] between scientists and policy makers on what a suitable metric could be, Megill et al. (2024) compared various metrics and evaluated these against various criteria which are evaluated in Table 51:

1. Neutrally represent the chosen climate indicator such that no inherent biases within a climate metric for different technologies or changes in aircraft design or trajectory exists.
2. Temporal stability, meaning that the metrics should not have a high variability over time to facilitate monitoring and the assessment of the effectiveness of new aviation-related policies.
3. Compatibility with existing climate policy.
4. Transparency and ease-of-use, including ease of understanding and (correct) interpretation by non-specialists.

Table 51: Comparative evaluation of climate metrics for aviation based on (Megill, Deck, & Grewe, 2024)

Metric	Neutrality	Stability	Compatibility	Simplicity
RF	Very low neutrality	Generally stable	Compatible	Simple to understand and implement
GWP	Low, but consistent neutrality	Stable	Compatible (standard climate metric)	Complex to understand, simple to implement
EGWP	High neutrality	Stable	Compatible	Complex to understand and implement
GTP	Low, but inconsistent neutrality	Generally stable	Compatible	Simple to understand, complex to implement
ATR & iGTP	High neutrality	Stable	Compatible	Simple/complex to understand, complex to implement
GWP*	Low, but consistent neutrality	Highly unstable	Not compatible	Highly complex to understand and implement
EGWP*	High and consistent neutrality	Highly unstable	Not compatible	Highly complex to understand and implement

Megill et al. (2024) proposes ATR and EGWP as more suitable metrics for the assessment of existing and future aircraft and also recommends the use of time horizons larger than 70 years. Of the typical set of time horizons of 20, 50 and 100 years, the latter hence is considered preferred. Again, this aligns with CO_2 equivalence metrics in other sectors, where GWP is also mostly used at a 100-year time horizon. Compared to shorter time horizons, this choice for a longer time horizon causes the total contribution of non-CO_2 climate effects to aviation-induced climate change to be lower.

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[131] An example for a use case is the determination of the climate impact of a single flight from an operational perspective, another use case is climate-optimised aircraft design and technology development and assessment.

[132] Some combinations, however, may be unsuitable for the specific use case or goal.

[133] Scientists often feel that policy makers should choose the metric to be used, whereas policy makers often feel they lack the understanding to effectively do so.

7.2.5 Methods to calculate CO_2-equivalent climate impact for aviation

Calculating the CO_2-equivalent climate impacts of aviation might seem straightforward once a metric, emission scenario and time horizon (if applicable) have been chosen, but is not. The detailed evaluation of the (time-integrated) metrics requires extensive modelling and data input, which might not be available, or might constitute a too large computation effort for a particular application. Instead, approximations could be used to determine the climate impact based on fewer parameters but still taking into account temporal and spatial climate sensitivity for example using algorithmic Climate Change Functions (aCCF) (Yin, et al., 2023). Various alternative calculation methods have been proposed that approximate the non-CO_2 impact per flight (e.g. Dahlmann, Grewe, Matthes, & Yamashita, 2021) at different levels of computational effort and accuracy. These are conceptually illustrated in Figure 37.

The least computationally intensive yet low fidelity calculation method – a constant multiplier – is shown at the top. Progressing downwards in the figure, the calculation methods require more effort (shown on the right-hand scale), but also bring a higher accuracy (shown on the left-hand scale). The most accurate is the weather-based approach, which takes the 4D position of the aircraft along a flown trajectory and weather recordings into account and thereby also enables optimisation of flight trajectories for climate impact. To evaluate the total climate impact of a flight that is yet to take place, weather forecasts are thus required – the uncertainty of which (especially over longer periods of time) carries over to the uncertainty of the resulting estimate for the climate effect.

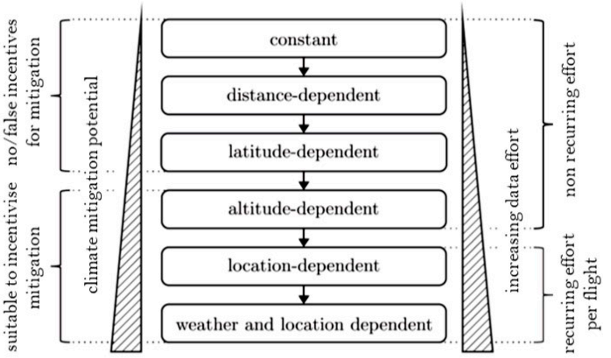

Figure 37: Climate mitigation potential and effort of various CO_2eq calculation methods, adapted from (Niklaß, Grewe, Gollnick, & Dahlmann, 2021)

It is relevant to note that both the left and right scales have two discrete segments. The left scale shows that constant, distance-dependent and latitude-dependent factors do not provide incentives for mitigation, or might even provide false incentives. This follows from the fact that these calculation methods are not detailed enough to capture particular intricacies, such as the fact that local atmospheric conditions are different from location to location, which are of key importance in (operational) mitigation strategies such as avoiding climate sensitive areas. Simply put: if the non-CO_2 effect of a flight is calculated based on a direct multiplication of CO_2, there is no point in doing anything else than reducing CO_2 – even though that might actually increase non-CO_2 effects. The calculation methods, which are altitude, location or weather and location dependent, do capture these details, and are hence suitable to incentivise behavioural changes with regards to non-CO_2 emissions. Similarly, the right scale shows that the four simplest calculation methods do not require trajectory data, but instead allow the determination of average multiplication factors that only depend on distance, latitude or altitude. If a location or weather and location dependent calculation method is chosen, actual trajectory data is required for each and every flight that is to be evaluated.

7.2.6 Contribution of aviation non-CO_2 to global warming based on historical emissions

It has been estimated that in 2011 [134], the cumulated effect of aviation accounted for approximately 3.5% of total anthropogenic climate change measured in Effective Radiative Forcing (ERF) compared to pre-industrial times (1750) (Lee, et al., 2021). The largest contributions are made by contrail cirrus (one-half), CO_2 (one-third) and NO_X (one-sixth). Figure 38 shows the best estimates and uncertainties of the effective radiative forcing for CO_2 and non-CO_2 climate effects of aviation. For the period 1940 to 2018, the CO_2 impact is about one third and the non-CO_2 impact is roughly two thirds in terms of Effective Radiative Forcing (ERF).

As indicated in the figure by both the error bars and the column expressing confidence levels, the uncertainties with respect to the contribution of non-CO_2 effects are notably higher (leading to low confidence levels) than for CO_2, which has been quantified with high confidence (Lee, et al., 2021).

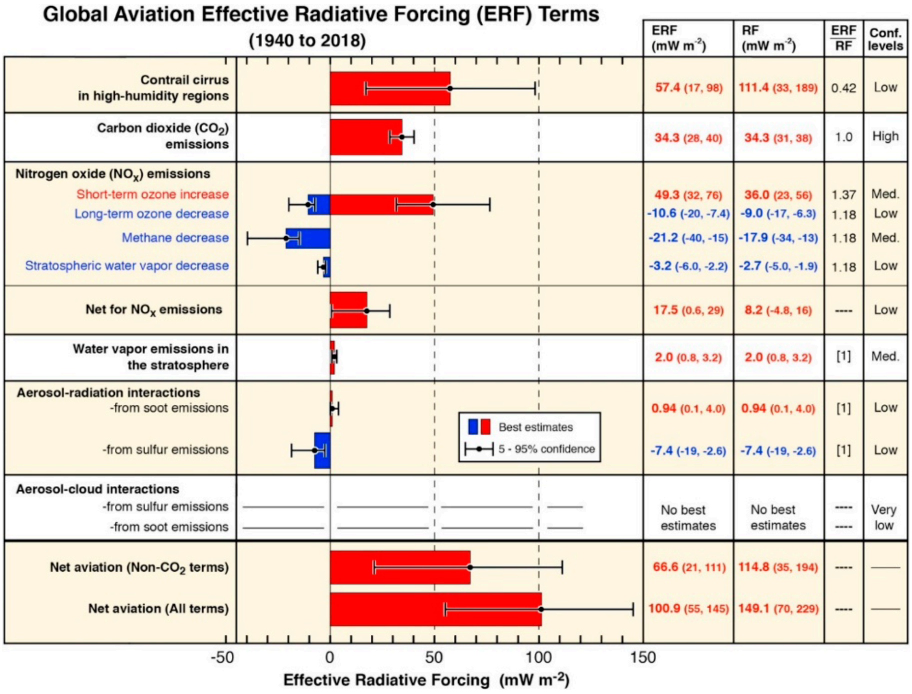

Figure 38: Effective Radiative Forcing (ERF) of different climate forcers for the period from 1940 to 2018 (Lee, et al., 2021)

7.2.7 Validation of the models and more data collection

To reduce the high uncertainties of non-CO_2 effects, validations of the climate models and of the individual models for the climate forcers are needed. This could be done through testing and the use of data from flight tests. Especially for contrails, observations with satellites or (ground-based) cameras offer the possibility to detect persistent contrails. In this way, it can be validated if predicted contrails by the models really occurred. As humidity is an important parameter for the formation of contrails which is still difficult to predict accurately, more in-situ humidity measurements onboard aircraft could offer the possibility to improve the prediction of ice-supersaturated regions where persistent contrails can form (IATA, 2024b).

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[134] The 2018 percentage is likely the same because aviation CO_2 emissions compared to total anthropogenic CO_2 emissions stayed nearly constant (Lee, et al., 2021).

The most recent development in the EU is the monitoring, reporting and verification (MRV) framework for non-CO_2 which is an activity for data collection of non-CO_2 effects from aircraft operators (EC, 2024a). From 1st January 2025 on, aircraft operators should monitor and report the non-CO_2 effects of each flight[135]. If the collected data can be made available to the research community, this will expand the validation possibilities to finally reduce the uncertainties of the climate impact assessment.

7.3 Developing solutions

To find a solution to the non-CO_2 effects, mitigation strategies are developed to reduce the non-CO_2 effects of aviation. While many mitigation measures can be thought of, it needs to be assessed whether they are feasible, effective and efficient considering that safety stays the top-priority and certification standards need to be adhered to. Also, the economical attractiveness, the compatibility of mitigation strategies with existing regulations and policies, the stakeholder perspectives and the infrastructure requirements need to be investigated.

The challenge is that due to the uncertainties in emission quantification, climate science and impact modelling, the mitigation measures could miss their targets and do more harm than good. Especially, given the long lifetime of CO_2 and the importance of reducing cumulative CO_2 emissions, trade-offs with CO_2 must be carefully assessed.

Actual weather data and flight emissions data are required for climate impact prediction and verification for individual flights. This information must be made available to airlines (and possibly to ANSPs) in advance and incorporated in the flight planning. Given the continuously changing weather conditions, the predictability is low and the variability per flight is high, hence more research and development is needed in this field. An upgrade of the infrastructure for climate impact modelling, prediction and verification is required. This can directly be used for the scientific improvements in these fields on a flight-by-flight basis.

Some mitigation measures will have the side-effect of increasing costs, such as direct operating costs (DOC) for airlines or airspace congestion. Some other measures may target only specific flights and therefore not all of the flights will be affected. Even some other measures may even provide win-win situations, where both CO_2 and non-CO_2 climate effects are reduced. Examples for this are increased use of SAF and free route airspace.

7.3.1 Overarching

Some considerations are essential for all mitigation measures. The improvement and public availability of reliable models for studying future policy scenarios and individual environmental impacts per flight needs to be stimulated. In addition, the work on standardisation and implementation of these models for societal cost-benefit analyses and environmental impact analysis requires further work. With these tools available, the projected impact on non-CO_2 effects current policies – which prioritise CO_2 reduction at the moment – can be studied more in detail. The priority with respect to non-CO_2 effects should be on deepening the understanding of non-CO_2 phenomena, reducing or stabilizing their uncertainties where feasible, and investigating the benefits of mitigation options. Research programmes like Horizon Europe, Clean Aviation and SESAR can make a substantial contribution to this[136].

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[135] For the years 2025 and 2026 the scope is limited to intra-European flights and from 1st January 2027 all flights departing and arriving in the European Economic Area (EEA) are covered.

[136] The Innovation Fund using revenues from the EU Emissions Trading System (ETS) could also possibly play a role in the future, but so far, no projects on aviation non-CO_2 effects have been funded.

7.3.2 Improvements in aircraft and engine technology

Changes in aircraft and engine design can yield benefits in terms of reducing the non-CO_2 climate effect of aviation. A few groups of changes are discussed.

Alternative propulsion: battery-electric, hydrogen fuel cell and hydrogen combustion

As indicated in Section 7.2 (specifically in Sections 7.2.1 to 7.2.3), current aviation non-CO_2 climate effects are caused by emissions stemming from the combustion of fuels. Aircraft that do not combust fuel, such as electrically propelled ones, hence prevent such emissions, and therefore also prevent the associated non-CO_2 climate effects completely. Only battery-electric aviation is truly without “tank-to-wake” emissions. Hydrogen-powered aircraft using a fuel cell (such as the future regional aircraft described in 3.4.2) typically emit water vapour, which is created from the reaction of hydrogen with oxygen that occurs in the fuel cell[137]. This can also lead to contrail formation which, however, have a smaller climate impact than contrails from jet engines (Gierens, 2021).

In case hydrogen is used in a gas turbine, combustion emissions are produced. These are, however, different: of the non-CO_2 emissions that occur when combusting kerosene (as listed in Section 7.2.1), only water vapour and nitrogen oxides remain, whereas sulphur dioxide, carbon monoxide, hydrocarbons, particulate matter and soot are avoided completely[138]. On the other hand, water emissions increase (Lammen, Peerlings, van der Sman, & Kos, 2022) potentially leading to more contrail formation and the non-CO_2 effect is currently assessed. Whether NO_X emissions could be reduced, is subject of ongoing research.

Improvements in kerosene-powered engines

A number of trends in the design of current kerosene-powered engines influences the total non-CO_2 climate effect of aviation:

- Engines that have lower fuel burn and CO_2 emissions, typically achieve this by increasing overall pressure ratios and combustion temperatures. All else equal, this increases NO_X emissions, which could lead to an increase in the associated non-CO_2 effect. Engine manufacturers can address the NO_X increase through the combustor technology.
- Particles (such as nvPM) are formed in fuel rich regions of the combustor and burning off these particles requires high temperatures. This marks a trade-off with NO_X which has slight tendency to form under leaner conditions (more excess oxygen) and high temperatures. Except for the requirement of a good mixture of fuel and air, nvPM and NO_X reduction from combustion have thus opposing requirements. Lean burn engines ensure lean conditions lowering soot emissions and temperatures below that needed for effective NO_X production resulting in minimized particle formation and low NO_X emissions.
- Besides the emission trade-offs, engines with a higher propulsive efficiency produce less heat and hence release (relatively) cooler exhaust air. This increases the likelihood of contrail formation (Section 7.2.3), as water droplets more easily freeze.
- Cleaner burning engines, such as lean burn engines, emit less soot particles. This may lead to less but (on average) bigger ice crystals, which is believed to reduce the optical thickness of contrails. This, in turn, reduces their radiative forcing. This is still subject to research in e.g. the VOLCAN campaign, as under some circumstances low-soot conditions might not reduce contrail ice crystal number (Kärcher, 2018).

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[137] Theoretically, the water produced by the fuel cell could be stored on board, to be discharged after landing, or in liquid form. The authors of this report are not aware of any hydrogen-powered aircraft concepts that aim to incorporate such a system.

[138] With the possible exception of such emissions that originate from, for example, lubrication oils (Posonby, King, Murray, & Stettler, 2023).

Engine certification standards can help guide engine development and ensure that performance in terms of NO_X and (non-volatile) particulate matter does not deteriorate as a consequence of increasing focus on fuel consumption, CO_2 emissions and (related) cost. The extent to which NO_X certification standards, which focus on emissions during the landing and take-off (LTO) cycle, also impact NO_X at higher altitudes (where NO_X emissions have a climate effect) is uncertain (EASA, 2020). This especially holds for engines with newer combustor types.

Having the capacity to determine the trade-off between NO_X/contrails and CO_2 climate impacts would be a critical improvement to find the optimum aircraft/engine pair for reduced climate impact during their development.

7.3.3 Improvements in ATM and operations

Whereas the climate impact of CO_2 is homogeneous in the sense that it does not matter at which exact location and time the CO_2 is emitted, the climate impact of non-CO_2 effects varies based on the emission location and time. In effect, there are certain areas, also called climate sensitive areas, where non-CO_2 effects are more likely to occur or their climate impact is bigger. Non-CO_2 mitigation strategies from an operations point of view often target the avoidance of the flight through climate sensitive areas.

Contrail avoidance

One dedicated non-CO_2 mitigation strategy is contrail avoidance where aircraft are rerouted around ice-supersaturated regions (ISSR) in the atmosphere which are prone to the formation and persistence of contrails and contrail-induces cirrus clouds. Depending on the time of the day and on other atmospheric parameters, the contrails are either warming or cooling, with warming effects being the predominant ones. It therefore makes more sense to avoid the warming contrails instead of all contrails. As contrails during the night are always warming, a variation of contrail avoidance is to avoid all night-time contrails. Due to the persistence of the contrails, night-time contrails stem from flights in the late afternoon, evening or night. Other mitigation strategies focus on the “Big Hits” [139], the contrails with the biggest warming effect and only deviate certain flight trajectories associated with highly warming contrails. The challenge is to identify these flights based on meteorological forecasts and their limited quality.

In general, there is a trade-off between contrail avoidance and additional fuel burn and therefore CO_2 and other emissions like NO_X. Deviating from the original flight trajectory means a detour and/or the flight on a different altitude which is not the fuel burn optimal one. A conversion of which additional amount of CO_2 is justified to avoid persistent contrails and the comparability between the effects must be guaranteed. This is currently one of the biggest issues and widely discussed in the scientific community as well as among policy makers (EASA, 2020). Contrail avoidance also comes with operational implementation issues. Higher complexity for air traffic controllers and air traffic management in general, increased flight times (including consequences for slots, time costs and network effects) and capacity issues are some of the limiting factors. A good collaboration between meteorological (MET)-services, science, air traffic control, the airspace users and pilots is needed to accommodate the changed flight trajectories. Different possible approaches for operationally avoiding contrails are a more tactical air traffic control (ATC) centred approach or a more strategic airline centred approach. So far, strategies for contrail avoidance were simulated, airlines performed flight trials and tests from an air traffic control perspective were performed in Europe (Sausen, et al., 2023). An application on the larger scale for commercial aviation[140] is not implemented yet.

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[139] The concept of “Big Hits” is also explained in Section 7.2.3.

[140] Flights with more scheduling flexibility (charter operators, flight tests, repositioning flights) could probably apply mitigation strategies more easily.

The weather-based approach to identify the ice-supersaturated regions requires weather forecasts which are available for the next hours to next few days to forecast the location and time of climate sensitive areas. The stakeholders need to be flexible enough to adapt to these changing conditions. However, the maturity level of the prediction of e.g. ISSR is still very low and more research work is still needed before those predictions can be widely used.

Other operational concepts

Concepts like free route airspace and flexible use of airspace can lead to win-win-situations where CO_2 effects and non-CO_2 effects are reduced at the same time.

Another operational concept is flying lower and slower with existing aircraft. On average the non-CO_2 climate impact decreases on lower altitudes which was deducted by a climatological approach (Matthes, et al., 2021). In order to limit the drag increase and therefore fuel burn increase at lower altitudes, the cruise speed is reduced. Future aircraft design could possibly optimise the aircraft to fly at these lower altitudes with a smaller Mach-number to reduce the climate impact. Climate optimised flight planning includes next to contrail avoidance also other effects from NO_X and water vapour in account. Climate optimised intermediate stop operations also offer a possibility to reduce the climate impact on a flight by choosing smaller cruise altitudes (Linke, et al., 2021; Dal Gesso, et al., 2022).

Reducing the fuel burn of ground operations also has the effect that NO_X emissions are reduced. When implementing an electric front wheel there is the trade-off between reduced CO_2 and NO_X emissions on the ground with increased CO_2 and NO_X during the cruise flight due to the added weight (Linke, et al., 2021; Dal Gesso, et al., 2022).

From a point of view of operational non-CO_2 mitigation strategies, changes in the traffic flow and resulting network effects[141] should be taken into account.

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[141] In addition, there is still no overall strategy to ensure that a climate sensitive area (e.g. area prone to contrail formation) is avoided by all airlines and not just one.

7.3.4 SAF and sustainable energy sources

Powering aircraft with SAF reduces the climate impact of aviation by lowering CO_2 and non-CO_2 emissions. SAF probably has the potential to reduce radiative forcing from contrails as the contrails have a lower optical thickness (Burkhardt, Bock, & Bier, 2018; Bier & Burkhardt, 2022), but research is still ongoing. Lee (2023) addresses the uncertainties in the climate science modelling and the interaction between fuel and engine technology. Research projects like VOLCAN and ECLIF3 are currently trying to compare the contrails formed by burning SAF and conventional aviation fuel. During cruise in-flight measurement campaigns, significant reductions in soot emissions and corresponding ice particle number concentrations have been reported for the burning of SAF blends (Moore, et al., 2017; Voigt, et al., 2021; Märkl, et al., 2024). This is -with the current understanding- the case for soot rich conditions while other effects such as activation of background particles or volatile particle matter could play a role in soot-poor conditions (Kärcher, 2018). This is investigated in the VOLCAN and the Boeing ecoDemonstrator campaign. The reduced soot emissions of SAF compared to conventional jet fuel are an effect of the different fuel compositions. Aviation turbine fuel made from fossil feedstock is naturally rich in aromatics (incl. naphthalene) and sulphur, which are typically nearly absent from all Synthetic Paraffinic Kerosene (SPK) fuels made from sustainable feedstocks[142]. Influencing the composition of conventional aviation fuel by hydrotreating to lower the aromatic content and sulphur levels can also lead similarly to reductions in non-CO_2 emissions (Faber, Király, Lee, Owen, & O'Leary, 2022).

Beneficial effects on the climate impact can be achieved when using SAF blends (up to 50%), but even more when going up to 100% [143]. Therefore, it is very important to scale up the use of SAF as soon as possible to enhance the climate benefits of SAF on both CO_2 and non-CO_2 impacts.

On the short term, when SAF supply is limited, preferential allocation to certain flights which are responsible for a strong warming effect due to contrails (e.g. at night and in winter) could drastically increase the climate benefit. This targeted use of SAF could increase the overall climate benefits of SAF by a factor of 9–15 relative to a scenario in which SAF is uniformly distributed (Teoh, et al., 2022). A requirement is that the flights with the highest warming effect can be identified accurately which is still challenging. Other challenges are fuel logistics at the airport i.e. whether SAF could be supplied separately from Jet A-1 (or if it is always blended with the ReFuelEU Aviation mandated blending values in the pipelines) requiring a (costly and space-consuming) parallel fuel infrastructure.

For airports and communities living around airports, improvements in local air quality are of major importance.
The positive effect of lower soot emissions on local air quality should therefore also be taken into account as a major driver for scaling up the use of SAF (Faber, Király, Lee, Owen, & O'Leary, 2022).

100% drop-in SAF – meets ASTM D1655

Drop-in SAF has the advantage that it can be used in all aircraft and engines in service and in production today. No changes are required to the aircraft or airport infrastructure and using 100% drop-in SAF has no impact on the current and future fleet. 100% drop-in SAF meets the specifications of conventional jet fuel. When entering the hydrant system, this fuel will adhere to ASTM D1655.

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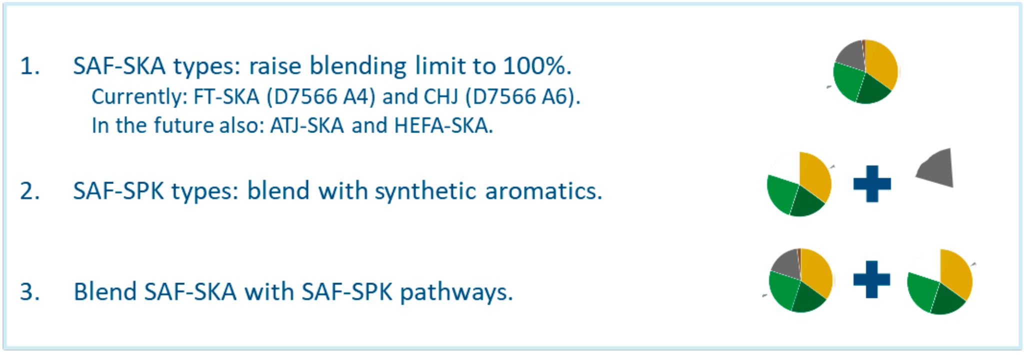
[142] Except if e.g. aromatics are added on purpose to create a fuel which adheres to the ASTM specifications.
[143] The benefits would be even higher for SAF without aromatics which is a non-drop-in fuel.

SAF types are currently certified in ASTM D7566 up to a blending limit of 50% (for more details see Section 5.1). This is mainly due to the lack of aromatics in the SPK-type SAFs. Increasing the blending level can therefore only be achieved by blending with synthetic aromatics or with a jet fuel which contains aromatics. Synthetic Kerosene with Aromatics (SKA) already includes aromatics as stated in the name. For SKA-type SAFs the blending levels could be increased to 100% while still meeting the conventional jet fuel specs (ASTM D1655). This overview is provided in Figure 39. 100% drop-in SAF will be certified under ASTM D7566. As such, the ASTM D7566 documentation has to be updated to include the options visualised in Figure 39. Option 2 may lead to logistical challenges as the producers of synthetic aromatics may not be co-located with the SAF producers. Similarly for option 3, the producers of SAF-SPK and SAF-SKA may also not be co-located. Once 100% drop-in SAF batches enter the fuel system, these batches will mix with conventional aviation fuel.



1. SAF-SKA types: raise blending limit to 100%.
   Currently: FT-SKA (D7566 A4) and CHJ (D7566 A6).
   In the future also: ATJ-SKA and HEFA-SKA.
2. SAF-SPK types: blend with synthetic aromatics.
3. Blend SAF-SKA with SAF-SPK pathways.

Figure 39: Drop-in SAF overview, different colours of the pie charts stand for different groups of components i.e. the grey part for aromatics

100% non-drop-in SAF – new specification

Based on recent in-flight measurement campaigns within the ECLIF3-project, the climate benefits of using a jet fuel without aromatics have been investigated. These campaigns contributed to understanding the soot and ice particle number reduction potential of 100% SAF without aromatics. The results show a promising reduction in climate forcing from contrails.

The aviation industry is actively working on developing a new ASTM standard for jet fuel without aromatics within an ASTM task force. Currently many OEMs (such as Airbus, Boeing, Embraer, P&W, GE, Safran, Rolls-Royce, Honeywell) are involved. In the coming years the aviation industry foresees a larger involvement of the fuel producers as well. Fully removing the aromatics, may lead to broadening the envelope for other Jet-A/A-1 properties. Work is currently in progress on assessing the new specifications. The new ASTM standard is expected in the period between 2025-2030.

This fuel will be used by new aircraft which are designed to meet the new specification. In-operation aircraft are not expected to use this fuel as retrofitting and recertification would be required. For in-production aircraft the feasibility is currently being studied. These aircraft would most probably need recertification for 100% non-drop-in SAF combined with the latest certification updates in other areas.

The impact of a new fuel specification is currently being assessed. Many safety aspects need to be evaluated, such as the compatibility of the aircraft materials. For example, seals in fuel systems are made of nitrile, which swells when exposed to aromatics. That ensures a seal. A fuel without aromatics may therefore causes leakages. Alternative materials such as fluorocarbons and fluorosilicone are used in next-generation engines. Some engine manufacturers such as Rolls-Royce have indicated full compatibility of their engines with 100% SAF (Rolls-Royce, 2023b). Next generation aircraft systems may still use some nitrile. The challenge of using fuels without aromatics is mainly on the airframe side and backwards-compatibility[144]. Another example, are the aircraft fuel gauging systems. These systems work based on conductivity, which is affected by aromatics. In some cases, a software update could solve the possible discrepancies in measurements; in others, additional sensors may be required.

7.3.5 Economic measures

The economic measures continue to be largely underexplored. This is to a large extent due to the sizable uncertainties associated with the non-CO_2 effects, and the lack of common metrics and models which can be used for economic impact assessments.

One of the main reasons for using economic measures is to encourage stakeholder behaviour towards the climate friendly solutions that are cost-efficient and welfare optimal. Preliminary results from the ClimOP-project show that, by pricing the non-CO_2 effects, the climate optimal flight may become economically more attractive than the fuel optimal flight (van der Sman, et al., 2023). Pricing the non-CO_2 effects might lead to substantial cost increases compared to the current situation for some flights. Another option would be positive incentives in the form of e.g. a bonus system. Next to further studying adequate pricing mechanisms, it is important to identify how stakeholders can mitigate the full climate impact. Measures like contrail avoidance, low aromatic fuels and improved aircraft and engine technology can be used to mitigate the non-CO_2 effects.

For any pricing mechanism or bonus system, decreasing the climate impact uncertainties based on high quality data remains a key enabler. The more precise the climate impact calculations can be made, the better the incentive will be to apply targeted mitigation strategies to avoid these climate impacts.

7.4 Towards implementation

The assessed projects are still in the “Design implementation” phase and did not reach the “Roll out implementation” phase yet. This reflects the limited attention for non-CO_2 effects in the past, but as the research progress continues, eventually non-CO_2 mitigation measures are likely to reach higher maturity levels.

The policy ReFuelEU Aviation is already implemented, originally with the intention to reduce CO_2 with an increased SAF use which also leads to non-CO_2 co-benefits.

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[144] An older aircraft not certified for 100% SAF could not land at an airport using 100% non-drop-in fuel in its tank system only (under the assumption that it does not perform tankering).

7.5 Ongoing and undertaken non-CO_2 projects and trials

The industry, together with academia and governments, is working on improving the scientific understanding of the non-CO_2 climate effects and the potential mitigation options to reduce their climate impact. This section provides an overview of 57 projects which contribute to understanding and mitigating the non-CO_2 effects of aviation. These projects are either completed or ongoing.

Project classification

Each project is assigned to one or more combinations of phases of the triple-diamond as discussed in Section 7.1 and topics discussed in Section 7.3. The grids and allocation of each project are shown in Figure 40. Additional information can be found in Appendix 4.5. This includes (if publicly available) a project's full name, funding budget and programme, start and end dates, participating parties, key objectives and results.

Each project is assigned a contribution factor value of 10, 25, 50, 75 or 100%. This is to differentiate between projects regarding the size of the contribution to non-CO_2 climate effects. If a project belongs to multiple grids, the scale factor is divided equally among those grids. The size of the marker in Figure 40 reflects the value of the scale factor. The colour of the marker indicates the project's status.

Table 52 displays the same categories. For each grid, the sum of the scale factors belonging to the projects is given. The values in the table indicate the effort put into each grid.

Results

For *understanding climate science,* most projects are concentrated in the first diamond. Whereas projects belonging to *aircraft/engine technology* and *operations*, are in the solution diamond. This shows that research into mitigation strategies is conducted in parallel to *climate science understanding*. This can be beneficial as investments can already be made into setting up, orienting, and defining promising strategies whilst others determine the size and certainty of the non-CO_2 effects.

No project has been assigned to the category *economic measures.* This delay may be expected, as a consensus in the fundamental research regarding non-CO_2 effects is lacking. For the same reason, projects regarding the last step in the triple-diamond method (*roll out implementation*) are not present.

The majority of the projects is a collaboration between the industry, research organisations and academia; 38 out of 57 projects (67%) are a public-private partnerships (PPP). A handful of projects are industry-only, these include DECOR and project Contrails by Breakthrough Energy. The remainder is undertaken by research organisations and/or academia.

As can be seen in Table 52, a difference is found between the diverging and converging parts of the triple-diamond method. The diverging topics *understanding climate science* and *develop measures* have a summed scale factor of more than double that of the converging topics *choice of metrics and models* and *validate measures.* For example, within the category *climate science/weather*, the table indicates that effort is largely invested in developing understanding. This indicates that a consensus might be missing, which corresponds with the uncertainties present currently in the non-CO_2 aviation climate effects.

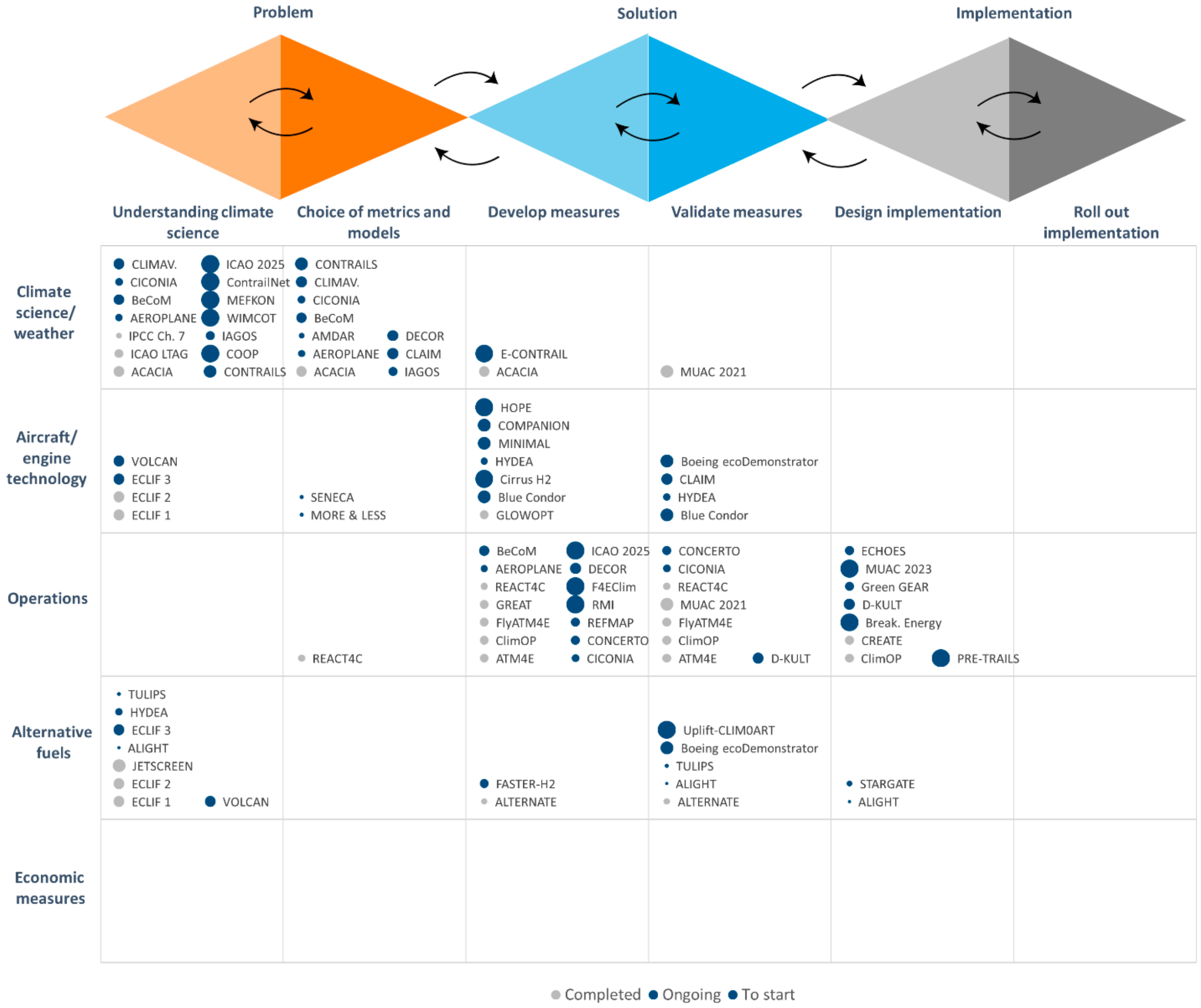

Figure 40: A categorised overview of completed and ongoing projects about non-CO$_2$ climate impacts of aviation. Projects can be placed in multiple grids. The size of the dots displays the scale factor (an assigned value that represents a projects' contribution to non-CO$_2$ climate impact research). If a project falls into multiple categories, the scale factor is divided equally across those grids. Economic measures are empty since no project was submitted

Table 52: Sum of scale factors of projects per grid. If a project falls into multiple categories, the scale factor is divided equally across those grids. The sums of each row and column are also provided

Sum of scale factors per grid	**Under-standing climate science**	**Choice of metrics and models**	**Develop measures**	**Validate measures**	**Design implemen-tation**	**Roll-out implemen-tation**	***Sum***
Climate science / weather	7.5	3.0	1.3	0.5	0.0	0.0	***12.3***
Aircraft and engine technology	1.5	0.1	3.9	1.5	0.0	0.0	***7.0***
Operations	0.0	0.2	5.7	2.2	4.4	0.0	***12.5***
Alternative fuels	2.3	0.0	0.4	1.7	0.1	0.0	***4.5***
Economic measures	0.0	0.0	0.0	0.0	0.0	0.0	***0.0***
Sum	***11.3***	***3.3***	***11.3***	***5.9***	***4.5***	***0.0***	

7.6 Non-CO_2 policy context

GLOBAL POLICY CONTEXT

On the global policy level, ICAO certification standards exist for aircraft engine emissions to quantify and limit aviation's effect on local air quality and climate effects. The engine certification process is based on the landing and take-off (LTO) cycle and four operating modes are evaluated including measurements. The standards comprise CO_2, hydrocarbon gaseous emissions (HC), CO, NO_X, as well as non-volatile particulate matter (nvPM), which are publicly available for turbojet and turbofan engines and stored in the ICAO emissions databank (ICAO, 2022b; EASA, n.d.). The ICAO Committee on Aviation Environmental Protection (CAEP) is a technical committee, which assists the ICAO Council on the topics emissions and climate impact with policies, standards and recommended practices. The CAEP WG3 "Emissions" (ICAO, n.d. - c) keeps the ICAO engine emissions and aeroplane CO_2 emissions certification standards up to date, reviews NO_X and nvPM regulatory levels and monitors trends in the emissions and composition conventional aviation fuel, SAF and blends. Related to operational mitigation measures, ongoing work of CAEP WG2 "Airports and Operations" (ICAO, n.d. - b) includes operational opportunities to reduce the impacts of non-CO_2 effects, especially with regards to contrails and aviation induced cirrus. The CAEP "Impacts and Science Group" (ISG) works on the analysis of air quality and climate impacts interdependencies, trade-offs of aviation emissions and the assessment of contrail and aviation induced cloudiness impact. ICAO is considering in 2024 what additional actions would be needed at global level to address non-CO_2 emissions from international civil aviation in the light of ongoing developments. One step forward was the three-day symposium aviation non-CO_2 emissions organised by ICAO in September 2024 that brought together atmospheric scientists, aerospace engineers, policy makers and airline operators (ICAO, 2024a).

EUROPEAN POLICY CONTEXT

Article 2 of the European Climate Law (EC, 2021c) defines the objective that the European Union shall be climate-neutral by 2050. The scope includes the reduction of greenhouse gas emissions to reach net zero emissions in 2050. The Kyoto Protocol (including the Doha amendment) comprises seven greenhouse gases by human activities: carbon dioxide, methane, nitrous oxide, hydrofluorocarbons, perfluorocarbons, sulphur hexafluoride and nitrogen trifluoride (EEA, n.d. - b) (United Nations Climate Change, n.d.). To ensure that the full climate impact of aviation is taken into account, new policy options are being considered to address the aviation non-CO_2 effects[145] as well. Even though there are no binding EU targets for the non-CO_2 climate effects of aviation, and the definitions of climate-neutrality being unclear (Peerlings & Paletti, 2024), the term "climate-neutral" implies that the whole climate impact is meant, under which non-CO_2 climate effects would also fall.

In the European policy context, the non-CO_2 report by EASA (2020) analysed and proposed potential financial, fuel-related and ATM-related policy options. The policy advice of the mandatory use of SAF has been implemented in the ReFuelEU Aviation mandate that was originally introduced to reduce the CO_2 emissions of aviation (EC, 2023a). The benefits of the usage of SAF instead of conventional aviation fuel extend beyond just mitigating CO_2 emissions to most likely reduce non-CO_2 effects (Voigt, et al., 2021).

The non-CO_2 monitoring, reporting and verification scheme (MRV) will require aircraft operators of aircraft with jet engines to monitor and report the non-CO_2 effects from each flight from 1st January 2025. For the years 2025 and 2026 the scope is limited to intra-European flights and from 1st January 2027 all flights departing and arriving in the European Economic Area (EEA) are covered. The MRV is a stand-alone data collection activity and a distinct exercise from carbon pricing (EC, 2024a). The goal is to enhance the scientific knowledge, scientific validation of the impacts of non-CO_2 effects and inform policies.

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[145] See Section 7.2.2; aviation non-CO_2 effects are not the included in the list of greenhouse gases from the Kyoto protocol.

Starting from June 2024, EASA will strengthen and coordinate a European network of experts (ANCEN) to support the non-CO_2 impact and policy assessment (EASA, 2024b).

NATIONAL POLICIES

At national level, only the Netherlands has implemented a policy addressing non-CO_2 effects which focuses on the three elements: more targeted research; policies in the European and global (ICAO) context; stronger collaboration and bringing different parties together (Ministry of Infrastructure and Water Management, 2023). Other countries support the research on non-CO_2 effects in research programmes (e.g. Climaviation and CORAC in France (Climaviation, n.d.) and LuFo Climate in Germany (The federal aviation research programme LuFo Climate, n.d.)).

EUROPEAN RESEARCH AND INNOVATION GOALS

Horizon Europe is the European Union's flagship research and innovation program, which includes significant efforts to minimize aviation's non-CO_2 emissions. The goals and strategies include enhancing the scientific understanding of non-CO_2 emissions and their climate effect, promoting the development and deployment of innovative technologies and alternative fuels that can reduce non-CO_2 climate impacts. Furthermore, operational improvements are addressed and policy measures that effectively reduce non-CO_2 (taking into account the trade-off with CO_2) investigated and supported. The European Commission's SESAR 3 research projects (such as CICONIA and CONCERTO) contribute to the understanding and mitigation strategies of non-CO_2 effects.

ACARE[146] sets goals for 2050 relative to 2000 for intra-EU flights and those departing the EU (ACARE, n.d.; ACARE, 2022). The goals are a 90% reduction of CO_2 emissions, a 90% reduction of non-CO_2 emissions, namely NO_X, nvPM and a 90% reduction of warming contrails. ACARE further states that by 2030, the non-CO_2 climate effects should be fully understood, managed, monitored and reduction targets updated with the scientific understanding and mitigation options. The goals for a 90% reduction of NO_X and nvPM mass and number are incorporated in the UK non-CO_2 roadmap (ATI, 2024).

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[146] ACARE is the Advisory Council for Aviation Research and Innovation is a high-level strategic advisory body representing the European aviation community – consisting of European aeronautics industry, research organisations, EU institutions such as the European Commission, national governments and other stakeholders.

7.7 Conclusions and Implications

Commercial aviation impacts the climate through both CO_2 and non-CO_2 emissions. While CO_2 emissions are fully understood and therefore have been the primary focus of climate policies, non-CO_2 emissions such as nitrogen oxides (NO_X), water vapour and particles (i.e. non-volatile particulate matter nvPM) are largely understood, but the resulting non-CO_2 effects are subject to uncertainties. Addressing non-CO_2 effects based on science in a holistic approach together with CO_2 emissions is crucial for achieving the broader climate goals set by international and regional bodies, including the European Union's objective of climate neutrality by 2050.

Whilst the non-CO_2 climate impacts from aviation activities are confirmed by the state of science presented in this report, they are not yet completely understood and therefore are subject to extensive ongoing research both in terms of science, weather forecasting and potential mitigating solutions. A few of the mitigation measures primarily targeting CO_2 emissions which also yield co-benefits for non-CO_2 climate effects are getting closer to operational implementation, but most of such potential mitigation measures are not considered ready for deployment. A scalable and iterative approach which considers the results of ongoing research when they become available is therefore recommended. Whenever policy options are assessed, it will be essential to adopt a holistic approach considering both CO_2 and non-CO_2 to avoid negative trade-offs from one mitigation measure (for non-CO_2) on the other emission types (such as CO_2).This results in a need to further study potential mitigation measures and policy options to address the non-CO_2 climate effects. The mitigation measures and policy options already taken to address CO_2 may offer co-benefits, but complementary measures and policies are required to address aviation's full climate impact.

The analysis performed during the writing of this report showed that, from an operational context, the prediction of the occurrence of the non-CO_2 effects is currently the main focus area based on more extensive and more accurate data, such as temperature and humidity at cruising altitude, e.g. measured by on-board humidity sensors. The weather forecast models required for this and their predictions need to be further improved, for example by adding data from additional on-board humidity sensors, which are important inputs for the weather models.

Multiple conditions have to be satisfied to progress in reducing the non-CO_2 climate impact of aviation, for instance a choice of climate metrics, the continuous improvement and cross-validation of actionable climate models, the validation of measures and the assessment of technical and operational feasibility. The data collection and data sharing, such as foreseen in the non-CO_2 MRV can also help accelerate the validation of the climate impact calculations and prediction of the occurrence of non-CO_2 effects.

An ongoing and important effort is taking place to implement new research, develop new technologies, validate the predictions of possible mitigation options and validate their efficiency, practicality and feasibility, despite the high uncertainties in the quantification of non-CO_2 climate impact (Lee, et al., 2023). The overview of the 57 projects related to non-CO_2 effects presented in this report underlines the fact that a strong collaboration between stakeholders from industry, research institutions, academia, politics, regulators and public-private partnerships is essential to accomplish this effort.

Fully understanding the impact of non-CO_2 emissions of aviation is a matter of intensive research. The aviation industry supports academic and research activity aiming at understanding these complex phenomena. Notwithstanding the urgency to act, it is necessary to improve knowledge and intensify scientific understanding to design the best solutions to mitigate non-CO_2 emissions in the future. The aviation industry is already supporting numerous projects linked to non-CO_2 emissions understanding and mitigation, works on new technologies, implementation trials, validation of predictions and the practicality and feasibility of the implementation of the possible mitigation options.

This report does not include an impact assessment of policy options. The focus of this chapter lies in the scientific and technological aspects. As such, the implications which follow from this chapter have a broader and more technical scope.

Continued research into understanding and quantifying non-CO_2 climate effects, the complex interactions between the aircraft operation, the engine technology and emissions and their interaction with the atmosphere is needed. This is closely tied to continued investments in climate science research. Specifically, investment in research and data-sharing initiatives is needed to improve the understanding of aircraft cruise emissions. Additional funding for meteorological forecasting and the development of better onboard sensors is also required. Furthermore, existing climate models need more cross-validation, and a decision on metrics and models is required in the short term to facilitate informed policy-making.

Investment in research on mitigation measures, as well as their validation and assessment of technical and operational feasibility, is essential. Policy options should go beyond analysing non-CO_2 effects and provide concrete schemes for mitigation measures, thereby enabling the aviation sector to take tangible steps towards reducing its climate impact. Additionally, a detailed impact assessment of potential policy options is necessary, given that the uncertainties in the climate impact assessment of non-CO_2 effects may lead to potential unintended consequences. Finally, the importance of global collaboration, particularly through the International Civil Aviation Organization (ICAO), cannot be overstated, as non-CO_2 effects are a global issue that requires a coordinated international response.

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Abbreviations

Abbreviation	Description
A4E	Airlines for Europe
ACARE	Advisory Council for Aviation Research and Innovation
aCCF	Algorithmic Climate Change Functions
ACI-EUROPE	Airports Council International Europe
ACT-SAF	Assistance, Capacity-building and Training for Sustainable Aviation Fuel programme
ADS-B	Automatic dependent surveillance-broadcast
AFIR	Alternative Fuels Infrastructure Regulation
AIC	Aviation-induced cloudiness
ANCEN	Aviation non-CO2 expert network
ANSP	Air navigation service provider
APAC SATM	Asia Pacific Seamless Air Traffic Management
APU	Auxiliary power unit
AR	Assessment Report
ASD	AeroSpace and Defence Industries Association of Europe
ASK	Available Seat Kilometres
ASMA	Arrival Sequencing and Metering Area
ASTM	American Society for Testing and Materials
ATAG	Air Transport Action Group
ATC	Air Traffic Control
AtJ	Alcohol-to-Jet
ATM	Air traffic management
ATR	Average Temperature Response
ATS	Air Traffic Services
AZEA	Alliance for Zero-Emission Aviation
BADA	Base of Aircraft Data
bn	Billion
BPR	Boundary layer injection
C	Commuter *Aircraft class*
CAAF/3	Third Conference on Aviation Alternative Fuels
CAAS	Civil Aviation Authority Singapore
CAEP	Committee on Aviation Environmental Protection
CAF	Conventional aviation fuel
CANSO	Civil Air Navigation Services Organisation
CAPEX	Capital expenditures
CASK	Cost per available seat kilometre
CATS	Complete Air Traffic System
CBAM	Carbon Border Adjustment Mechanism
CCO	Continuous climb operations
CCS	Carbon Capture and Storage
CCUS	Carbon Capture Utilization and Storage

Abbreviation	Description
CDO	Continuous descent operations
CEN	European Committee for Standardization
CEN-CENELEC	European Committee for Electrotechnical Standardization
CH4	Methane
CHJ	Catalytic hydrothermolysis jet
CO	Carbon monoxide
CO_2	Carbon dioxide
CO_2e	CO_2 equivalent
CORSIA	Carbon Offsetting and Reductions Scheme for International Aviation
CP1	Common Project One
CRCF	Carbon Removals and Carbon Farming
CS	Certification Specification
CSRD	Corporate Sustainability Reporting Directive
DACCS	Direct Air Carbon Capture and Storage
DOA	Design Organisation Approval
DOC	Direct Operating Costs
EASA	European Union Aviation Safety Agency
EC	European Commission
ECAC	European Civil Aviation Conference
EEA	European Economic Area
EF	Energy forcing
EFTA	European Free Trade Association
e-GPU	Electrical ground power unit
EGWP	Efficacy of the GWP
EGWP*	Efficacy of the GWP*
EIS	Entry into service
EMH	Efficient Market Hypothesis
ER	Extended range
ERA	European Regional Airlines Association
ERF	Effective Radiative Forcing
ESRS	European Sustainability Reporting Standards
ETD	European Tax Directive
EU	European Union
EU ETS	European Union Emissions Trading System
EU+	EU, UK and EFTA
EUA	EU Allowances
EUR	Euro
FAA	Federal Aviation Administration
FBI	Fuel burn improvement
FEGP	Fixed Electrical Ground Power
FF-ICE	Flight & Flow Information for a Collaborative Environment
FMS	Flight management system
FRA	Free route airspace

Abbreviation	Description
FT	Fischer-Tropsch
FUA	Flexible use of airspace
GHG	Greenhouse Gas
GHGP	Greenhouse Gas Protocol
GMF	Global Market Forecast *Airbus industry forecast*
GMI	Gravimetric index
GPU	Ground power unit
Gt	Gigatonne
GTP	Global Temperature change Potential
GWh	Gigawatt-hour
GWP	Global Warming Potential
GWP*	GWP as a function of time
H_2	Hydrogen
H_2O	Water (vapour)
HC	Hydrocarbon
HEFA	Hydroprocessed Esters and Fatty Acids
IAG	International Airlines Group
IATA	International Air Transport Association
ICAO	International Civil Aviation Organisation
ICCT	International Council on Clean Transportation
ICL	Imperial College London
ICVCM	Integrity Council for the Voluntary Carbon Markets
IEA	International Energy Agency
IEC	International Electrotechnical Commission
iGTP	Integrated GTP
IPCC	Intergovernmental Panel on Climate Change
IRA	Inflation Reduction Act
IRENA	International Renewable Energy Agency
ISG	Impact and Science Group
ISO	International Organisation for Stadardization
ISSR	Ice-super saturated region
JU	Joint Undertaking
kg	Kilogrammes
KPI	Key Performance Indicator
kt	Kilotonne
kW	Kilowatt
LCA	Life-cycle analysis
LCAF	Low-Carbon Aviation Fuel
LDC	Least Developed Countries
LH	Long-haul
LH_2	Liquid H_2
LR	Long range *Aircraft class*

Abbreviation	Description
LRC	Long Range Cruise
LTA	Large twin aisle *Aircraft class*
LTAG	Long-Term Aspirational Goal
LTO	Landing and take-off
MBM	Market-based measures
MET	Meteorological
MFSP	Minimal fuel selling price
MJ	Megajoule
MoU	Memorandum of Understanding
MRO	Maintenance, Repair and Operations
MRV	Monitoring, reporting and verification
Mt	Megatonnes
Mtoe	Megatonne oil equivalent
MW	Megawatt
MWh	Megawatt-hour
N_2	Nitrogen
NASA	National Aeronautics and Space Administration
NATS	National Air Traffic Services
neo	New engine option
NET	Negative emission technology
NextGen	Next Generation Air Transport System
NGFS	Network for Greening the Financial System
NLR	Royal Netherlands Aerospace Centre
NM	nautical miles
NO_x	Nitrogen oxides
nvPM	Non-volatile PM
O_2	Oxygen
O_3	Ozone
OAG	Official Airline Guide
OECD	Organisation for Economic Co-operation and Development
OEM	Original equipment manufacturer
OTS	Organised Track System
PCA	Preconditioned Air
PIP	Performance improvement packages
PM	Particulate matter
PPP	Public-private partnership
PRR	Performance Review Report
PSO	Public Service Obligation
PtL	Power-to-Liquid
R	Regional *Aircraft class*
R&D	Research and development

Abbreviation	**Description**
RED	Renewable Energy Directive
RF	Radiative Forcing
RFNBO	Renewable fuel of non-biological origin
RISE	Revolutionary Innovation for Sustainable Engines
RP	Reference Period
RTK	Revenue tonne kilometre
SA	Single aisle *Aircraft class*
SAATM	Single African Air Transport Market
SAE	Society of Automobile Engineers
SAF	Sustainable aviation fuel
SAF_{eq}	SAF equivalent
SARPs	Standards and Recommended Practices
SBC	Synthetic blend component
SBTi	Science-based Targets initiative
SDG	Sustainable Development Goal
SEO	SEO Amsterdam Economics
SES	Single European Sky
SES2+	Single European Sky Regulation
SESAR	Single European Sky ATM Research
SESAR DM	SESAR Deployment Manager
SESAR JU	SESAR Joint Undertaking
SH	Short-haul
SIDS	Small Island Developing States
SIP	Synthesized iso-paraffins
SKA	Synthetic Kerosene with Aromatics
SMTA	Small/medium twin aisle *Aircraft class*
SNIP	SESAR Deployment and Infrastructure Partnership
SO_2	Sulphur dioxide
SPK	Synthetic Paraffinic Kerosene
SPK/A	Synthetic Paraffinic Kerosene with Aromatics
SRIA	Strategic Research and Innovation Agenda
t	tonne
TBO	Trajectory based operations
TE	Technology Evaluator
TEN-T	Trans-European Transport Network
TG	Task Group
TRL	Technology Readiness Level
TtW	Tank-to-Wake
TWh	Terawatt hour
UCO	Used cooking oil
UHBR	Ultra-high bypass ratio

Abbreviation	Description
UK	United Kingdom
UNFCCC	United Nations Framework Convention on Climate Change
USD	United States dollar
VCMI	Voluntary Carbon Market Initiative
WEF	World Economic Forum
WG	Working group
WtT	Well-to-Tank
WtW	Well-to-Wake

Appendix A Consulted parties

Throughout the process of developing this updated edition of the DESTINATION 2050 roadmap, numerous industry and research parties provided valuable input in interviews and workshops.

- DESTINATION 2050 partners:
  - AeroSpace and Defence Industries Association of Europe (ASD) and members
  - Airports Council International Europe (ACI-EUROPE) and members
  - Airlines for Europe (A4E) and members
  - European Regional Airlines Association (ERA) and members
  - Civil Air Navigation Services Organisation of Europe (CANSO) and members
- Other:
  - EUROCONTROL
  - BP
  - NESTE
  - SkyNRG
  - SESAR

Appendix B Background and context

Appendix B.1 Aviation’s contribution to society

The benefits of aviation to society are well documented in terms of economic development and growth (Pot & Koster, 2022; Green, 2007; Zhang & Graham, 2020; Blonigen & Cristea, 2015; Bilotkach, 2015; Brueckner, 2003). Similarly, there is sufficient evidence that airports and airlines provide direct and indirect employment opportunities (Lieshout, Boonekamp, Tempelman, & Burghouwt, 2015; InterVISTAS, 2015).

Counterbalancing the benefits to aviation are the costs. There are various (external) cost associated with aviation that are borne by the public and not the travellers in terms of climate change from the CO_2 and non-CO_2 climate effects addressed in this study, as well as local pollutants such as noise, NO_X and PM (Dings, Wit, Leurs, Davidson, & Fransen, 2003; Schipper, 2004).

Appendix B.2 Aviation’s contribution to climate change

Commercial aviation contributes to climate change through the emission of CO_2, and non-CO_2 climate effects caused by the combustion of hydrocarbon jet fuel, and non-CO_2 climate effects. Acknowledging the uncertainty about the impact of these non-CO_2 effects, they were estimated to be responsible for 2/3^{rds} of the effective radiative forcing caused by aviation in 2018 (EASA, 2020; Lee, et al., 2021). CO_2 forms the other 1/3rd – meaning that the total contribution of aviation to climate change is estimated to be three times as large as the contribution from CO_2 alone. Although more recent publications find different contributions of the various non-CO_2 effects (Quaas, Gryspeerdt, Vautard, & Boucher, 2021; Skowron, Lee, Rodriquez de Leon, Lim, & Owen, 2021; Bier & Burkhardt, 2022; Teoh, et al., 2024; Lee, et al., 2023), the conclusion that their (combined) effect is significant, also when compared to CO_2, firmly stands.

In 2019, global aviation caused 1036 Mt of CO_2 emissions (IEA, 2023a). Compared to a global total of 38 Gt of anthropogenic (man-made) CO_2 (excluding the effects of land use change; Olivier & Peters, 2020, p. 19), this means aviation contributed 2.7% of man-made CO_2 emissions in 2019. According to IATA (2021), commercial aviation emitted 915 Mt CO_2 in 2019, yielding a share of 2.4%. In Europe (EU27 + EFTA, excluding the UK), the shares are higher: 2019 full-flight CO_2 emissions totalled 147 Mt and thereby contributed 5.2% of total European greenhouse gas emissions (EASA; EEA; EUROCONTROL, 2022, pp. 31-35).

Of the total amount of CO_2, long-haul flights contribute most – due to the longer distances travelled: 5.5% of flights are over 4000 km, but result in 46% of aviation CO_2 emissions in Europe (EASA; EEA; EUROCONTROL, 2022, p. 34).

Especially at a global level, the relative contribution of aviation could drastically increase – by up to a factor 10 – if aviation does not address its carbon emissions while other industries do (Pidcock & Yeo, 2016; Becken & Pant, 2020).

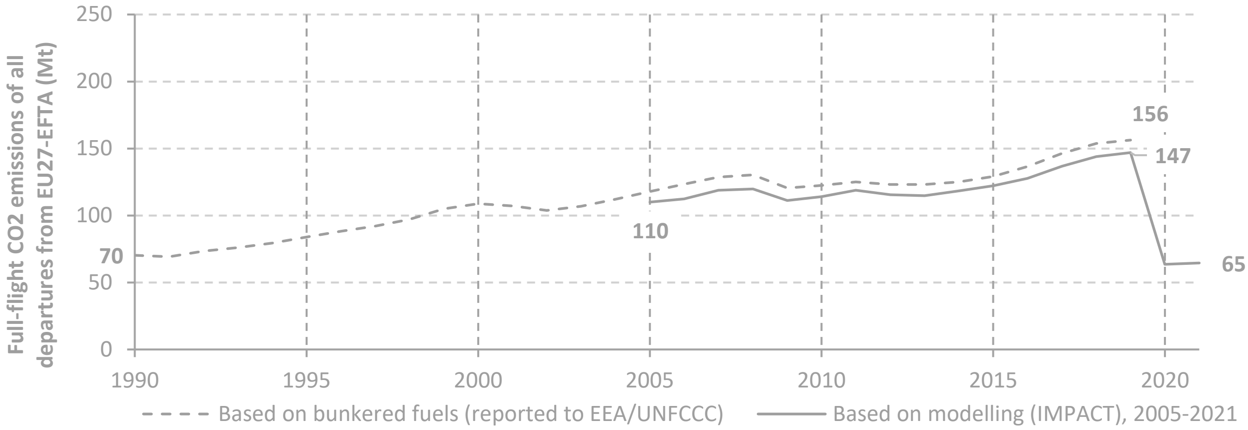

Figure 41: Full-flight CO_2 emissions of flights departing from the EU27 + EFTA, as reported by EASA, EEA & EUROCONTROL (2022). More recent data is not available from the European Aviation Environmental Report series

Appendix B.3 Climate change and tipping points

Considering the global state of the climate, it is essential that aviation and all other industries do reduce greenhouse gas emissions such as CO_2. The IPCC AR6 showed that over the 2010–2023 period, practically all global surface temperature increase was anthropogenic, with negligible contributions by solar and volcanic drivers and internal climate variability. The rate of human-induced warming is currently estimated to equal 0.26 °C per decade with a range of [0.2–0.4] °C per decade (Forster P. M., et al., 2023), having reached 1.1 °C above preindustrial temperatures already, such that the risk of reaching dangerous tipping points is increasing (Armstrong McKay). Once these thresholds are reached a tiny perturbation may alter the state of the Earth significantly and severely damage the Earth’s ecosystems threatening the stability of our societies. Some of these thresholds are estimated to be already reached within the 2.0 °C target of the Paris Agreement as visualised in Figure 42, stressing the importance of minimising any further tenth of degree global warming. Swift decarbonisation of aviation may minimise further warming and help avoid the risk of reaching irreversible climate tipping points.

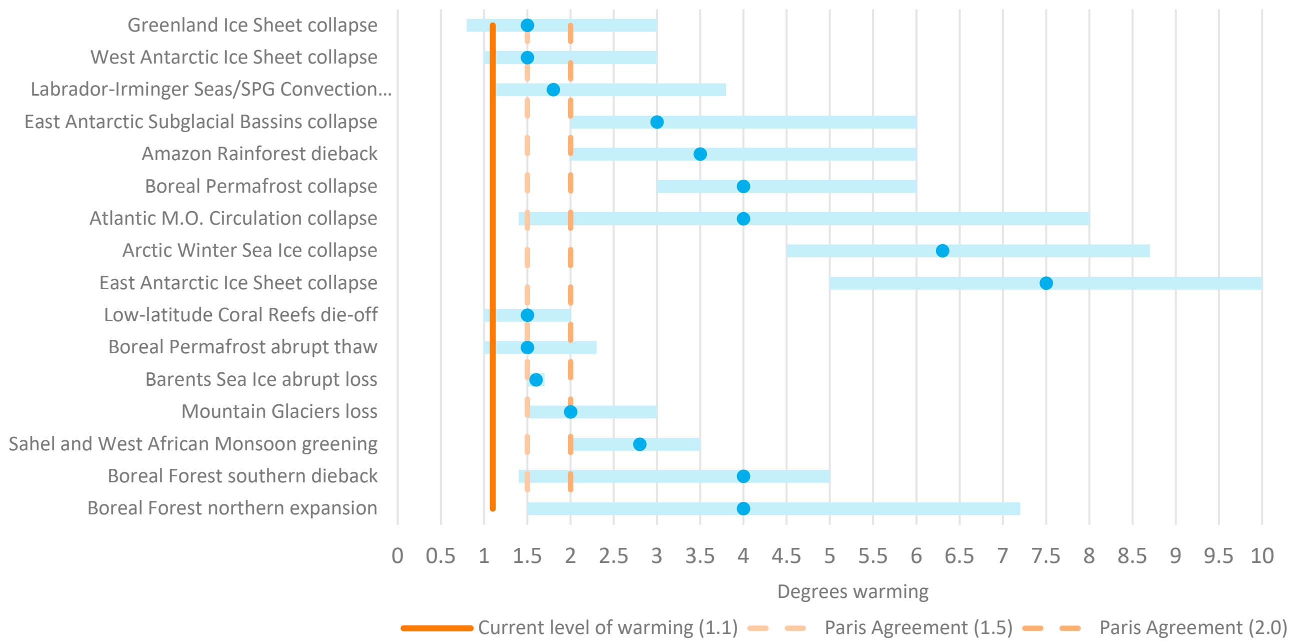

Figure 42: Foreseen climate tipping elements of global and regional impact and the threshold for reaching those, based on Armstrong McKay. Current level of warming with respect to pre-industrial temperature as well as the Paris Agreement temperature range is indicated also

Appendix C Comparison to other roadmaps

Various decarbonisation roadmaps for aviation have seen the light in recent years. This appendix briefly compares this updated and revised DESTINATION 2050 roadmap report to the Waypoint 2050 report by ATAG (second edition of September 2021; Appendix C.1) and the IATA Net-Zero Roadmaps (published in June 2023; Appendix D.2).

Appendix C.1 Waypoint 2050 (September 2021)

This section briefly compares the results presented in this work to the Waypoint 2050 report published by (ATAG, 2021) to clarify any potential differences and highlight similarities.

Approach

Published in September 2021, the second edition of Waypoint 2050 (ATAG, 2021) report presents a view of “how the industry can accelerate working together to contribute to the world’s climate action mission”. Both reports focus on CO_2 emissions from flight operations and develop scenarios how to reach sector-wide net zero emissions by 2050. Waypoint 2050 takes global aircraft emissions as its scope, whereas this study was limited to flights within and departing from the EU+ region (defined and further specified in Section 2.2).

Similar to the DESTINATION 2050 report, Waypoint 2050 projects an aviation traffic forecast and evaluates different scenarios on improvements in aircraft and engine technology, operations and ATM, the use of sustainable aviation fuel, and economic measures. These four pillars are, however, respectively called "innovating with technology", "improvements in operations and infrastructure", "deploying sustainable aviation fuel (SAF)", and "investing in out-of-sector carbon reduction market-based measures" by Waypoint 2050.

Both reports emphasise that a concerted, international, and cross-sectoral approach is needed to reach net zero CO_2 emissions by 2050. The ambition level presented in the DESTINATION 2050 roadmap is aligned with the ATAG objective to encourage “all parts of the industry to focus on how they can play a role in accelerating a decarbonisation pathway”.

Reference scenario and traffic forecast

The Waypoint 2050 reference year is 2019, the last pre-COVID year. This is the same reference year as in this report. Waypoint 2050 assumes 3.1% per year compound growth in global aviation traffic. The DESTINATION 2050 report assumes a passenger lower rate of 2.0% per year compound growth in the EU+ region. Waypoint 2050's reference scenario (the baseline, "scenario 0") projects a continuation of current efficiency trends across the four pillars of action but does not incorporate any acceleration of these efficiency improvements. Whereas, the DESTINATION 2050 reference scenario is a hypothetical no-action scenario.

Comparison between pathways

Waypoint 2050's consolidated scenario 3 ("aspirational and aggressive technological perspective") matches best with the DESTINATION 2050 results per pillar by 2050 (Figure 4, p.20). When comparing intercontinental flights departing the EU+ region (Figure 7, p.22), Waypoint 2050's consolidated scenario 1 ("aggressive sustainable fuel deployment") matches best with the results per pillar by 2050.

IMPROVEMENTS IN AIRCRAFT AND ENGINE TECHNOLOGY

Waypoint 2050 projects low, medium, of high use of advancements across five technology scenarios, ranging from a baseline (included in this study as ‘recent and imminent aircraft’, described in Section 3.4.1 of this report) to an aspirational technology scenario with zero emissions aircraft ('future aircraft', see Section 3.4.2 of this report). This study includes both currently in production or recently announced upcoming aircraft, as well as future aircraft equipped with open-rotor technology, battery systems, hybrid-electric propulsion, or fully hydrogen-powered aircraft.

With four scenarios increasing in their use of novel technology, starting with "evolutionary technology" which continues the standard ‘tube and wing’ configuration with turbofan engine propulsion system, to "Aspirational technology" where a shift to zero emissions aircraft for the narrow body segment aircraft and electrification of the small aircraft segment and hybridisation of the larger aircraft segments is foreseen. The time of anticipated entry into service of new aircraft is similar in both reports but differences between regions are expected.

IMPROVEMENTS IN OPERATIONS AND ATM

Improvements in operations and ATM were modelled in more detail in the DESTINATION 2050 report, as more detailed information was available for the region studied, compared with a global analysis. Waypoint 2050's mid and high scenarios project a 3% and 6% overall contribution in CO_2 reductions by 2050, respectively. The latter is comparable to those projected by the DESTINATION 2050 report.

Waypoint 2050 discuss a wide range of measures can be implemented by airlines, airports and air traffic management to reduce CO_2 from the operation, and emphasise the vital role of collaboration between stakeholders. the DESTINATION 2050 report includes load factor improvements in the reference traffic scenario and are not seen as an additional decarbonisation measure, but Waypoint 2050 includes additional load factor improvements in scenario 1.

ALTERNATIVE FUELS AND SUSTAINABLE ENERGY

Waypoint 2050 has modelled four SAF scenarios, one baseline and three backcasting scenarios. The backcasting scenarios determine the amount of SAF needed to replace 90% of conventional jet fuel with SAF assuming a 100% emissions reduction factor by 2050. The DESTINATION 2050 report models an 80% SAF uptake by 2050. It follows the ReFuelEU Aviation regulation with an additional 10% uptake. The DESTINATION 2050 report therefore projects 10% less SAF in the fuel mix by 2050 compared to the Waypoint report.

ECONOMIC MEASURES

Per scenario, Waypoint 2050 has identified which quantity of sustainable aviation fuel needed to meet 90% of the sector’s liquid fuel requirements. Remaining emission in 2050 are projected to be offset by out-of-sector carbon reductions. These reductions could be initially primarily the form of offsetting through carbon credits and (re)forestry and move more towards direct (air) capture and storage and sequestration of CO_2 towards 2050.

The DESTINATION 2050 report can be more explicit in modelling economic measures (market-based measures) being more narrowly scoped to EU+. It is assumed that EU ETS applies on flights within the EEA and CORSIA (or other market-based measure) to all flights leaving the EEA and international flights outside the EEA. By 2050 any residual emissions need to be compensated by carbon removals.

Results

Waypoint 2050 and the DESTINATION 2050 report have similar approaches to scenario building. The DESTINATION 2050 report presents a single scenario particular to the EU+ region set against a reference scenario; Waypoint 2050 has global scope and presents three scenarios. The conclusion that net zero is possible by 2050 is shared by both reports.

Appendix C.2 IATA Net-Zero Roadmaps (June 2023)

Approach

The DESTINATION 2050 report presents a single, unified roadmap, whereas IATA (IATA, 2024c) presents five roadmaps that show an integrated path to net zero aviation by 2050. These five areas: aircraft technology, energy infrastructure, operations, finance, and policy. These contrast with the four DESTINATION 2050 pillars "technology", "operations", "sustainable fuels", and "economic measures" mainly by separating off policy on its own as an area through which to enable change.

IATA additionally identify three levers to reduce, neutralize or eliminate emissions: "reduce in-flight energy use", "change the fuel", and "re-capture emitted CO_2". Each roadmap shows a contribution to one or more of these levers. However, there are five components to reduce CO_2 emission to reach net zero: efficiency improvements, hydrogen aircraft, operational improvements, the use of SAF, and carbon removal through market-based mechanism.

Reference scenario and traffic forecast

The reference scenario assumptions are not clearly specified but seems to use the same CAGR as Waypoint 2050 (3.1%) for passenger growth to match the baseline emission scenario. The DESTINATION 2050 report assumes a passenger lower rate of 2.0% per year compound growth in the EU+ region. The reference scenario also assumes that fleet replacement will be done using the best-in-class available today but no new technological advancements with happen. No new technological advancements are in line with the DESTINATION 2050 report assumptions.

Comparison between pathways

Each IATA roadmap has its own scenarios defined to arrive at a projected effect with an associated uncertainty bandwidth. There is "central case" about which the uncertainty bands are drawn. Of these central case components, SAF uptake is the major component with more than half the reduction, which is comparable to DESTINATION 2050 in magnitude. Carbon removals (including market-based mechanisms) is second with a quarter of the reduction which is more than the DESTINATION 2050 report projects. The remaining three components (efficiency improvements, hydrogen use, and operational improvements) account for less than a quarter of the reduction and amounts to less than DESTINATION 2050 projects.

The IATA roadmaps are global in scope, whereas the DESTINATION 2050 report is restricted to the EU+ region.

IMPROVEMENTS IN AIRCRAFT AND ENGINE TECHNOLOGY

IATA includes three types of innovations, "Best in class" which may or not be powered by hydrogen (included in this study as ‘recent and imminent aircraft’, described in Section 3.4.1 of this report), to "Future aircraft" which might also come with additional energy efficiency ('future aircraft', see Section 3.4.2 of this report). The DESTINATION 2050 report includes both currently in production or recently announced upcoming aircraft, as well as future aircraft equipped with open-rotor technology, battery systems, hybrid-electric propulsion, or fully hydrogen-powered aircraft.

IMPROVEMENTS IN OPERATIONS AND ATM

Improvements in operations and ATM were modelled in more detail in the DESTINATION 2050 report, as more detailed information was available for the region studied, compared with a global analysis. IATA refers to Waypoint 2050's three scenarios and discuss operational improvements that might yield the corresponding pathways. Waypoint 2050's mid and high scenarios project a 3% and 6% overall contribution in CO_2 reductions by 2050, respectively. The latter is comparable to those projected in the DESTINATION 2050 report.

ALTERNATIVE FUELS AND SUSTAINABLE ENERGY

IATA makes use of ICAO’s LTAG SAF availability scenarios and also projects SAF production capacities for use by aviation. The central scenario shows 80-90% of fuels use to be SAF by 2050. The DESTINATION 2050 report models 80% SAF by 2050.

ECONOMIC MEASURES

The economic measures from a policy perspective are about enabling higher SAF uptake. This can be done at the refineries and eliminating needed SAF distribution barriers. On a longer time horizon innovation in non-biological SAF is fostered. Additionally, more investment in R&D for carbon capture is advocated. These are also the two components projected to contribute most to reaching net zero by 2050.

The DESTINATION 2050 report is more explicit in modelling economic measures. It is assumed that EU ETS applies on flights within the EEA and CORSIA (or other market-based measure) to all flights leaving the EEA and international flights outside the EEA. By 2050 any residual emissions need to be compensated by carbon removals.

Results

IATA and the DESTINATION 2050 report present their roadmaps differently. The DESTINATION 2050 report presents a single scenario particular to the EU+ region set against a reference scenario; IATA has global scope and presents different roadmaps for five different areas. The conclusion that net zero is possible by 2050 is shared by both reports, though IATA presents a more varied set of possible combinations for the pathway to reach this goal.

Appendix D Supplementary material

This appendix provides additional and more detailed supplementary material to material discussed in the main report.

Appendix D.1 Modelling background

SEO's NetCost model is a detailed passenger choice model that can be applied to estimate the impact of cost increases for passengers, thus impacting passenger demand and the number of aircraft movements in 2030, 2040 and 2050. The NetCost model determines the total generalised travel costs for each travel alternative, including the cost of the airfare and travel time. Higher costs, that are passed-through to consumers, increase the cost of air travel and therefore reduce demand, and in turn lead to a reduction in the number of flights and therefore connectivity. The NetCost model estimates the impact of such cost increases on an airport level.

The model distinguishes between direct and indirect flights, as cost increases may differ between direct and indirect flights serving the same market. The model estimates the distribution of passengers over different route options, including indirect route options via individual (European or non-European) hubs. As European policy measures do not apply to non-European hubs, the model can identify a shift of traffic from European hubs to non-European hubs. As such, the model is well applicable to identify potential carbon leakage impacts. In the DESTINATION 2050 study the NetCost passenger choice model has been used to assess the impacts of higher fuel prices and costs of economic measures on demand and supply.

Model validity

The internal and external validity of the model is guaranteed through alignment with fuel bunker data, rigorous quality controls, back testing and sensitivity analysis. In comparison to the modelled and bunker-derived data reported in the 2022 European Aviation Environmental Report (EASA; EEA; EUROCONTROL, 2022), shown in Figure 41 (147 Mt CO_2 and 156 Mt CO_2, respectively), the model finds a CO_2 emission of 152 Mt. Operations and passenger data of the model are calibrated according to data from ACI (2023) [147], IATA (2020) and ICAO (2020).

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[147] Annual World Airport Traffic Dataset: https://aci.aero/resources/data-center/

Appendix D.2 Additional results

This appendix presents additional results, notably with respect to time-averaged energy efficiency improvements (Appendix D.2.1) and detailed results per horizon year (Appendix D.2.2).

Appendix D.2.1 Emissions development in the reference scenario

Figure 43 shows how CO_2 emissions from EU+ aviation develop over time in the reference scenario. In that situation, CO_2 emissions from EU+ aviation are expected to increase by 1.5 percent per year until 2050.

In 2019, estimated CO_2 emissions for both passenger and cargo operations accrue to 185 Mt. The majority of these emissions (96%) arise from passenger operations. In 2030, aviation emissions are 13% higher than in 2019, and by 2050 CO_2 emissions are 41% above 2019 levels. By 2050, CO_2 emissions from intra-EU+ aviation add up to 114 Mt, whereas flights to destinations outside the EU+ are expected to emit 180 Mt of CO_2. Cargo flights add an additional 22 Mt of CO_2.

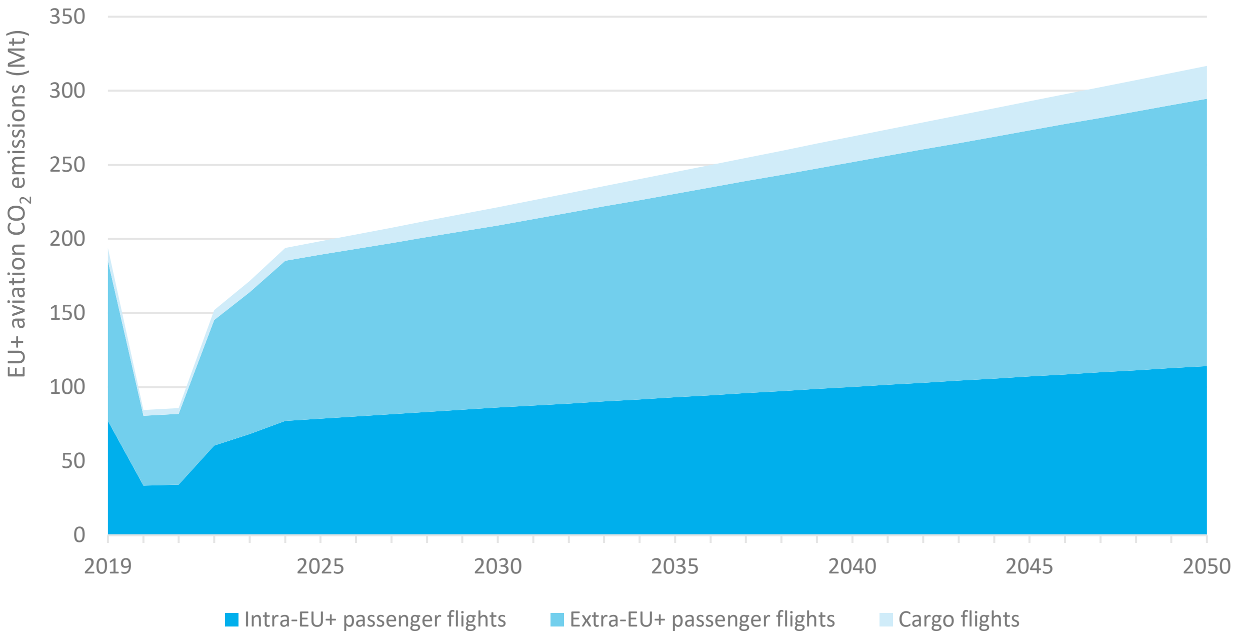

Figure 43: CO_2 emissions from EU+ aviation in the reference scenario

Appendix D.2.2 Detailed results per horizon year

Tables 53, 54 and 55 show the total and per-pillar emissions reduction as modelled for 2030, 2040 and 2050, compared to the reference scenario. In addition to the main pathway graphs (Figures 4, 6 and 7), these tables also show the separate contributions by recent and imminent aircraft on one hand, and future aircraft on the other.

In the tables, zero values indicate values below 0.5, values might not sum to (sub-)totals shown due to rounding, and percentage changes are expressed with respect to the reference emissions level. Figure 44 shows the contributions per pillar with respect to the total (net) emissions reduction achieved in each of the horizon years.

2030

Table 53: Total and per-pillar CO_2 emissions reduction, modelled for 2030, compared to the reference scenario

Change in CO_2 emissions in 2030 compared to the reference scenario	**All**		**Intra-EU+**		**Non-EU+**	
	Mt	**%**	**Mt**	**%**	**Mt**	**%**
CO_2 emissions in the reference scenario	209		86		123	
Hydrogen (technology + energy cost) induced demand impacts	not applicable					
Sustainable aviation fuels (SAF) induced demand impacts	7	3%	2	3%	5	4%
Economic measures induced demand impacts	5	2%	5	5%	0	0%
Total CO_2 emissions reduction due to demand impacts	12	6%	7	8%	5	4%
Improvements in aircraft and engine technology, recent and imminent conventionally-fuelled aircraft	17	8%	7	8%	10	8%
Improvements in aircraft and engine technology, future conventionally-fuelled aircraft	not applicable					
Improvements in aircraft and engine technology, hydrogen-powered aircraft	not applicable					
Improvements in Air Traffic Management (ATM) and aircraft operations	14	7%	7	8%	7	6%
Alternative fuels and sustainable energy: SAF	12	6%	5	5%	7	6%
Alternative fuels and sustainable energy: hydrogen	not applicable					
Economic measures	50	24%	49	57%	1	1%
Total CO_2 emissions reduction due to sustainability measures	93	45%	68	79%	25	21%
Total combined net CO_2 emissions reduction	**105**	**50%**	**75**	**87%**	**31**	**25%**
Remaining net CO_2 **emissions in the sustainability scenario**	**104**	**50%**	**11**	**13%**	**92**	**75%**

2040

Table 54: Total and per-pillar CO_2 emissions reduction, modelled for 2040, compared to the reference scenario

Change in CO_2 emissions in 2040 compared to the reference scenario	**All**		**Intra-EU+**		**Non-EU+**	
	Mt	**%**	**Mt**	**%**	**Mt**	**%**
CO_2 emissions in the reference scenario	252		100		152	
Hydrogen (technology + energy cost) induced demand impacts	0	0%	0	0%	n.a.	
Sustainable aviation fuels (SAF) induced demand impacts	29	11%	7	7%	21	14%
Economic measures induced demand impacts	5	2%	3	3%	2	1%
Total CO_2 emissions reduction due to demand impacts	33	13%	11	11	23	15%
Improvements in aircraft and engine technology, recent and imminent conventionally-fuelled aircraft	27	11%	10	10%	17	11%
Improvements in aircraft and engine technology, future conventionally-fuelled aircraft	17	7%	6	6%	11	7%
Improvements in aircraft and engine technology, hydrogen-powered aircraft	1	1%	1	1%	n.a.	
Improvements in Air Traffic Management (ATM) and aircraft operations	16	6%	8	8%	9	6%
Alternative fuels and sustainable energy: SAF	62	25%	26	26%	37	24%
Alternative fuels and sustainable energy: hydrogen	1	< 1%	1	1%	n.a.	
Economic measures	40	16%	30	30%	10	6%
Total CO_2 emissions reduction due to sustainability measures	165	65%	82	82%	83	55%
Total combined net CO_2 emissions reduction	**197**	**78%**	**91**	**91%**	**106**	**70%**
Remaining net CO_2 emissions in the sustainability scenario	**54**	**21%**	**8**	**8%**	**46**	**30%**

2050

Table 55: Total and per-pillar CO_2 emissions reduction, modelled for 2050, compared to the reference scenario

Change in CO_2 emissions in 2050 compared to the reference scenario	All		Intra-EU+		Non-EU+	
	Mt	%	Mt	%	Mt	%
CO_2 emissions in the reference scenario	295		114		180	
Hydrogen (technology + energy cost) induced demand impacts	3	1%	3	3%	n.a.	
Sustainable aviation fuels (SAF) induced demand impacts	47	16%	10	9%	37	21%
Economic measures induced demand impacts	5	2%	2	1%	3	2%
Total CO_2 emissions reduction due to demand impacts	55	19%	15	13%	40	22%
Improvements in aircraft and engine technology, recent and imminent conventionally-fuelled aircraft	36	12%	12	11%	24	13%
Improvements in aircraft and engine technology, future conventionally-fuelled aircraft	34	12%	13	11%	22	12%
Improvements in aircraft and engine technology, hydrogen-powered aircraft	5	2%	5	5%	n.a.	
Improvements in Air Traffic Management (ATM) and aircraft operations	19	6%	9	8%	10	5%
Alternative fuels and sustainable energy: SAF	105	35%	38	33%	67	37%
Alternative fuels and sustainable energy: hydrogen	11	4%	11	10%	n.a.	
Economic measures	29	10%	10	9%	18	10%
Total CO_2 emissions reduction due to sustainability measures	239	81%	99	87%	140	78%
Total combined net CO_2 emissions reduction	**295**	**100%**	**114**	**100%**	**180**	**100%**
Remaining net CO_2 emissions in the sustainability scenario	**0**	**0%**	**0**	**0%**	**0**	**0%**

Contributions per measure

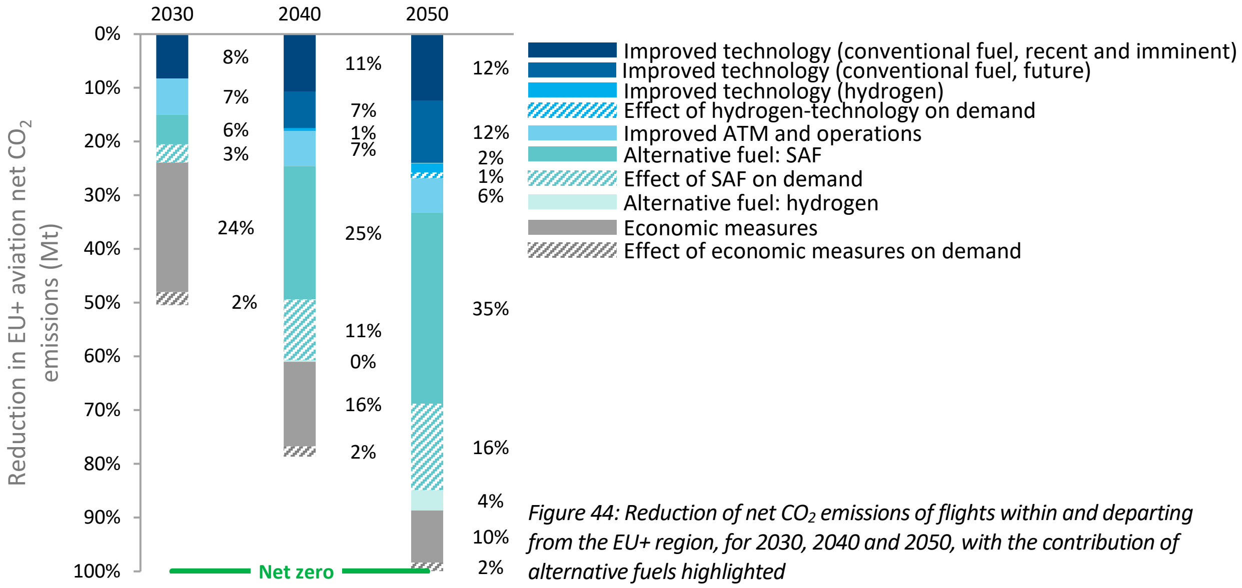

Figure 44: Reduction of net CO_2 emissions of flights within and departing from the EU+ region, for 2030, 2040 and 2050, with the contribution of alternative fuels highlighted

Appendix D.3 Carbon budgets for global and EU+ aviation

This appendix provides further background and details to the comparison of cumulative emissions anticipated in the DESTINATION 2050 pathway and the carbon budgets these are compared to, presented in Section 2.6.2. Specifically, Appendix 4.3.1 details the derivation of a carbon budget share for global aviation and for EU+ aviation, Appendix 4.3.2 compares the cumulative emissions to the (original) carbon budgets published by IPCC's Working Group I (whereas Section 2.6.2 has limited the comparison to the updated carbon budgets), and Appendix 4.3.3 elaborates on some of the key uncertainties and sensitivities highlighted in Section 2.6.2.

Appendix D.3.1 Derivation of a carbon budget share for global and EU+ aviation

As noted in Section 2.6.2, the carbon budgets calculated by IPCC (2022a) and Forster et al. (2023) are global budgets, that encompass all human induced carbon emissions. Which industries, countries or groups of people get what share of these budgets is a fundamental societal and political choice, to which science cannot provide a single correct answer. This is illustrated by, who provide an overview of different allocation principles, of which grandfathering, cost-optimality and equality approaches are just three examples. The first principle allocates carbon budgets based on current emission shares, the second prioritises emissions reductions in industries where it is less expensive to do so (yielding relatively larger budgets for sectors that are more costly to decarbonise), and the third could divide the budget into individual, personal shares.

This DESTINATION 2050 roadmap report does not necessarily subscribe to any single one of these principles. It embraces an ambitious but feasible level of technological innovation on various fronts as the primary and preferred means to reduce aviation CO_2 emissions and strives for cost-effective solutions sustaining economic growth. On the other hand, it recognises more limited growth in established markets compared to higher growth rates in upcoming markets. This is argued to be in line with the approach taken by the International Energy Agency in its global Net Zero Emissions scenario, published in 2021 (IEA, 2021) and updated in 2023 (IEA, 2023c). That scenario was designed "to maximise technical feasibility, cost-effectiveness and social acceptance while ensuring continued economic growth and secure energy supplies" (IEA, 2021, p. 13). Total cumulative CO_2 emissions across all sectors of the economy between 2020 and 2050 sum to 502 Gt [148]. To this total, worldwide aviation has contributed and is anticipated to further contribute 20 Gt [149], yielding the share of 4.0% used in Section 2.6.2.

> **A 500GT-PATHWAY SPECIFICALLY FOR 1.5°C**
> The IEA Net-Zero Emissions scenario has explicitly been designed to limit the rise in global temperatures to 1.5°C (at a likelihood of 50%), using the 500 Gt carbon budget determined by Working Group I and published by the IPCC (2022a). The analysis presented in this DESTINATION 2050 roadmap report assumes that sectoral emissions shares in this 1.5°C-pathway also provide a valid approximation of emissions shares in a scenario limiting global temperatures to 1.7°C (with a 66% likelihood), and in a scenario with a 400 Gt carbon budget available to limit global temperatures to 1.5°C (50% likelihood).

These figures correspond to global aviation, whereas the DESTINATION 2050 roadmap report is limited in scope to emissions from flights departing the EU+ region (Section 2.2). Just as the carbon budget for global aviation is a sub-share of the total global carbon budget, the budget for European aviation is a sub-share of the budget for global aviation. The IEA report takes into account differences between advanced economies and emerging markets and

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[148] Computed from reported emissions in 2020 (34 Gt) and 2021 (37 Gt) sourced from IEA (2022) and IEA (2023c) projected emissions between 2022 and 2050 totalling 432 Gt.

[149] Again, summing emissions in 2020 (582 Mt) and 2021 (665 Mt) as reported by IEA (2023b) and IEA (2023c) projected emissions between 2022 and 2050 summing to 19 Gt.

developing economies. Advanced economies have to “reach net zero before emerging markets and developing economies, and assist others in getting there” (IEA, 2021, p. 13). In the IEA report, 43% of cumulative aviation emissions occur in advanced economies[150]. This group of countries includes all states in the EU+ region, but also includes, for example, the United States and Canada. Based on an analysis of emission data from 2019, prepared by Graver, Rutherford and Zhang (2020), CO_2 emissions from EU+ aviation are determined to equal 35% of aviation CO_2 emissions from all advanced economies. Multiplication of the various factors, as schematically presented in Figure 45, yields a carbon budget share for flights departing from airports in the EU+ region equal to 0.61% of the global carbon budget.

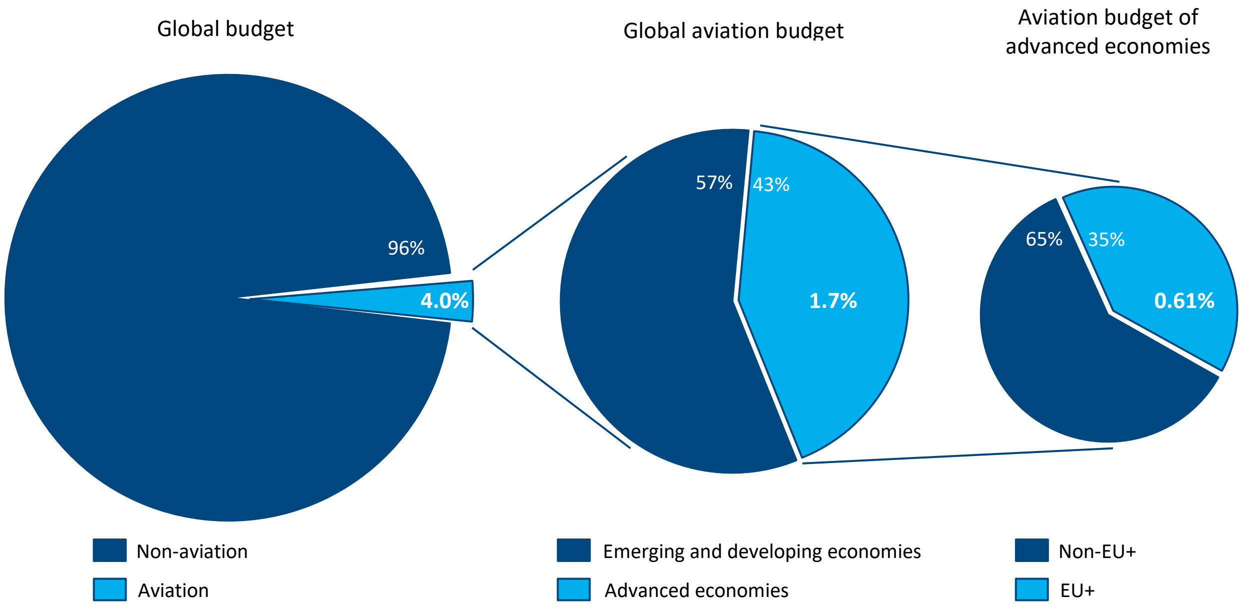

Figure 45: Schematic representation of the derivation of carbon budget shares for global and EU+ aviation. Bold-faced percentages show shares as part of global budget

As noted in Section 2.6.2, it is stressed again that different allocation principles could yield (drastically) different carbon budget shares for aviation in general, as well as for EU+ aviation in particular. Taking a grandfathering approach based on an emission share of 2.4% (valid for scheduled aviation traffic in 2019, per Graver, Rutherford, & Zheng, 2020) would, for example, yield an EU+ aviation carbon budget share of 0.49% (20% lower than 0.61%). Alternatively, a current emission share of 2.7% (computed for all aviation in 2019, based on IEA, 2023a; Crippa, et al., 2013) would yield an EU+ aviation carbon budget share of 0.55% (10% lower than 0.61%). A grandfathering approach based on the proportion of aviation CO_2 emissions compared to total manmade CO_2 emissions over the period 1940 to 2019, equal to 1.8% (Lee, et al., 2021), would imply lower budgets still – at least on a global scale[151]. Similarly, a different share of EU+ aviation emissions compared to global aviation emissions – due to, for example, other markets developing more rapidly than the EU+ market, may yield a different carbon budget share.

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[150] This has been derived from 10.7 Gt cumulative aviation emissions in emerging markets and developing economies and 8.2 Gt cumulative aviation emissions in advanced economies over the period 2022-2050 as visualised by IEA (2023c, p. 94)

[151] Determining an EU+ share from this total is not straightforward: using the 2019 share of EU+ versus global aviation emissions would imply a share of 0.37% (39% lower than 0.61%) but whether this approach is fully consistent with the concept of ‘grandfathering’ can be debated. Conceptually more consistent would be to determine the EU+ share based on the share of EU+ versus global aviation emissions over the same 1940 – 2019 period. This would likely apportion a notably larger share to EU+ aviation (although of a smaller global aviation budget share) but lacking the data, this could not be analysed.

Appendix D.3.2 Comparison of cumulative emissions to WG1 carbon budgets

Section 2.6.2 has compared cumulative emissions in the DESTINATION 2050 pathway to an EU+ aviation share of various updated carbon budgets as determined using the methodology of IPCCs Working Group III (Forster P. , et al., 2023). These updated carbon budgets differ from the first carbon budgets, published by the IPCC in (2022a), due to an emulator update. For two selected scenarios (limiting global warming to 1.5°C with a likelihood of 50% and limiting global warming to 1.7°C with a likelihood of 66%), Table 56 shows global carbon budgets.

Table 56: Global carbon budgets based on the IPCC Sixth Assessment Report from 2022 and the 2023 update

Reference	50% likelihood of 1.5°C	66% likelihood of 1.7°C
Working Group I contribution to the Sixth Assessment Report (IPCC, 2022a)	500 Gt	700 Gt
Updated, based on Working Group III methodology (Forster P. , et al., 2023)	400 Gt	600 Gt

Apportioning 0.61% of the global carbon budget to EU+ aviation (derived in Appendix 4.3.1) yields the sector-specific carbon budgets shown in Table 57.

Table 57: EU+ aviation carbon share and budget derived from IEA Net-Zero scenario

EU+ aviation share based on IEA Net-Zero scenario	EU+ aviation carbon budget (2020-2050) derived from IEA Net-Zero scenario		
	Reference	50% likelihood of 1.5°C	66% likelihood of 1.7°C
0.61%	IPCC AR6 WG1 (IPCC, 2022a)	3.07 Gt	4.30 Gt
	Update based on WG3 (Forster P. , et al., 2023)	2.46 Gt	3.68 Gt

Recalling the cumulative in-sector CO_2 emissions of 3.30 Gt derived in Section 2.6.2 shows that, just as for the updated budgets, the DESTINATION 2050 pathway presented in this report is not compatible with limiting global warming to 1.5°C with a likelihood of 50%, but is compatible with limiting global warming to 1.7°C with a likelihood of 66%.

Appendix D.3.3 Discussion and implications

The budget available to aviation is largely dependent on the total remaining carbon budget still available to all anthropogenic induced carbon emissions. The total remaining carbon budgets as derived by WG1 (IPCC, 2022a) and the update based on WG3 (Forster P. , et al., 2023) involve the assessment of five factors, the most recent decade of human-induced warming, the transient climate response to cumulative emissions of CO_2, the zero emissions commitment, the temperature contribution of non-CO_2 emissions and an adjustment term for remaining Earth system feedbacks.

Based on the variation in non-CO_2 effects due to e.g. warming effects of methane and cooling effects of aerosols, the total remaining carbon budget could be around 200 Gt higher or lower (Rogelj & Lamboll, 2024; Lamboll, et al., 2023). Therefore, the total carbon budget for the assessed temperature targets would range from 200Gt to 800Gt, leading to budgets available to aviation ranging from 1.23 to 4.91 Gt.

Table 58: EU+ aviation carbon share and budget derived from IEA Net-Zero scenario at various levels of non-CO_2 contribution

EU+ aviation share based on IEA Net-Zero scenario	EU+ aviation carbon budget (2020-2050) derived from IEA Net-Zero scenario		
	Reference	**50% likelihood of 1.5°C**	**66% likelihood of 1.7°C**
0.61%	Update based on WG3 (Forster P. , et al., 2023) minus 200 Gt	1.23 Gt	2.46 Gt
	Update based on WG3 (Forster P. , et al., 2023)	2.46 Gt	3.68 Gt
	Update based on WG3 (Forster P. , et al., 2023) plus 200 Gt	3.68 Gt	4.91 Gt

Moreover, uncertainty lies, as stressed before, in the allocation of the budget to aviation. In the share derived from IEA Net-Zero scenario, a share of 0.61% would be available to EU+ aviation. Due to the estimation that aviation may be difficult and costly to abate this share is, however, larger than the 2019 EU+ aviation contribution to global CO_2 emissions. If the share in 2019 (0.49%) was used for the entire period 2020-2050, this would mean an EU+ carbon budget would span 1.96 to 2.93 Mt for 1.5˚C and 1.7˚C targets, respectively, which is less than the projected 3.30 Gt required for the DESTINATION 2050 pathway.

An exemplary range of budgets for the 1.5˚C and 1.7˚C targets is shown in Figure 46 as well as the annual and cumulative emissions of the DESTINATION 2050 pathway and reference scenario. Grey lines show the bandwidth of budgets when considering the uncertainty of non-CO_2 effects in the global budget, leading to a surpass of the smallest budget by 2028. Green lines show the budgets in case the 2019 shares are allocated for the entire period of 2020-2050, resulting in a surpass of the studied 1.5˚C (50% likelihood, 400 Gt) and 1.7˚C (66% likelihood, 600 Gt) budgets in 2033 and 2042, respectively.

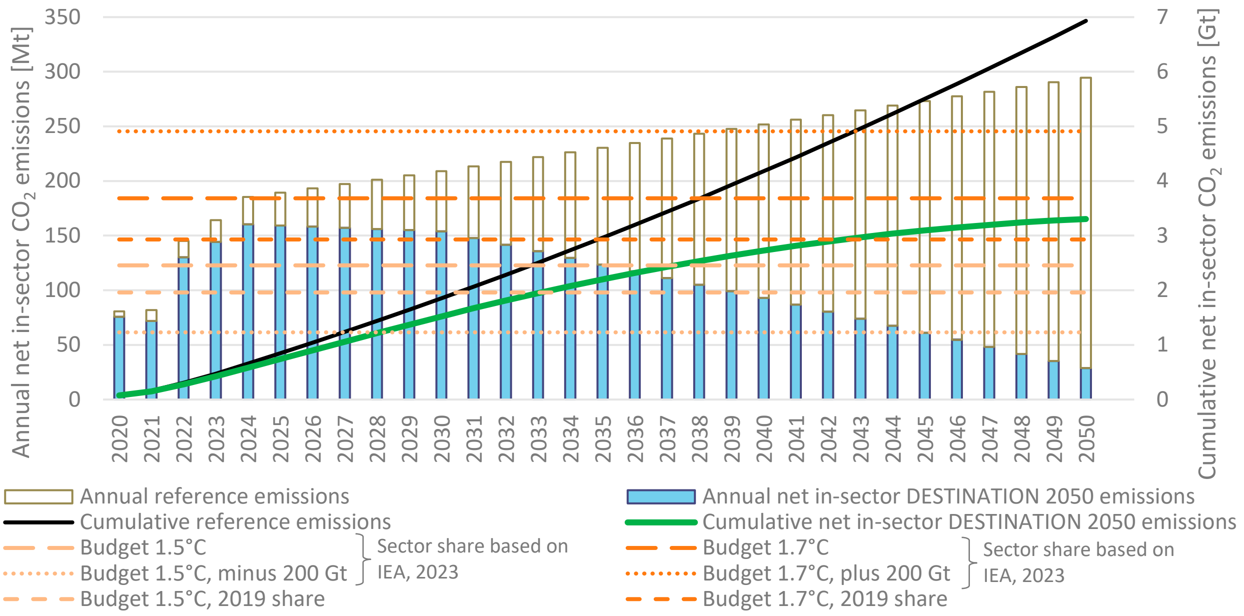

Figure 46: Annual (left axis, Mt) and cumulative (right axis, in gigatonnes) emissions of the reference scenario (open) and DESTINATION 2050 scenario (filled) compared to several carbon budgets for EU+ aviation with maximum temperature increases of 1.5˚C and 1.7˚C (orange lines). Long-dashed lines are based on 400 Gt and 600 Gt budgets, and assuming a 4.0% budget share for global aviation and a 0.61% share for EU+ aviation, based on the 2023 of the IEA Net Zero Roadmap. Dotted lines show the bandwidth of budgets when considering the uncertainty of global non-CO_2 effects in the global carbon budget, estimated at ±200 Gt, and assuming the same 0.61% budget share for EU+ aviation. The short-dashed lines are again based on the 400 Gt and 600 Gt budgets, but assume an EU+ aviation share based on its share of global anthropogenic CO_2 emissions in 2019, equal to 0.49%

The projected requirement of 3.30 Gt depends on the expected rate of decarbonisation enabled by improvements in operations, technology and alternative fuel. If technology improvements would be delayed or yield less CO_2 reductions than expected or in case SAF uptake does not surpass the mandate. A delay of 5 years now (returning to the reference scenario between 2024 and 2028, hatched in Figure 47, repeated from Figure 8 shown in Section 2.6.2) increases CO_2 emissions by 165 Mt, larger than the total required budget (147 Mt) for the years between 2047 and 2050.

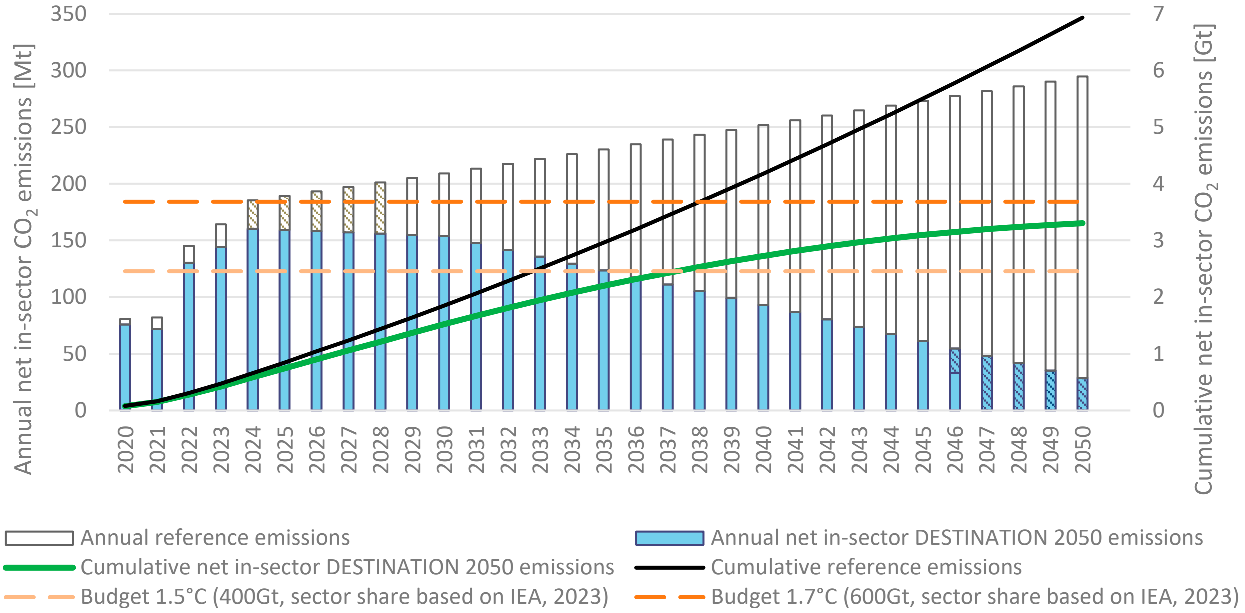

Figure 47 (repeated from Figure 8): Annual (left axis, in Mt) and cumulative emissions (right axis, in gigatonnes) of the reference scenario (open) and DESTINATION 2050 scenario (filled) compared to the remaining carbon budgets for EU+ aviation with maximum temperature increases of 1.5˚C (400 Gt) and 1.7˚C (600 Gt), both assuming a 4.0% budget share for global aviation and a 0.61% share for EU+ aviation, based on the 2023 of the IEA Net Zero Roadmap. Hatched area shows equal summed emissions between 2024-2028 and 2046-2050

Appendix D.4 Decarbonisation measures

This appendix provides supplementary information about the decarbonisation measures discussed in the main report.

Appendix D.4.1 Improvements in aircraft and engine technology

This appendix groups supplementary material related to improvements in aircraft and engine technology, discussed in Chapter 3.

Appendix D.4.1.1 Performance estimates of recent and imminent aircraft

Compared to the first edition of the DESTINATION 2050 roadmap report, the overview of upcoming aircraft (Table 17) has been updated. This appendix provides an overview of changes, grouped per class.

Regional

- Added Deutsche Aircraft D328eco (Deutsche Aircraft, 2023);
- Added ATR EVO (ATR, 2022; Schuurman, 2022b; Schuurman, 2023);
- Added turboprop project[152];
- Updated the entry into service of the Embraer E175-E2 from 2021 to 2027 (Schuurman, 2022a).

Besides the additions of these three aircraft types, the calculation method for determining the class-averaged fuel efficiency improvement potential has been revised, in order to more clearly explicate modelling assumptions made with respect to the replacement of regional jets by turboprop aircraft. This is now done as follows:

1. First, the effect of one-to-one replacements is modelled for legacy types that have a direct successor. These types produced about 50% of 2019 ASKs in the regional class[153]. Legacy types are the Dornier D328 (< 1% of ASKs; modelled to be replaced by Deutsche Aircraft D328eco), ATR 72-600 (10% of ASKs; modelled to be replaced by ATR EVO) and the Embraer E175 and E190 (9% and 30% of ASKs; modelled to be replaced by respective E2-variants).
2. Second, fleet renewal is modelled for turboprop aircraft that do not have a direct successor, such as the De Havilland Canada DHC-8. This group accounts for 17% of 2019 ASKs in the regional class. These aircraft are modelled to be replaced by upcoming turboprop aircraft.
3. At this point, approximately 27% of ASKs are produced by turboprop aircraft (of various generations). The remaining 73% of ASKs are produced by jet aircraft, split between 39% that has (or is) a direct successor and 33% that is of a type without a direct successor (such as the Canadair Regional Jets). That group of aircraft is modelled to be replaced by a combination of upcoming turboprop aircraft and upcoming jet aircraft to such an extent that – following completed fleet renewal of these aircraft – as many ASKs are produced by turboprops as by regional jets[154]. That means that of the jet aircraft without a direct successor, approximately 23% is replaced by an upcoming turboprop, whereas the remaining 10% are replaced by an upcoming regional jet.

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[152] Modelled based on a concept aircraft announced by Embraer. As also noted in 35 on page 46, personal communication with Embraer received during the finalisation of this report suggests this aircraft is no longer planned to be introduced. As it has been included in the modelling on which the results presented in Section 2.6 are based, its (modelled) performance figures are still included in this report.

[153] ASKs produced by the Embraer E195 are excluded from these totals, as the successor of that aircraft is categorised as single-aisle, due to its increased seat count.

[154] In 2019, the split was 27 to 73%.

INCREASED USE OF TURBOPROP AIRCRAFT

This updated roadmap report explicitly models an increase in the use of turboprop aircraft. This choice is based on a number of factors:

- For the same mission, turboprop aircraft have substantially lower fuel consumption compared to regional jets. With fuel and fuel-related costs anticipated to rise (due to mandated use of SAF and increasing carbon costs), this factor is anticipated to play a larger role in airlines' fleet renewal decisions.
- The difference in operating speed between (slower) turboprops and (faster) regional jets is anticipated to have a limited effect. As the time spent in cruise, where the speed difference is most material, is limited for regional missions, the impact of the lower speed on block time is limited.
- The announcement of new aircraft studies by both ATR (ATR EVO) and, previously, Embraer (Embraer Turboprop[155]). De Havilland planning to resume Dash 8 production is also seen as an indication of a possible 'revival of the turboprop' (Airspace Africa, 2022).
- A larger order backlog for ATR turboprop aircraft of 160 aircraft (ATR, 2023) compared to Embraer regional jets in the regional class (i.e., excluding the Embraer E195-E2, which is in this study considered single-aisle) of 98 aircraft (Embraer Commercial Aviation, 2023).

The fuel efficiency improvements of turboprop to turboprop and regional jet to regional jet replacements are based on the average fuel burn improvement delivered by upcoming types (ATR EVO and Embraer Turboprop[155] and Embraer E175-E2 and E190-E2, respectively), compared to older models (ATR 72-600 and Embraer E175 and E190, respectively) – equal to approximately 15%. This figure for fuel efficiency improvement potential is subsequently increased by some five percentage points to 20%. This additional 5% accounts for a reference fleet that is – on average – less fuel efficient (older) than the models used as reference for the fuel efficiency improvement of the upcoming types (in the 'Reference'-column in Table 17). The regional jet to turboprop replacement pathway is assumed to consist for 50% of replacement by currently available turboprop types and 50% of replacement of replacement by the upcoming turboprop aircraft entering service by 2030. The former offers a 35% fuel efficiency improvement with respect to regional jets; the latter improves fuel efficiency by another 15% - for a (multiplicative) total of 45% [156]. On average, given the 50/50 share of replacement pathways, fuel efficiency improvement averages 40%.

Table 59 summarises the average fuel efficiency improvement potential – separately for various replacement pathways as well as averaged for the entire regional class. This approach captures the average fuel efficiency improvement in a hypothetical upcoming regional aircraft type with 29% lower fuel consumption entering into service in 2019. That means that by 2030, the fuel efficiency of flights operated by not-already-replaced regional aircraft has improved 14% [157].

Table 59: Average fuel efficiency improvement potential for different replacement pathways and averaged for the regional class

Segment	Fuel efficiency improvement per flight [158]	EIS (upcoming)	Share of ASKs
Turboprop to turboprop	20%	2030	17%
Regional jet to regional jet	20%	2022	10%
Regional jet to turboprop	40%	2010	23%
Average (weighted)	**29%**	**2019**	**50%**

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[155] Modelled based on a concept aircraft announced by Embraer. As also noted in 35 on page 46, personal communication with Embraer received during the finalisation of this report suggests this aircraft is no longer planned to be introduced. As it has been included in the modelling on which the results presented in Section 2.6 are based, its (modelled) performance figures are still included in this report.

[156] 1 – [(1 – 35%) × (1 – 15%)] = 45%.

[157] (2030 – 2019) / 22.5 × 29% = 14%.

[158] Based on average fuel efficiency improvement figures for applicable one-to-one replacements, listed in Table 17. Regional jet to turboprop efficiency improvement based on Babikian (2002), confirmed by internal analyses.

Single aisle

- Updated the entry into service of the Embraer E195-E2 from 2021 to 2019;
- Updated the entry into service of the Airbus A321XLR from 2023 to 2024 (Kaminski-Morrow, 2022) and updated the fuel efficiency improvement (per seat; identical per flight) from 20 to 30% (Airbus, 2023c);
- Updated the entry into service of the Boeing 737 MAX 7 and MAX 10 from 2021 and 2020, respectively, to 2023 and 2024 (Hemmerdinger, 2022).

Small/medium twin-aisle

No changes were made with respect to the upcoming aircraft in the small/medium twin-aisle class.

Large twin aisle

- Corrected the fuel efficiency improvement for the Airbus A350-900 from 30% to 23% per seat;
- Updated the seat capacity for the Boeing 777-8X from 355 to 384 (typical two-class lay-out, to improve the comparison with the reference aircraft two-class lay-out; Perry, 2023) and the entry into service from 2024 to 2027 (Perry, 2023);
- Updated the entry into service for the Boeing 777-9X from 2021 to 2025 (Villamizar, 2022).

Appendix D.4.1.2 Cost estimates of upcoming and future kerosene-powered aircraft

In the Price of Net Zero, Adler et al. (2023), investigated cost of upcoming and future aircraft.

Upcoming aircraft

- As the majority of upcoming aircraft has already entered into service, research and development costs only need to be incurred for a few remaining types. Summarised in Section 3.4.1, these costs were determined using the following guiding principles:
- Clean-sheet development costs per aircraft (size) class, as determined in The Price of Net Zero (Adler, et al., 2023), based on the Clean Aviation Partnership (2020) and other literature (Bowen, 2010, p. 68; Rodrigue, 2020), and updated based on recent publications (Benjamin, 2024), summarised later in this section (Table 62).
- 85% lower development costs for derivative designs (Johnson & Hepher, 2021).
- For the upcoming aircraft that are yet to enter into service, this leads to the development costs estimated in Table 60.

Table 60: Estimated remaining product development costs for upcoming aircraft yet to enter into service

Class	Type	Class-based clean-sheet development costs (Table 62)	Required remaining development need	Remaining development costs
Regional (R)	Deutsche Aircraft D328eco	€10.0 bn	Derivative design, smaller (40 passengers) than typical present-day regional	€0.7 bn
	ATR EVO	€10.0 bn	Derivative design, maintaining airframe type certificate, new engine / propulsion system. Development to start.	€1.5 bn
	Turboprop project [159]	€10.0 bn	New design, but assuming some re-use. Development to start.	€5.0 bn
	Embraer E175-E2	€10.0 bn	Derivative design, development to start (Schuurman, 2022a).	€1.5 bn
Single-aisle (SA)	Airbus A321XLR	€15.0 bn	Derivative design, development estimated to be 90% complete (first flight completed; Airbus, 2022b), EIS expected 2024.	€0.2 bn
	Boeing 737 MAX 7	€15.0 bn	Derivative design, development estimated to be 90% complete (first flight completed; Hepher, 2018), EIS expected 2024.	€0.2 bn
	Boeing 737 MAX 10	€15.0 bn	Derivative design, development estimated to be 90% complete (first flight completed; Boeing, 2021), EIS expected 2024.	€0.2 bn
Large twin-aisle (LTA)	Boeing 777-8X	€20.0 bn	Derivative design, development estimated to be 40% complete (based on e.g. Perry, 2023).	€1.5 bn
	Boeing 777-9X	€20.0 bn	Derivative design, development estimated to be 80% complete (first flight completed; Boeing, 2020), EIS expected 2025.	€0.6 bn
Total				€11.4 bn

Based on list prices and average discount rates published by Schonland (2016), Adler et al. (2023) derived average sales prices. The resulting data are replicated as Table 61, showing average prices ranging from 25 to approximately €160 m.

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[159] Modelled based on a concept aircraft announced by Embraer. As also noted in 35 on page 46, personal communication with Embraer received during the finalisation of this report suggests this aircraft is no longer planned to be introduced. As it has been included in the decarbonisation modelling on which the results presented in Section 2.6 are based, the associated expenditures are also still included.

Table 61: Class-based list prices, discount rates and sales prices for upcoming aircraft (based on Schonland, 2016). Average sales prices are highlighted in bold

Class	Example aircraft	List price [€ m] Average / min / max			Discount	Sales price [€ m] Average / min / max		
Regional (R)	ATR72-600, Embraer E175-E2	39	21	49	35%	**25**	14	32
Single-aisle (SA)	Airbus A220, Airbus A320neo, Boeing 737MAX	94	56	126	45%	**52**	37	69
Small/medium twin-aisle (SMTA)	Airbus A330neo, Boeing 787	238	202	276	45%	**131**	111	152
Large twin-aisle (LTA)	Airbus A350, Boeing 777X	319	269	361	50%	**159**	134	180

Future aircraft

Based on the Clean Aviation Partnership (2020) and other literature (Bowen, 2010, p. 68; Rodrigue, 2020), the Price of Net Zero (Adler, et al., 2023) estimated clean-sheet product development costs for future kerosene-powered aircraft. For single-aisle and larger aircraft, these estimates have been maintained. For a hybrid-electric regional, an updated figure of €10 bn is selected (based on Benjamin, 2024), leading to the overview shown in Table 62. Development costs for future hydrogen-powered aircraft are estimated in Appendix D.4.1.3.

Table 62: Estimated product development costs for future aircraft

Class	Product development cost	Remarks
Regional (R)	€10.0 bn	Estimated for hybrid-electric, based on Benjamin (2024).
Single-aisle (SA)	€15.0 bn	Baseline value.
Small/medium twin-aisle (SMTA)	€20.0 bn	Estimated.
Large twin-aisle (LTA)	€22.5 bn	Estimated.

Figures provided by the Clean Aviation Partnership (2020) were also used to estimate the acquisition cost of future aircraft. Based on a €5,000 bn investment for 26,000 new aircraft, an average (list) price of €192 m per aircraft was determined. Compared to the average list price in Table 61, this represents a 25% increase, leading to the list prices shown in Table 63. Assuming that discount policies remain unchanged, this 25% increase can also be applied to the sales prices.

Table 63: Class-based list prices, discount rates and sales prices for future aircraft, increased 25% from values reported in Table 62

Class	Example aircraft	List price	Discount	Sales price
Regional (R)	ATR72-600, Embraer E175-E2	€49 m	35%	€31 m
Single-aisle (SA)	Airbus A220, Airbus A320neo, Boeing 737MAX	€118 m	45%	€65 m
Small/medium twin-aisle (SMTA)	Airbus A330neo, Boeing 787	€298 m	45%	€163 m
Large twin-aisle (LTA)	Airbus A350, Boeing 777X	€388 m	50%	€199 m

Prices for future hydrogen-powered aircraft are determined in Appendix D.4.1.3.

Appendix D.4.1.3 Performance, cost and market share estimates of future hydrogen-powered aircraft

As indicated in Section 3.4.2, this updated DESTINATION 2050 roadmap includes three hydrogen-powered aircraft:

- a smaller retrofit hydrogen-powered regional turboprop aircraft, modelled for entry into service in 2030;
- a larger clean-sheet hydrogen-powered regional turboprop aircraft, modelled for entry into service in 2035;
- a single-aisle hydrogen-powered aircraft, modelled for entry into service in 2040.

This appendix provides further detail to the performance (capacity, range, energy efficiency improvement, …), cost (acquisition cost, cost per ASK, …) and market share figures that have been assumed.

Retrofit hydrogen-powered regional turboprop

This revised edition of the DESTINATION 2050 roadmap report anticipates the introduction of a retrofit hydrogen-powered regional turboprop by 2030. For this aircraft, the powertrain of existing turboprop aircraft would be replaced by new, hydrogen-based, propulsion units. Currently, companies like ZeroAvia (2023), Universal Hydrogen (2023) and Conscious Aerospace (2024) are developing such units.

AIRCRAFT PERFORMANCE

The modelling for the retrofit hydrogen-powered regional turboprop is primarily based on McKinsey & Company (2020), Mukhopadhaya (2023, who modelled performance of fuel cell retrofit aircraft) and Lammen et al. (2022, who did a conceptual sizing of derivative fuel cell powered aircraft), augmented with literature on the performance of relevant systems and components. Table 64 compares some key parameters between the aforementioned three design studies.

Table 64: Comparison of parameters of smaller to mid-sized hydrogen-powered regional turboprop design studies

	McKinsey & Company (2020)	Mukhopadhaya (2023)	Lammen et al. (2022)
Payload capacity	80 passengers	58 passengers	5.1 tonnes = 50 passengers
Range	1000 kilometres	783 kilometres	1000 kilometres (design)
Entry into service	2030-2035	2030 [160]	2035
Tank gravimetric index	30%	27.5%	30%
Fuel cell efficiency	59% (peak)	55% (average)	60% (peak), 53% (cruise)
Fuel consumption	771 kg [161]	200 kg [162]	300 kg
Energy intensity	1.16 MJ/ASK [163]	0.53 MJ/ASK (-31% vs. ATR72 [164] at 0.77 MJ/ASK)	-45% vs. current ATR42 [165]

As the aircraft modelled in this study is to be a retrofit aircraft, the figures provided by Mukhopadhaya (2023) are considered the most relevant reference. The fuel cell efficiency of 55% seems rather high, though, as Lammen et al. (2022) anticipate to reach an average efficiency of 53% only with technology introduced into service by 2035. Similarly, the Clean Hydrogen Joint Undertaking (Clean Hydrogen JU, 2022, p. 165) targets an efficiency of 50% by 2030. None of these references seem to include the power requirements of the cooling system. When taken into account, that would further reduce efficiency. As such, a fuel cell efficiency of 47% is assumed – approximately 15% lower (multiplicative) than the 55% used by Mukhopadhaya (2023).

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[160] No entry into service year provided. Cost analyses are however given for 2030, such that it is assumed that technology assumptions fit with a 2030 EIS.

[161] Computed from a (dry) LH_2 tank weight of 2000 kg, a gravimetric index of 30% and 90% usable fuel fraction (assumed to include reserve fuel) to arrive at 771 kg LH_2.

[162] Computed from 0.53 MJ/ASK, 58 × 783 = 45.000 ASK and 120 MJ/kgLH_2.

[163] Based on fuel burn, which is equivalent to 92.520 MJ (based on 120 MJ/kgLH_2). Transporting 80 passengers over 1000 kilometres yields 80.000 ASK, yielding an energy intensity of 1.16 MJ/ASK.

[164] Does not include technology upgrades.

[165] Or -30% compared to a redesigned ATR42, including technology upgrades that bring weight reduction (-10%) and drag reduction (-3%) to reduce thrust-specific fuel consumption by 13%.

The lower efficiency has a knock-on effect: first, it increases the energy intensity to 0.61 MJ/ASK, such that the improvement with respect to the reference ATR72 reduces to 20%. Then, given the on-board energy is consumed more quickly, the higher energy intensity affects payload and/or range. Keeping the passenger capacity constant at 58, energy consumption per kilometre is 35.5 MJ, such that 200 kg of liquid hydrogen (containing 24.000 MJ of energy) are consumed in approximately 675 kilometres. Alternatively, the range can be kept constant (783 kilometres), in which only 50 passengers can be transported. For the modelling, a more-or-less central point is chosen at a capacity of 55 passengers and a range of 700 kilometres.

AIRCRAFT COST

Product development costs are estimated at half of the product development cost of a clean-sheet traditional regional aircraft, previously estimated at €10 bn, and therefore leading to a product development cost estimate of €5.0 bn.

Aircraft acquisition cost is modelled to be equivalent to a kerosene-powered regional turboprop (€25 m, per Table 61). The investment related to the hydrogen powertrain is hence assumed to be compensated by the fact that the acquisition costs of the (previously used or already owned) airframe will be lower[166]. Cost per ASK will however increase, mainly due to lower productivity (-24%, due to lower seating capacity), and as maintenance costs estimated to increase by 47% (McKinsey & Company, 2020). Based on average costs per available seat-kilometre (ASK) for current regional turboprop aircraft (IATA, 2019), these increases combined yield an increase in cost per ASK of 28%. This excludes cost changes related to the change in fuel. This is detailed in Table 65.

Table 65: Cost per available seat kilometre for retrofit hydrogen-powered regional turboprop, excluding the influence of energy carrier (based on McKinsey & Company, 2020; IATA, 2019, with an exchange rate of 1 EUR = 1.12 USD)

CASK-factor	Current CASK (Dash 8 / ATR)	Changes due to		CASK, excl. LH$_2$
		CAPEX and MRO	Productivity	
Fuel and Oil	€0.0250			€0.0250
Aircraft Ownership	€0.0392		+ 24% (€0.0094)	€0.0486
Maintenance and Overhaul	€0.0363	+ 47% (€0.0171)	+ 24% (€0.0087)	€0.0621
Flight Deck Crew	€0.0218		+ 24% (€0.0052)	€0.0270
Flight Equipment Insurance	€0.0062		+ 24% (€0.0015)	€0.0077
Air Navigation Charges	€0.0081		+ 24% (€0.0019)	€0.0100
Airport Charges	€0.0206		+ 24% (€0.0049)	€0.0255
Station and Ground	€0.0169			€0.0169
Total	**€0.1740**			**€0.2229**
Difference				**+ €0.0488 (+ 28%)**

MARKET SHARE

In its ambitious scenario, AZEA's Working Group 1 anticipates that approximately 75% of hydrogen-powered aircraft that will have been delivered to the market by 2050 are of a retrofit nature (Ternel, 2024). Assuming hydrogen-powered aircraft will capture a market share of about 50%, retrofits are modelled to operate on 50% × 75% = 37.5% of applicable routes.

Clean-sheet hydrogen-powered regional turboprop

After the entry into service of the (smaller-sized) retrofit hydrogen-powered regional turboprop in 2030, hydrogen-powered aircraft are anticipated to further penetrate into airlines' fleets. Accordingly, this edition of the DESTINATION 2050 roadmap report models the introduction of a larger-sized clean-sheet hydrogen-powered regional turboprop aircraft in 2035. This aircraft could materialise as the smaller of the ZEROe concepts put forward by Airbus (Kaminski-Morrow, 2024).

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[166] This is e.g. supported by ACC (2024), noting an average price for a pre-owned ATR 72-600 aircraft is some 18M$, currently equivalent to some €16.5 m.

AIRCRAFT PERFORMANCE

As for the retrofit hydrogen-powered regional turboprop, the modelling of the clean sheet version is based on selected studies from literature. As the clean sheet design is anticipated to have a larger seating capacity of approximately 100 passengers, different reference studies are deemed relevant. Less information is however available for such types, such that the aircraft performance is approximated somewhat more rudimentarily, taking account the following considerations:

- Technology developed and matured in Clean Aviation is targeting a 30% reduction in fuel consumption for a single-aisle aircraft, compared to recent and imminent models. Apart from weight and energy consumption penalties introduced by the hydrogen powerplant, a 30% reduction is also deemed feasible for this 100-seat hydrogen-powered turboprop.
- For a set of 70-seater concept designs (using technology available for aircraft entry into service in 2040), including one conventionally fuelled and one hydrogen-powered version, Atanasov (2023) shows the higher powertrain efficiency (notably caused by the higher efficiency of the fuel cell) more than makes up for the increase in weight, e.g. caused by the fuel cell system and LH_2 tanks. This increases with distance, as the powertrain efficiency benefits are higher during off-design conditions (such as take-off and climb-out). Specifically, energy consumption of the hydrogen-powered concept versus the conventionally fuelled aircraft is modelled to be reduced by 35% for a 200 nm mission with a negligible cruise phase, by 30% on an average fleet, and by 8% for mid-cruise performance. McKinsey & Company (2020) anticipate an 8% reduction in mission energy for an 80-seat hydrogen-powered aircraft with 2030 to 2035 entry into service. Conservatively averaging the mission-averaged figures yields an energy saving of 15%.
- Atanasov (2023) estimates the absolute fleet-average transport energy for the hydrogen-powered concept at 135 Wh/passenger-kilometre, equivalent to 0.49 MJ/passenger-kilometre, or 0.44 MJ/ASK with a passenger load factor of 90%. This is substantially lower than the 1.16 MJ/ASK computed from McKinsey & Company (2020) presented in Table 64 (for 80 passengers), but rather well in line with other concepts shown there – especially taking into account the more advanced technology enabled by the later EIS of the concept by Atanasov.

Taken together, a 30% improvement from non-propulsive technologies is anticipated, to which a 15% efficiency improvement from the switch to hydrogen is added, yielding a (multiplicative) total of 40% compared to recent and imminent aircraft.

AIRCRAFT COST

The product development cost of a clean-sheet traditional regional aircraft was previously estimated at €12.5 bn. Re-using the €2.5 bn premium for powertrain development (based on Adler, et al., 2023, also used for the hydrogen-powered single aisle) yields a total product development cost of €15 bn. Aircraft acquisition cost is modelled as €30 m, which is 20% above the cost of a kerosene-powered regional turboprop (€25 m, per Table 61). The increase reflects estimates that CAPEX of hydrogen-powered aircraft is likely larger, e.g. due to the larger structure to house the hydrogen tanks (McKinsey & Company, 2020). The impact on costs per ASK, excluding fuel, is lower than for the retrofit aircraft, as the larger cabin of the clean-sheet design mitigates productivity losses. As such, only CAPEX and MRO costs increase (by €0.0171 per ASK), resulting in a relative increase in cost per ASK of almost 10%.

MARKET SHARE

With 75% of cumulative hydrogen-powered aircraft deliveries up to 2050 being retrofit types, 25% are anticipated to be clean sheet designs (Ternel, 2024). With a 50% market share of all hydrogen-powered aircraft types in this class, the clean-sheet regional turboprop is modelled to operate on 50% × 25% = 12.5% of applicable routes.

MODELLING HYDROGEN-POWERED REGIONAL AIRCRAFT

The previous paragraphs have elaborated on the two hydrogen-powered regional aircraft that are included in this edition of the DESTINATION 2050 roadmap report. Given their inclusion in the group of 'future' aircraft, the models presented should be seen as an illustration of the effect of anticipated technologies, rather than definitive products. As such, rather than including each of these types in the modelling, an 'average' aircraft has been used, with the performance and cost[167] details as documented in Table 66.

Table 66: Performance, cost and market share estimates for the two hydrogen-powered regional aircraft, alongside the performance, cost and market share estimates of an 'averaged' aircraft used in the modelling

	Retrofit hydrogen-powered regional turboprop	Clean-sheet hydrogen-powered regional turboprop	Weighted 'average' aircraft, as modelled
Payload capacity	55 seats	100 seats	66 seats
Range	700 km	1000 km	775 km
Entry into service	2030	2035	2031
Efficiency improvement	20%	40%	25%
CASK change	28% (€0.0488)	10% (€0.0171)	€0.0171
Acquisition cost	€25 m	€30 m	€26.3 m
Share (of total H_2)	75%	25%	

Hydrogen-powered single aisle

As the first edition of the DESTINATION 2050 roadmap report, the current decarbonisation pathway includes a hydrogen-powered single-aisle aircraft – thereby further scaling hydrogen technology to larger aircraft classes. The single-aisle Airbus ZEROe aircraft could be representative of a first product in this segment (Airbus, 2020).

AIRCRAFT PERFORMANCE

The first edition of the DESTINATION 2050 roadmap report modelled its hydrogen-powered single-aisle (Section 3.3.3, pp. 41-44) based on McKinsey & Company (2020). Capacity (165 passengers), range (2000 kilometres) and aircraft speed (Mach 0.72) have been reused from that report, whereas the entry into service has been postponed from 2035 to 2040 (based on the ambitious roll-out scenario foreseen by AZEA, reported by Ternel, 2024; AZEA, 2024) – noting that the first clean-sheet hydrogen-powered aircraft, envisaged to start operations from 2035 (EC, 2020a; Airbus, n.d.), will likely be of a smaller class (i.e., the regional segment, seating up to 100 passengers; Kaminski-Morrow, 2024; Ternel, 2024). Furthermore, aircraft performance estimates have been critically reviewed and updated, for two reasons in particular:

- The reduction in energy consumption compared to a kerosene-powered aircraft estimated by McKinsey & Company (2020) is not observed in Lammen et al. (2022) and recent work by the German Aerospace Centre in the EXACT-project (Silberhorn, 2023). The latter two both anticipate an increase in energy consumption due to the switch to a hydrogen-powered propulsion system.
- The design put forward by McKinsey & Company (2020) assumes a fuel cell system will be capable of providing the majority of power during cruise. Although hybrid hydrogen architectures are common in single-aisle aircraft design studies, these typically see turbofans delivering the majority of thrust and only see fuel cells providing additional power during select flight phases (take-off and climb-out, notably).

Table 67 shows a comparison of some key parameters between the aforementioned three design studies.

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[167] As the average payload capacity is well comparable to current types in the segment, productivity losses are not modelled for the 'average' aircraft. As such, the CASK change is limited to the increased cost for CAPEX and MRO, equal to €0.0171 for both types.

Table 67: Comparison of parameters of hydrogen-powered single-aisle design studies

	McKinsey & Company (2020)	**Lammen et al. (2022)**	**EXACT / Silberhorn (2023)**
Propulsion system configuration	Fuel cells (11 MW; primary cruise power source), supported by turbofans	Turbofans (primary cruise power), supported by fuel cells (2.3 MW)	Turbofans (primary cruise power), supported by fuel cells (2 MW)
Payload capacity	165 passengers	15.9 tonnes = 156 passengers	250 passengers
Range	2000 kilometres	3704 kilometres (design)	2808 kilometres (design)
Entry into service	2035	2035	2040
Tank gravimetric index	35%	35%	50 – 65%
Fuel cell efficiency	60% (peak)	60% (peak), 53% (cruise)	45% (peak)
Fuel consumption	1938 kg [168]	3700 kg	
Energy intensity	0.70 MJ/ASK [169]	0.77 MJ/ASK [170] (-5% vs. A320neo, +10% vs. upgraded A320neo [171])	+3.8% – +8.8%

The results obtained from studies by McKinsey & Company (2020) and Lammen et al (2022) align rather well, with the 10% difference in energy consumption likely (at least partly) explained by the lower design range[172] and cruise speed of the McKinsey-aircraft. McKinsey & Company (2020, p. 29) however state the energy intensity represents a 4% decrease in energy demand compared to an A320neo with "similar conditions such as the technology in 2035 projections, shorter ranges, or lower speeds", whereas Lammen et al. (2022) note an increase of 10%. The results from Silberhorn (2023, pp. 17-18), too, see an energy increase of 3.8%, further increased to 8.8% if the assumed (but uncertain) efficiency savings from hydrogen combustion are not taken into account.

Also notable are the substantially higher gravimetric index (based on Burschyk, Cabac, Silberhorn, Boden, & Nagel, 2023) and lower fuel cell efficiency reported by Silberhorn (2023). Both seem somewhat extreme: the time between 2035 and 2040 might yield some increases in GMI, but advances to the extent are deemed unlikely based on other literature. Similarly, the fuel cell efficiency seems rather low, given aforementioned Clean Hydrogen JU targets of 50% by 2030 (Clean Hydrogen JU, 2022, p. 165). The 60% (peak) efficiency used by McKinsey & Company (2020) and Lammen et al. (2022) might on the other hand be somewhat too optimistic.

Taking all this into account, an energy intensity of 0.75 MJ/ASK is assumed for the hydrogen-powered single-aisle, based on airframe and engine technology projections by McKinsey & Company (2020) and Lammen et al. (2022). Noting an energy intensity of approximately 0.82 MJ/ASK for the Airbus A320neo (based on Lammen, Peerlings, van der Sman, & Kos, 2022), this implies a reduction of 7.5%. The expected improvement in energy efficiency due to advances in airframe and engine technology estimated by Lammen et al. (2022) between the current Airbus A320neo and a version with 2035-level technology, is however lower (approximately 15%: 0.82 MJ/ASK vs. 0.69 MJ/ASK) than what is anticipated for the future kerosene-powered single-aisle aircraft in this report (-30%, based on Clean Aviation). Correcting for this difference (i.e., assuming the future hydrogen-powered single-aisle also benefits from the further advances from Clean Aviation), the energy intensity would reduce from 0.75 MJ/ASK to 0.64 MJ/ASK, representing a decrease in energy efficiency of 8%. This difference, which purely represents the change in energy carrier and propulsion system from kerosene to hydrogen, is in line with that same difference as computed by Lammen et al. (2022), finding approximately 10%. This way, the energy efficiency improvement compared to an upcoming aircraft (used as reference for the future aircraft category) is 22%, conservatively rounded to 20%.

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[168] Computed from a (dry) LH_2 tank weight (including fuel) of 4000 kg, a gravimetric index of 35% and 91% usable fuel fraction (assumed to include reserve fuel) to arrive at 1938 kg LH_2.

[169] Based on fuel burn, which is equivalent to 232.560 MJ (based on 120 MJ/$kgLH_2$). Transporting 165 passengers over 2000 kilometres yields 330.000 ASK, resulting in an energy intensity of 0.70 MJ/ASK.

[170] Based on fuel burn, which is equivalent to 444.000 MJ (based on 120 MJ/$kgLH_2$). Transporting 156 passengers over 3704 kilometres yields 577.824 ASK, resulting in an energy intensity of 0.77 MJ/ASK.

[171] Based on energy different per flight, with identical payload and flight distance. Technology upgrades included weight reduction (-5%) and drag reduction (-5%), reducing thrust-specific fuel consumption by 9%.

[172] Due to the lower range, the wings can reduce in size, which reduce weight, which reduces energy consumption. In a study conducted by NLR, reducing the design range of a single-aisle aircraft from some 3700 to 2200 kilometres resulted in a reduction energy consumption of about 4% (for a 2200-kilometre mission).

AIRCRAFT COST

Product development cost was previously estimated at €17.5 bn, based on a €15 bn cost estimate for the development for a traditional single-aisle program and a €2.5 bn premium to take into account additional cost associated to the hydrogen-based powertrain (Adler, et al., 2023).

Aircraft acquisition cost was previously estimated to be 31% higher than a traditional single-aisle aircraft (McKinsey & Company, 2020), due to the cost of the tank structure, the fuel distribution and the longer fuselage. Given the €65 m cost for a conventional single-aisle aircraft (Appendix D.4.1.2), acquisition cost for the hydrogen-powered single-aisle is estimated at €85 m.

This increase is also assumed to affect flight equipment insurance costs. Maintenance and overhaul costs were estimated to be 47% higher (McKinsey & Company, 2020), mostly related due to the longer fuselage. A last cost impact is caused by a somewhat lower productivity, due to longer refuelling times (+7%) [173] and a lower seating capacity (+12%). Based on average costs per available seat-kilometre (ASK) for current single-aisle aircraft (IATA, 2019), these increases combined yield an increase in cost per ASK of 21%. This excludes cost changes related to the change in fuel. This is detailed in Table 68.

Table 68: Cost per available seat kilometre for hydrogen-powered single-aisle, excluding the influence of energy carrier (based on McKinsey & Company, 2020; IATA, 2019, with an exchange rate of 1 EUR = 1.12 USD)

CASK-factor	**Current CASK (737NG / A320)**	**Changes due to**		**Hydrogen-SA CASK, excl. LH_2**
		CAPEX and MRO	**Productivity**	
Fuel and Oil	€0.0189			€0.0189
Aircraft Ownership	€0.0073	+ 31% (€0.0023)	+ 18% (€0.0013)	€0.0109
Maintenance and Overhaul	€0.0086	+ 47% (€0.0040)	+ 18% (€0.0015)	€0.0142
Flight Deck Crew	€0.0110		+ 18% (€0.0020)	€0.0130
Flight Equipment Insurance	€0.0008	+ 31% (€0.0002)	+ 18% (€0.0001)	€0.0012
Air Navigation Charges	€0.0041		+ 18% (€0.0007)	€0.0048
Airport Charges	€0.0043		+ 18% (€0.0008)	€0.0051
Station and Ground	€0.0068			€0.0068
Total	**€0.0618**			**€0.0749**
Difference				**+ €0.0131 (+ 21%)**

MARKET SHARE

Whereas the first version of the DESTINATION 2050 roadmap report anticipated all flights on eligible routes would, following the complete fleet rollover period, be operated by hydrogen-powered aircraft, a lower market share of 60% is now assumed. As the fleet penetration during initial phases is likely somewhat slower and because the modelling assumes linear phase-in rates, a final market share of 50% is modelled.

Geographical limitation

All hydrogen-powered aircraft are only modelled to enter service on intra-European routes. This acknowledges that hydrogen availability and supporting infrastructure might not be available outside the EU+ to the extent it is estimated to be inside the EU+.

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[173] As these longer refuelling times might be circumvented through the introduction of innovative refuelling technologies or processes (e.g. Postma-Kurlanc, Leadbetter, & Pickard, FlyZero - Hydrogen Infrastructure and Operations - Airports, Airlines and Airspace, 2022), the cost increase is a conservative estimate.

Larger hydrogen-powered aircraft

Even though McKinsey & Company (2020) as well as other sources (e.g. Lammen, Peerlings, van der Sman, & Kos, 2022; ATI, 2022; Debney, et al., 2022) also note the potential of hydrogen-powered aviation in larger classes, these are not included in this roadmap for two reasons:

- As already observed for the hydrogen-powered single aisle aircraft modelled, the energy consumption of hydrogen-powered aircraft compared to kerosene-powered ones is anticipated to be higher, primarily caused by the size (and weight) of hydrogen tanks large enough to carry the energy required for typical twin aisle (i.e.: long-range) missions. Whereas the 8% higher in-flight energy consumption derived for the single aisle aircraft is compensated for lower well-to-tank energy consumption of hydrogen versus synthetic SAF production (Kos, et al., 2022, pp. 32-33, 74-75), that is not the case for the increases in energy consumption reported for twin-aisle aircraft (+22% and +42%) as reported by McKinsey & Company (2020, pp. 34-35).
- Hydrogen availability and supporting infrastructure might not be available outside the EU+, whereas anticipated future twin-aisle aircraft are typically used on intercontinental routes.

Appendix D.4.1.4 Cost estimates for infrastructure for alternatively fuelled future aircraft

Cost estimates for infrastructure for alternatively fuelled future aircraft – notably hydrogen-powered regional and single-aisle aircraft and a regional hybrid-electric aircraft – are modelled largely based on The Price of Net Zero (Adler, et al., 2023).

> CONCENTRATION OF ALTERNATIVELY POWERED FLIGHTS AND INFRASTRUCTURE NOT MODELLED
> A key assumption in the modelling approach employed in this report is that alternatively powered aircraft are evenly distributed over the flight network, or over the subset of the flight network to which these aircraft are applicable (e.g. intra-EU+, and/or limited to particular ranges). As is illustrated by the results presented in the next paragraphs, this yields relatively large amounts of airports with rather low amounts of energy required for recharging hybrid-electric aircraft or refuelling hydrogen-powered ones. In reality, and further stimulated by the fact that infrastructure development in support of only a small number of flights is expensive, such concentrations will likely take place.

Hybrid-electric aircraft

The cost for recharging infrastructure of hybrid-electric aircraft is primarily determined based on the electric energy required at each airport served by hybrid-electric aircraft, assuming these are evenly distributed over the flight network. This data is obtained from intermediate modelling output and therefore fully consistent with the decarbonisation roadmap results presented in this report.

Results show that the total annual electricity demand for recharging hybrid-electric aircraft by 2050 is a little over 230 GWh, or an average some 650 MWh per day. It is approximated that daily demand will be at least 10 MWh (ranging from 10 MWh to 62 MWh) for only 11 airports. For 100 airports, the daily demand varies between 1 and 10 MWh, averaging at about 3.5 MWh. The daily demand for the largest group – comprising almost 250 airports – is lower and averages approximately 0.2 MWh. For 2040, when lower numbers of hybrid-electric regional aircraft have entered into service, these numbers are also lower: just 2 airports have a daily demand of more than 10 MWh, 50 have a daily demand between 1 and 10 MWh (2.1 MWh on average) and over 300 airports would require less than 1 MWh per day, averaging a little more than 0.1 MWh per day per airport.

For finding the cost for recharging infrastructure, the aforementioned electricity demand (per airport) is combined with a number of assumptions and literature-sourced parameter values related to infrastructure use and unit cost:

- It is assumed that 10 hours of each day are effectively available for charging, such that the average hourly electricity demand is 10% of the average daily demand.
- For redundancy reasons, 20% additional charging capacity is modelled (up from 10% in Adler, et al., 2023), and the minimum amount of chargers per airport is set at 3 units. The 20% additional charging capacity is assumed to be sufficient to cater to (seasonal) variations in demand.
- A charging speed of 400 kW (or, equivalently, 0.4 MW) is modelled (based on Driessen & Hak, 2021) and the cost of charging infrastructure is estimated at 2M€/MW, based on Driessen & Hak (1.7 to 2.5M€/MW, 2021) and Van Oosterom (2M€/MW, 2021). It is noted that these costs are substantially higher than for fast-chargers used for road transport (0.5M€/MW, as estimated by EC, 2021b, p. 129), but due to the complexities of the airport environment (compared to a recharging station near a motorway), the estimate is considered realistic.

Summed across all 365 airports that are modelled to be served by hybrid-electric regional aircraft in 2050, the total investment requirement is calculated at €910 m. The figure for 2040 is just a little lower (at €880 m) due to the minimum number of chargers per airport – meaning that the majority of investments needs to take place in the period up to 2040. If operations by hybrid-electric aircraft will be concentrated to a smaller number of routes and airports, costs will likely be lower due to reduced 'overhead' [174]. Compared to the results presented in The Price of Net Zero (Adler, et al., 2023, p. 14, noting an investment of 1.5B€), these updated figures are lower due to the introduction of hydrogen-powered aircraft in the regional segment – which reduce the market share (and, accordingly, energy consumption) of hybrid-electric models.

Hydrogen-powered aircraft

The cost for refuelling infrastructure for hydrogen-powered aircraft is computed in a fairly similar approach as used for determining the cost for recharging infrastructure for hybrid-electric aircraft. As this updated roadmap however anticipates the introduction of three hydrogen-powered aircraft types (two in the regional segment; one in the larger single-aisle class) with different entry into service years (2030, 2035 and 2040, respectively), the annual hydrogen uptake does not grow linearly with time. By 2040, the annual demand for liquid hydrogen for refuelling hydrogen-powered aircraft is less than 80 kt, whereas it is anticipated to grow to approximately 1.25 Mt by 2050.

For 2050, the model identifies about 215 airports anticipated to have an average daily demand of at least one tonne of hydrogen. 80 of these will require at least 10 tonnes per day, with just three surpassing the marker of 100 tonnes per day (up to about 110 tonnes/day) [175]. For the remaining 232 airports potentially served by hydrogen-powered aircraft, daily demand is below one tonne per day. Given a lower share of hydrogen-powered aircraft in service by 2040, demand figures for that year are lower as well: almost 60 airports would have a daily demand of at least a tonne (averaging at approximately 2.5 tonnes), with a maximum of just over 7.5 tonnes. For the remaining group of almost 400 airports, daily demand would be lower than one tonne, and just 0.17 tonnes on average.

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[174] In 2050, almost 360 airports are modelled to require only 3 charges – the minimum amount set – while (jointly) explaining almost 95% of the total investment for that year.

[175] Average demand levels are 3.8 tonnes per day for the group of airports with a daily demand between 1 and 10 tonnes, 32.5 for those with a daily demand between 10 and 100 tonnes, and almost 105 tonnes per day for the three airports with highest hydrogen uptake.

HYDROGEN SUPPLY PATHWAYS

The supply pathway – from renewable electricity generation to ultimately aircraft refuelling, and all steps in between – depends on the volumes used per day. *Figure* 48 illustrates two main routes. In the first one, hydrogen liquefaction happens not on the airport. Rather, liquid hydrogen is transported to the airport, then stored, and subsequently supplied to aircraft. The local hydrogen storage can be a fixed facility (as illustrated), but can also be realised by decoupling the LH_2-trailer from the delivery truck. In the second route, hydrogen liquefaction does occur on the airport premises. Supply to the airport is then gaseous.

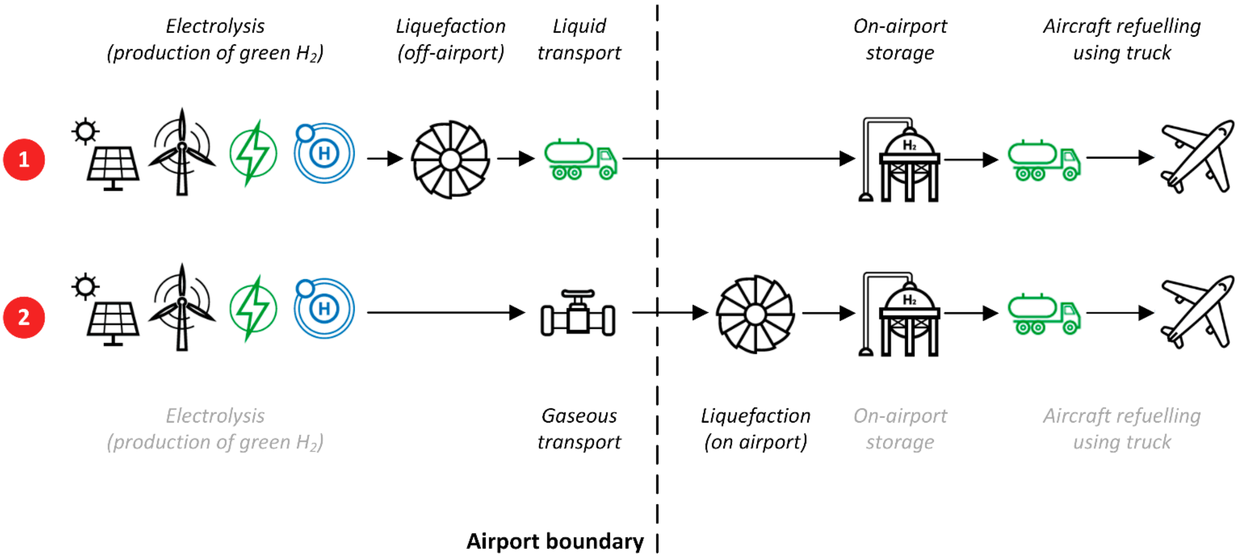

Figure 48: Hydrogen supply pathways from production to airport and aircraft considered (reproduced from Adler, et al., 2023; adapted from ACI World & ATI, 2021)

Which of these routes is most feasible depends on local circumstances, but a key determinant is the daily volume of hydrogen used: there are practical limits to the magnitude of a (liquid) hydrogen supply line that can be safely sustained using truck deliveries. McKinsey & Company (2020, p. 40) estimate that 25 truckloads of 4 tonnes each are 'feasible'. This figure seems in line with remarks in other sources (ACI World & ATI, 2021). Based on an economic analysis, Hoelzen et al. (2022) set a higher cut-off point at 125 kt per year, equivalent to some 350 tonnes per day.

Based on the aforementioned demand figures, the investment costs are computed based on a similar methodology as employed in The Price of Net Zero (Adler, et al., 2023), but with updated economic estimates from Hoelzen et al. (2022). Lacking exact scheduling information and daily demand, annual demand figures are translated into peak daily demands by dividing by 365 and taking a 25% margin.

- Liquefaction CAPEX (in € m) is estimated at $C_{LF,m} = 1.2 \times P + 87.4$ for a medium-sized plant (96 – 192 tonnes of LH_2 per day) and at $C_{LF,s} = 1.6 \times P + 45.8$ for a smaller plant (24 – 96 t LH_2 per day), with P the plant capacity per day. Consistent with the first edition of the DESTINATION 2050 roadmap, but contrary to Hoelzen et al. (2022), on-site liquefaction is modelled to be used for airports with a (peak) daily demand of more than 100 tonnes (4 25-tonne trucks).
- The investment costs for on-airport storage are estimated at 39 €/kg for a storage capacity up to 100 tonnes, and at 33.6 €/kg for a larger storage capacity (up to 250 tonnes), for which a one-time investment of €540 k is also required. Local storage facilities are modelled to be sized to hold two truckloads (of four tonnes each), or a 7-day supply (based on IATA, 2008) – whichever is highest.

- The unit costs for assets used to refuel aircraft – bowsers with a 2.8 tonne capacity – are estimated at €640 k. The number of bowsers required is found by assuming the daily demand for hydrogen is to be uplifted to aircraft in 10 hours and that one loaded bowser can provide liquid hydrogen to two aircraft[176] in one hour (based on Postma-Kurlanc, Leadbetter, & Pickard, 2022). In addition to the bowsers, cryopumps are required to transfer the hydrogen, at an estimated cost of some €250 k per tonne of LH_2 per hour (computed as 1/10th of the daily demand).

For 2050, the total investment – across all airports modelled to be served by hydrogen-powered aircraft – is computed as €2.9 bn. This is primarily governed by the costs for on-site liquefaction, totalling more than €1.6 bn for the seven airports with highest hydrogen demand, and for which on-site liquefaction is anticipated to be feasible. For airports with a hydrogen demand between 1 and 100 tonnes per day in 2050, the required investment ranges from less than €1 m to €22 m, averaging approximately €4 m per airport. The total investment required to meet the demand in 2040 is substantially lower, as demand figures never warrant the construction of an on-site liquefaction facility, at €450 m (of which about €90 m would be required for the approximately 75 airports with a demand of more than 1 tonne per day). In comparison to The Price of Net Zero (Adler, et al., 2023, p. 16), the 2050 investment figure computed in this work is a factor 5 lower – down from €16.4 bn - primarily due to the lower share of hydrogen-powered aircraft in the fleet (following a later entry into service of the hydrogen-powered single-aisle and, in general, lower anticipated market shares, as noted in Section 3.4.2).

As for infrastructure required for recharging hybrid-electric aircraft, concentration of hydrogen-powered flights could prevent investments for the share of airports that would only see a small number of such aircraft. Furthermore, operators could tanker hydrogen for the shortest routes, allowing them to fly to airports where no hydrogen refuelling infrastructure is available. Although this would result in a slightly increased energy consumption (as the aircraft is carrying 'excess' fuel on the first leg, which requires energy to transport), the increase is much smaller than seen with conventionally-fuelled aircraft, as the weight of the hydrogen fuel is much lower.

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[176] Based on the 48 MWh – or 1.44 tonnes – energy requirement of a hydrogen-powered aircraft (van der Sman, Peerlings, Kos, Lieshout, & Boonekamp, 2021, p. 40).

Appendix D.4.2 Improvements in Air Traffic Management (ATM) and aircraft operations

This appendix groups supplementary material related to improvements in ATM and aircraft operations, discussed in Chapter 4.

Appendix D.4.2.1 Airspace and air traffic management (ATM)

To calculate the non-European improvement potential from SES(AR), the split per flight phase in Figure 49 from the EASA Environmental Report 2022 (EASA; EEA; EUROCONTROL, 2022) is used, where the 2019 baseline year is compared with the remaining 2035 excess CO_2 according to the European ATM Master Plan 2020 Edition ambition. Departing flights to countries outside the EU+ will benefit from the improvements of the “additional average ATM-related inefficiency” concerning the taxi-out inefficiency, vertical flight inefficiency during climb, horizontal and vertical flight inefficiency during cruise/en-route. For improvements of cruise/en-route from SES(AR) a scaling factor of 50% is used to account that the cruise phase is partly inside EU+ and partly outside EU+ airspace. With the average fuel burn per flight 17000kg, the equation: $\frac{(104-35)+(11-6)+50\%*(389-227)+50\%*(183-28)}{17000} = 1.4\%$ gives an estimation of 1.4% of SES(AR) improvements for departing flights to outside EU+.

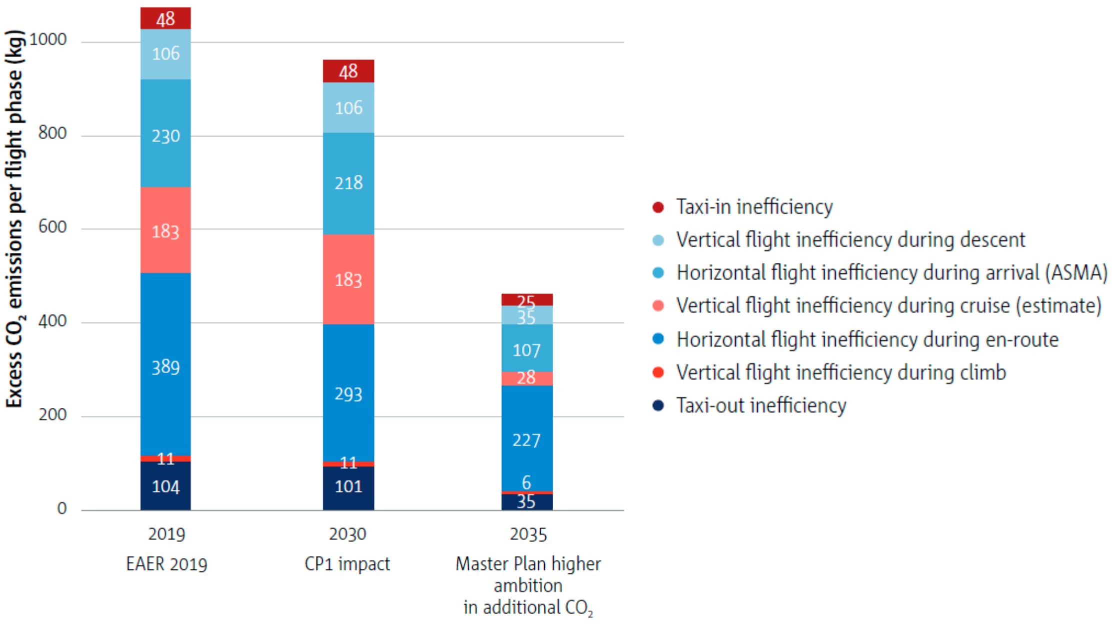

Figure 49: Excess CO_2 emissions for an average flight in Europe, adapted from (EASA; EEA; EUROCONTROL, 2022)

For the SES(AR) unimpeded improvements, the assumption is taken that the improvement potential for departing flights is half of the improvement potential for EU+ internal flights leading to 2%*50%=1%.

Appendix D.4.3 Alternative fuels and sustainable energy

This appendix groups supplementary material related to alternative fuels and sustainable energy, discussed in Chapter 5.

Appendix D.4.3.1 Production processes for SBCs approved in ASTM D7655

Currently 8 production processes for Synthetic Blend Component (SBC) production are approved by ASTM D7655 version 23b, as shown in Table 69.

Table 69 (continuous on next page): Production processes for SBCs approved in ASTM D7655

Pathway	Definition	Max. blend percentage with conventional jet fuel	Materials and manufacture
FT SPK	Fischer-Tropsch hydroprocessed synthesized paraffinic kerosine (FT-SPK) SPK produced from one or more precursors synthesized by Fischer-Tropsch processing.	50%	A1.4.1 FT-SPK synthetic blending components shall be comprised of hydroprocessed synthesized paraffinic kerosene wholly derived from: Paraffins and olefins derived from synthesis gas via the Fischer-Tropsch (FT) process using Iron or Cobalt catalyst. Subsequent processing of the product shall include hydrotreating, hydrocracking, or hydroisomerization and is expected to include, but not be limited to, a combination of other conventional refinery processes such as polymerization, isomerization, and fractionation.
HEFA SPK	Hydroprocessed esters and fatty acids (HEFAs) Mono-, di-, and triglycerides, free fatty acids and fatty acid esters (for example, fatty acid methyl esters) that have been hydroprocessed to remove essentially all oxygen.	50%	Synthetic blend components shall be comprised of hydroprocessed synthesized paraffinic kerosine wholly derived from: Paraffins derived from hydrogenation and deoxygenation of fatty acid esters and free fatty acids. Subsequent processing of the product shall include hydrocracking, or hydroisomerization, or isomerization, or fractionation, or a combination thereof, and may include other conventional refinery processes.
SIP	Synthesized iso-paraffins from hydroprocessed fermented sugars Farnesane that is produced by hydroprocessing and fractionation of farnesene derived from fermentation of sugars.	10%	Synthetic blend components shall be comprised of hydroprocessed synthesized iso-paraffins wholly derived from farnesene produced from fermentable sugars. Subsequent processing of farnesene into iso-paraffins shall include a combination of hydroprocessing and fractionation operations, and may include other conventional refinery processes. In particular, hydroprocessing operations consist of reacting hydrogen with farnesene feedstock and fractionation operations consist of gas/liquid separation and isolation of synthesized iso-paraffins. For example, fractionation typically includes a distillation step.
SPK/A	Fischer-Tropsch hydroprocessed synthesized paraffinic kerosine plus aromatics (FT-SPK/A) Fischer-Tropsch Synthesized Paraffinic Kerosine plus aromatics, producedby alkylation of nonpetroleum derived light aromatics (primarily benzene).	50%	SPK/A synthetic blending component shall be comprised of FT SPK as defined for the FT SPK section combined with synthesized aromatics from the alkylation of non-petroleum derived light aromatics (primarily benzene). Subsequent processing of the product shall include hydroprocessing, fractionation, and other conventional refinery processes.

Pathway	Definition	Max. blend percentage with conventional jet fuel	Materials and manufacture
AtJ	Alcohol-to-jet synthetic paraffinic kerosene (ATJ-SPK) An SPK produced starting from alcohol and processed through the following steps: dehydration, oligomerization, hydrogenation, and fractionation.	50%	ATJ-SPK synthetic blending components shall be comprised of hydroprocessed synthesized paraffinic kerosene wholly derived from ethanol or isobutanol processed through dehydration, oligomerization, hydrogenation, and fractionation.
CHJ	Catalytic hydrothermolysis jet (CHJ) CHJ is a synthetic blending component that is comprised essentially of normal paraffin, cycloparaffin, isoparaffin, and aromatic compounds.	50%	Synthetic blending component shall be comprised of hydroprocessed synthesized kerosene containing aromatics that is wholly derived from hydrothermal conversion of fatty acid esters and free fatty acids. Subsequent processing of the product Includes any combination of hydrotreating, hydrocracking, or hydroisomerization, and other conventional refinery processes, and shall include fractionation.
HC-HEFA SPK	Hydroprocessed hydrocarbons, esters and fatty acids (HC-HEFAs) Bio-derived hydrocarbons and free fatty acids and fatty acid esters (for example, fatty acid methyl esters) that have been hydroprocessed to saturate the hydro carbonmolecules and to remove essentially all oxygen.	10%	Synthetic blend components shall be comprised of hydroprocessed synthesized paraffinic kerosine wholly derived from: Paraffins derived from hydrogenation and deoxygenation of bio-derived hydrocarbons, fatty acid esters, and free fatty acids. Recognized Bio Sources: • Botryococcus braunii species of algae Subsequent processing of the product shall include hydrocracking, or hydroisomerization, or isomerization, or a combination thereof and may include other conventional refinery processes. Final processing of the product shall include fractionation performed to produce a jet fuel blending component consistent with requirements.
ATJ-SKA	alcohol-to-jet synthetic paraffinic kerosene with aromatics (ATJ-SKA) An SKA produced starting from alcohol and composed of the streams of two subprocesses processed through the following steps: A non-aromatic product stream comprising dehydration, oligomerization, hydrogenation, and fractionation, and an aromatic product stream comprising dehydration, aromatization, hydrogenation, and fractionation.	50%	ATJ-SKA synthetic blending components shall be comprised of hydroprocessed synthesized paraffinic kerosene with aromatics wholly derived from any single C2 to C5 alcohol or combination of two or more C2 to C5 alcohols and composed of the streams of two subprocesses processed through the following steps: A non-aromatic product stream comprising dehydration, oligomerization, hydrogenation, and fractionation, and an aromatic product stream comprising dehydration, aromatization, hydrogenation, and fractionation.

Appendix D.4.3.2 Feedstock comparison

In DESTINATION 2050 the biomass availability as presented by Concawe is used to determine the amount of non-synthetic SAF that can be produced. However, the scope of Concawe does not cover all approved feedstocks in Annex IX of the Renewable Energy Directive II. Therefore, the biomass availability for non-synthetic SAF production might be higher. A comparison of the eligible feedstock and included feedstocks is given in Table 70.

Table 70: Comparison of considered feedstocks in the Concawe project and eligible feedstocks for biofuel production as specified in the RED II.

Annex IX	Sub	Description	Concawe
Part A	a	Algae if cultivated on land in ponds or photobioreactors	Yes
Part A	b	Biomass fraction of mixed municipal waste, but not separated household waste subject to recycling targets under point (a) of Article 11(2) of Directive 2008/98/EC	Yes
Part A	c	Biowaste as defined in point (4) of Article 3 of Directive 2008/98/EC from private households subject to separate collection as defined in point (11) of Article 3 of that Directive	Yes
Part A	d	Biomass fraction of industrial waste not fit for use in the food or feed chain, including material from retail and wholesale and the agro-food and fish and aquaculture industry, and excluding feedstocks listed in part B of this Annex	Yes
Part A	e	Straw	Yes
Part A	f	Animal manure and sewage sludge	Yes
Part A	g	Palm oil mill effluent and empty palm fruit bunches	
Part A	h	Tall oil pitch	
Part A	i	Crude glycerine	
Part A	j	Bagasse	
Part A	k	Grape marcs and wine lees	
Part A	l	Nut shells	
Part A	m	Husks	
Part A	n	Cobs cleaned of kernels of corn	
Part A	o	Biomass fraction of wastes and residues from forestry and forest-based industries, namely, bark, branches, pre- commercial thinnings, leaves, needles, tree tops, saw dust, cutter shavings, black liquor, brown liquor, fibre sludge, lignin and tall oil	Yes
Part A	p	Other non-food cellulosic material	Yes
Part A	q	Other ligno-cellulosic material except saw logs and veneer logs	Yes
Part B	a	Used cooking oil	Yes
Part B	b	Animal fats classified as categories 1 and 2 in accordance with Regulation (EC) No 1069/2009	Yes

Appendix D.4.3.3 ICAO LTAG global SAF uptake

Table 71: Model assumptions for global SAF uptake based on F2 from ICAO LTAG.
** Data for 2040 is linearly interpolated between 2035 and 2050 data.*

	2030							**2040 ***							**2050**						
	Global	Share	Intl	GHG red	MFSP	MFSP	Market price	Global	Share	Intl	GHG red	MFSP	MFSP	Market price	Global	Share	Intl	GHG red	MFSP	MFSP	Market price
Units	Mt/ year	%	Mt/ year	%	USD/L	EUR/t	EUR/t	Mt/ year	%	Mt/ year	%	USD/L	EUR/t	EUR/t	Mt/ year	%	Mt/ year	%	USD/L	EUR/t	EUR/t
SAF from biomass and solid/liquid waste	20	3%	7	70%	1.11	1239	1363	135	30%	84	70%	1.1	1228	1351	305	53%	189	70%	1.1	1228	1351
SAF from waste CO_2	0	2%	5	81%	3.01	3360	3696	65	14%	40	83%	1.88	2099	2309	109	19%	68	86%	1.55	1730	1903
SAF total	**20**	**5%**	**12**	**74%**	**1.87**	**2088**	**2296**	**200**	**44%**	**124**	**74%**	**1.35**	**1507**	**1658**	**415**	**72%**	**257**	**74%**	**1.22**	**1362**	**1498**
LCAF	13	3%	8	10%	0.55	614	614	99	22%	62	10%	0.63	703	703	162	28%	101	10%	0.71	793	793
Jet A/A-1	367	92%	224	0%	0.55	614	614	153	34%	95	0%	0.63	703	703	0	0%	0	0%	0.71	793	793
Total aviation fuel demand	**400**	**100%**	**244**	**4%**	**0.61**	**684**	**694**	**453**	**100%**	**280**	**32%**	**1.01**	**1128**	**1123**	**577**	**100%**	**357**	**56%**	**1.08**	**1206**	**1301**

Appendix D.4.3.4 SAF production prices

SAF production prices for HEFA, FT, AtJ and PtL-based SAF are identified via desk research for 2030, 2040 and 2050. The found data is presented in Table 72, data is converted to €/t from data in the original study. Prices are averaged per feedstock category (waste fats, oils and greases = HEFA, advanced biomass = FT and AtJ, and waste gases and CO_2 = PtL). FT and AtJ are taken together, at a 50/50 share, since they can make use of the same feedstocks and have similar prices ranges.

Table 72: SAF production prices for HEFA, FT, AtJ, and PtL-based SAF for 2030, 2040 and 2050. Prices are converted to €/t from original data. Cells in light orange show data points that are linearly interpolated from other data in the considered study

	2030				2040				2050			
Conversion pathway	**HEFA**	**FT**	**AtJ**	**PtL**	**HEFA**	**FT**	**AtJ**	**PtL**	**HEFA**	**FT**	**AtJ**	**PtL**
Source \ Unit	**€/t**	**€/t**	**€/t**	**€/t**	**€/t**	**€/t**	**€/t**	**€/t**	**€/t**	**€/t**	**€/t**	**€/t**
(WEF, 2020)	1,275	1,875	2,100	2,125	1,225	1,750	1,975	1,400	1,225	1,625	1,900	1,225
(McKinsey & Company, 2023)	1,697	2,233		2,099	1,652	1,563		1,563	1,608	1,340		1,228
(LBST, 2023)				2,975				2,625				2,750
(Bain & Company, 2023)	1,734	2,761	1,827	2,374	1,667	2,322	1,652	1,786	1,608	1,965	1,563	1,429
(de Jong, 2018)	1,300	2,877	4,018		1,300	2,055	2,870					
(ICCT, 2019b)									1,232	2,007	2,563	
(EEA, EASA & EUROCONTROL, 2019)									983			
(German Environment Agency, 2016)												1,675
(ICCT, 2022)				3,004				2,569				2,073
(Detsios, et al., 2023)	1,360	2,187	1,840	2,013	1,293	2,067	1,733	1,520	1,253	1,933	1,640	1,320
(McKinsey & Company, 2020)				2,338				1,934				1,530
Average	1,473	2,300		2,418	1,428	1,921		1,914	1,318	1,845		1,654

Appendix D.4.3.5 Market factor

It is observed in the market that the production price of SAF is not the market price of SAF. Table 73 shows the production price of SAF in 2022 and 2023 and the market prices observed in that period by Argus Media and Reuters. Based on this data *market factors* were developed for 2030, 2040 and 2050, to convert production prices to market prices. The market factor for 2050 is the average of a 10% premium, as estimated by the EC, and the 2030 market factor; the market factor for 2040 is the average of 2030 and 2050. All market factors are given in Table 74. Finally, production prices are converted to market prices and rounded to hundreds, see Table 75.

Table 73: Production cost of SAF vs market price of SAF

Production cost		**2022**	**2023**	**Market price**		**2022**	**2023**	**Ratio**
Source	Unit	HEFA	HEFA	Source	Unit	HEFA	HEFA	
McKinsey	€/t	1,876		Argus Media	€/t	3,037		1.78
ICCT	€/t	1,533		Reuters	€/t		2,625	1.47
Bain & Co	€/t		1,786					
Average	€/t	1,704	1,786		€/t	3,037	2,625	1.63

Table 74: Market factors for 2030, 2040 and 2050 to convert production cost of SAF to market price

Year	**Market factor**
2030	1.63
2040	1.49
2050	1.36

Table 75: Market prices of various SAF types for 2030, 2040 and 2050.

		2030			**2040**			**2050**		
Source	Unit	HEFA	FT/AtJ	PtL	HEFA	FT/AtJ	PtL	HEFA	Ft/AtJ	PtL
Production cost (average)	€/t	1,473	2,416	2,418	1,428	2,004	1,914	1,318	1,845	1,654
Market factor		1.63			1.49			1.36		
Market price	€/t	2,395	3,929	3,932	2,133	2,995	2,860	1,796	2,515	2,254
Market price (rounded)	€/t	2,400	3,900	3,900	2,100	3,000	2,900	1,800	2,500	2,300

Appendix D.4.3.6 Hydrogen prices

The same approach is used for hydrogen for hydrogen-powered aircraft. Production prices for hydrogen are available, but it is likely that the market price will remain higher. Additionally, hydrogen needs to be liquified in order to be used in an aircraft, therefore additional costs are included. Table 76 shows production prices of gaseous hydrogen, with liquefaction costs in Table 77, resulting in average liquid hydrogen prices in Table 78.

Subsequently the market factor determined in Appendix D.4.3.5. is used to convert liquid hydrogen production prices to market prices, see Table 79, this is also expressed in price per SAF equivalent (based on energy content) in Table 80.

Table 76: Production cost of gaseous hydrogen for 2030, 2040 and 2050 in €/t H_2

Source	Unit	2030	2040	250
(Aurora Energy Research, 2023)	€/t H_2	4,450		
(PwC, 2024)	€/t H_2			1,250
(Hydrogen Council, 2023)	€/t H_2	2,903		
(van Wijk & Chatzimarkakis, 2020)	€/t H_2	1,500		
(Trinomics, 2020)	€/t H_2	4,750		

Table 77: Hydrogen liquefaction costs in €/t H_2

H_2 to LH_2 correction		2030	2040	2050
(LBST, 2023)	€/t H_2	1,063	1,063	1,063

Table 78: Production cost of liquefied hydrogen for 2030, 2040 and 2050 in €/t LH_2

Source	Unit	2030	2040	2050
(Aurora Energy Research, 2023)	€/t LH_2	5,513		
(PwC, 2024)	€/t LH_2			2,313
(Hydrogen Council, 2023)	€/t LH_2	3,965		
(van Wijk & Chatzimarkakis, 2020)	€/t LH_2	2,563		
(Trinomics, 2020)	€/t LH_2	5,813		
(BCG, 2023)	€/t LH_2	6,109		
(LBST, 2023)	€/t LH_2		5,045	4,909
(Hölzen, 2024)	€/t LH_2			2,233
(McKinsey & Company, 2020)	€/t LH_2		3,050	
(van Wijk & Chatzimarkakis, 2020)	€/t LH_2			1,800
(Blanco Reano, Nijs, Ruf, & Faaij, 2018)	€/t LH_2			4,600
Average	€/t LH_2	4,793	4,048	3,171

Table 79: Market price of liquefied hydrogen for 2030, 2040 and 2050 in €/t LH_2

	Unit	2030	2040	2050
Production cost (average)	€/t LH_2	4,793	4,048	3,171
Market factor		1.63	1.49	1.36
Market price	€/t LH_2	7,792	6,049	4,322
Market price (rounded)	€/t LH_2	7,800	6,000	4,300

Table 80: Market price of liquefied hydrogen for 2030, 2040 and 2050 in €/t SAF_{eq} (energy based)

	Unit	2030	2040	2050
Production cost (average)	€/t SAF_{eq}	1,757	1,484	1,163
Market factor		1.63	1.49	1.36
Market price	€/t SAF_{eq}	2,857	2,218	1,585
Market price (rounded)	€/t SAF_{eq}	2,900	2,200	1,600

Appendix D.5 Overview of non-CO_2 projects

This appendix provides more detailed information about the various completed, ongoing and planned projects investigating the non-CO_2 climate impact of aviation, or contributing to the mitigation thereof, shown in Figure 40 in Section 7.5. Projects are listed in alphabetical order. The information is taken from CORDIS [177], project's and organisations' websites. Provided it is available, the following information is shown for each project:

- Project acronym and name
- Timelines
- Status
- Partners: industry organisations, research institutes and academia
- Objectives
- Key results

NAME	**TIMELINE**	**STATUS**
ACACIA (Advancing the Science for Aviation and ClimAte)	01-01-2020 - 30-06-2023	Completed
PARTNERS – INDUSTRY	**– RESEARCH INSTITUTES**	**– ACADEMIA**
	DLR; CICERO; FZ Jülich; CNRS;	MMU; Uni. Reading; Uni. Wien; ETH; TU Delft; Uni. Leipzig; ZHAW;
OBJECTIVES		
1. improve scientific understanding of impacts with largest uncertainty (in particular, indirect effect of soot and aerosol on clouds); 2. identify needs for measurement campaigns; 3. putting all aviation effects on a common scale will provide an updated climate impact assessment; 4. provide knowledge basis and strategic guidance for future implementation of mitigation options;		
KEY RESULTS		
n/a		

NAME	**TIMELINE**	**STATUS**
AEROPLANE (Advancing mEasures to Reduce aviatiOn imPact on cLimate and enhAnce resilieNce to climate-changE)	01-09-2023 - 28-02-2026	Ongoing
PARTNERS – INDUSTRY	**– RESEARCH INSTITUTES**	**– ACADEMIA**
Deep Blue; Amigo;	Eurocontrol;	Uni. Leipzig;
OBJECTIVES		
1. develop toolset for reducing aviation impact on climate and enhance the sector's resilience to climate change; 2. advance knowledge and operationalize the monitoring on the impact of aviation on climate;		
KEY RESULTS		
n/a		

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[177] https://cordis.europa.eu/

Name	Timeline	Status
ALIGHT (Copenhagen Airport: a Lighthouse for the introduction of sustainable aviation solutions for the future)	01-11-2020 - 31-10-2025	Ongoing

Partners – industry	– research institutes	– academia
Copenhagen Airport; NISA; Rome Airport; Hybrid Greentech Aps; IATA; Centralny Port Komunikacyjny Sp Zoo; Air Bp Limited; Gindroz Bernard; Valstybes Imone Lietuvosoro Uostai; Rsb Roundtable On Sustainable Biomaterials Association; Airbus; Airbus Operations Limited; SAS; Braendstoflageret Kobenhavns Lufthvn Is;	Teknologisk Institut; DLR;	TU Hamburg; Uni. Di Parma;

Objectives
1. demonstrate how an airport can be designed to operate completely without carbon emissions and deliver infrastructure to carbon-neutral aircraft; 2.integration of SAF; 3. implement and demonstrate smart energy in ground equipment and energy supply;

Key results
n/a

Name	Timeline	Status
ALTERNATE (Assessment on alternative aviation fuels development)	01-01-2020 - 31-12-2022	Completed

Partners – industry	– research institutes	– academia
Airbus Operations Limited; Safran Sa; Safran Aerosystems; IATA;	CIMNE; ONERA; IIASA;	Uni. Politecnica de Madrid; Uni. Hasselt;

Objectives
1. identify the possibilities for extensive sustainable fuel use in aviation considering new technical areas and production procedures;

Key results
1. alternative fuel production technologies for SAF have been selected, and overall feedstock-to-fuel pathways determined; 2. fuel database from open literature created;

Name	Timeline	Status
AMDAR (Aircraft Meteorological DAta Relay)	n/a - n/a	Ongoing

Partners – industry	– research institutes	– academia
Various airlines;	WMO;	

Objectives
1. using sensors on aircraft to collect, process, format and transmit meteorological data.; 2. measure humidity in climb/descent phase;

Key results
n/a

Name	Timeline	Status
ATM4E (Air Traffic Management for Environment)	01-05-2016 - 30-04-2018	Completed

Partners – industry	– research institutes	– academia
ENVISA SAS;	DLR;	Uni. Reading; MMU; TU Delft; TUHH;

Objectives
1. establish a multi-dimensional environmental change function (ECF) concept, which includes air quality impact (LAQ for key pollutants) and perceived noise in addition to climate impact; 2. plan flight trajectories which mitigate the environmental impact taking the actual weather situation and ATM constraints into account; 3. evaluate environmentally-optimized routes in a comprehensive climate-chemistry modelling allowing a proof of concept of climate-optimization with daily route analysis; 4. prepare a Roadmap on implementation of climate-optimized trajectory planning in air traffic management;

Key results
1. ECF concept has strong potential for assessing aircraft trajectories and identify climate-optimized routes; 2. 10-20% reduction in climate impact at the expense of additional fuel burn in the order of less than a few percent for the majority of the flights due to avoidance of environmental sensitive regions.; 3. conceptual roadmap with recommendations for industry based on implementation strategy;

Name	Timeline	Status
BeCoM (Better Contrails Mitigation)	01-06-2022 - 31-05-2026	Ongoing

Partners – industry	– research institutes	– academia
Thales; Enviva; ECATS;	Deutscher Wetterdienst; DLR; CNRS;	TU Delft; UVSQ; Uni. Of Birmingham;

Objectives
1. obtaining a larger and higher resolution database of relative humidity and ice supersaturation at cruise levels for assimilation into numerical weather prediction (NWP) models; 2. providing more adequate representation of ice clouds in their supersaturated environment in the NWP models; 3. validation of the predictions to determine and reduce the remaining uncertainties of contrail forecasts;

Key results
n/a

Name	Timeline	Status
Blue Condor (Blue Condor: Measurement of non-CO_2 emissions)	2016 - n/a	Ongoing

Partners – industry	– research institutes	– academia
Airbus UpNext; Perlan Project;	DLR;	

Objectives
1. take a small hydrogen-combustion engine as high as 30,000 feet and compare its emissions to a similar-sized kerosene engine, flying alongside onboard a second aircraft; 2. analyse hydrogen combustion’s impact on contrail properties;

Key results
n/a

Name	Timeline	Status
Boeing EcoDemonstrator	2021 - n/a	Ongoing

Partners – industry	– research institutes	– academia
Boeing;		

Objectives

1. enable aviation’s relentless pursuit to improve efficiency, minimize its environmental footprint and enhance safety; 2. the ecoDemonstrator program takes promising technologies out of laboratories and tests them in an operational environment to solve real-world problems for airlines and passengers, and to help mitigate the climate impact of our industry; 3. Perform emission tests

Key results

n/a

Name	Timeline	Status
Breakthrough Energy pilot studies (Project Contrails)	2021 - n/a	Ongoing

Partners – industry	– research institutes	– academia
American Airlines; Breakthrough Energy Contrails; Google Research;		

Objectives

1. created software that enables airlines to forecast where high-climate-impact contrails may be most likely to form and plan flight routes that avoid them; 2. contrails predictions combine the latest in AI research with massive amounts of satellite imagery, weather data and flight data;

Key results

1. the pilots were able to reduce contrails by 54%. This is the first proof point that commercial flights can verifiably avoid contrails and thereby reduce their climate impact.; 2. flights that attempted to avoid creating contrails burned 2% additional fuel. Recent studies show that a small percentage of flights need to be adjusted to avoid the majority of contrail warming. Therefore, the total fuel impact could be as low as 0.3% across an airline’s flights;

Name	Timeline	Status
CICONIA (Climate effects reduced by Innovative Concept of Operations - Needs and Impacts Assessment)	07/2023 - 06/2026	Ongoing

Partners – industry	– research institutes	– academia
Airbus; Air France SA; DSNA; Boeing; Swiss Airlines; NATS;	Meteo France; Eurocontrol; DLR; NLR; ONERA; FZ Julich;	Uni. Politecnica de Catalunya; ENAC; Univ. of Manchester;

Objectives

1. improve the understanding of non-CO_2 emissions with regards to the current aircraft/engine technologies and operating fleet, as well as their evolution and their climate effects, but with the clear objective to evaluate and develop impact reduction solutions covering several promising mitigation options on flight operations, through the definition of innovative dedicated Concepts of Operations (CONOPS) and their assessment in comparison to legacy operations;

Key results

n/a

NAME	TIMELINE	STATUS
Cirrus H2 (Cirrus H2)	n/a - n/a	Ongoing
PARTNERS – INDUSTRY	**– RESEARCH INSTITUTES**	**– ACADEMIA**
Airbus; Safran; Dassault;	ONERA; DGAC;	
OBJECTIVES		
1. analyse the formation and properties of condensation trails generated by the combustion of hydrogen; 2. explore experimental approaches for in-situ data acquisition used to validate numerical studies;		
KEY RESULTS		
n/a		

NAME	TIMELINE	STATUS
CLAIM (Clean Aviation Support for Impact Monitoring)	2024 - 2026	Ongoing
PARTNERS – INDUSTRY	**– RESEARCH INSTITUTES**	**– ACADEMIA**
	DLR; NLR; ONERA; CIRA;	
OBJECTIVES		
1. Have a broad Literature review to expand the current understanding of Aviation Climate Impact; 2. Discuss on various climate metrics with aviation stakeholders; 3. Discuss on uncertainties & assessment challenges for climate metrics; 4. Identify dependences between different technologies, vehicle concepts and operational measures with climate metrics; 5. Bridge the gap between Climate and Technology Impact Monitoring		
KEY RESULTS		
n/a		

NAME	TIMELINE	STATUS
CLIMAVIATION (Climate Aviation)	2021 - 2026	Ongoing
PARTNERS – INDUSTRY	**– RESEARCH INSTITUTES**	**– ACADEMIA**
	IPSL; ONERA;	Sorbonne University;
OBJECTIVES		
1. better understand and quantify the most uncertain mechanisms of the climate impact of aviation; 2. assess the impacts of new fuels (biofuels, electrofuels, hydrogen); 3. study and propose minimisation strategies based on synergies and/or trade-offs between CO_2 and non-CO_2 effects;		
KEY RESULTS		
n/a		

Name	Timeline	Status
ClimOP (Climate assessment of innovative mitigation strategies towards OPerational improvements in aviation)	01-01-2020 - 30-06-2023	Completed

Partners – industry	– research institutes	– academia
IATA; SEA Milan; Deep Blue; Amigo; SEA;	NLR; DLR;	TU Delft; ITU (Istanbul);

Objectives
1. select operational improvements to reduce the climate impact of aviation; 2. assess the climate impact produced by the selected operational improvements; 3. Evaluate the impact of the operational improvements on aviation stakeholders; 4. Determine a set of harmonized and most-promising mitigation strategies; 5. produce policy recommendations to foster the application of mitigation strategies;

Key results
1. shown that aviation can readily mitigate its climate impact with feasible operational improvements in the short- to midterm: for example, via a) charging climate sensitive areas, b) include non-CO_2 in CORSIA and EU ETS, and c) sustainable taxiing;

Name	Timeline	Status
COMPANION (COMmon Platform and Advanced Instrumentation ReadIness for ultra-efficient propulsion demonstratiON)	01-01-2024 – n/a	Ongoing

Partners – industry	– research institutes	– academia
Airbus; EASN	DLR; ONERA; NLR; DNW	Ecole Centrale de Lyon; INSA Lyon

Objectives
1. driving forward the future of efficient flight propulsion; 2. integration of advanced propulsion systems on an Airbus A380 test platform;

Key results
n/a

Name	Timeline	Status
CONCERTO (dynamicC cOllaboration to geNeralize eCo-friEndly tRajecTOries)	01-07-2023 - 30-06-2026	Ongoing

Partners – industry	– research institutes	– academia
Thales Las France Sas; DSNA; Air France Sa; Enav Spa; Air Support A/S; Thales Avs France Sas; Thales; Ids Airnav Srl; Udaras Eitliochta Na Heireann The Irish Aviation Authority; Naviair; Luftvartsverket; Avinor Flysikring As; Lennuliiklusteeninduse As; Valsts Akciju Sabiedriba Latvijas Gaisa Satiksme; Deep Blue; Icelandair; Ans Finland; NATS; Isavia;	Deutscher Wetterdienst; Eurocontrol; DLR;	TU Delft;

Objectives
1. maximize the opportunities for CO_2 reduction and to introduce non-CO_2 impact management in daily operations; 2. reach TRL6 processes and tools that allow the ecosystem to achieve more eco-friendly trajectories and thus higher climate impact reduction without requiring major changes on legacy ATM and airlines systems;

Key results
n/a

Name	Timeline	Status
CONTRAILS (Comprehensive Observation Network for Trace gases by Airliner)	2005 - n/a	Ongoing
Partners – industry	**– research institutes**	**– academia**
JAMCO Corporation; JAL Foundation; Japan Airlines;	National Institute for Environmental Studies; Japan Meteorological Agency;	
Objectives		
1. clarify the mechanisms of the global carbon cycle using commercial aircraft to monitor greenhouse gases over a wide area and observe any changes;		
Key results		
1. created large datasets for mostly Northern hemisphere on trace gasses in atmosphere;		

Name	Timeline	Status
ContrailNet (Comprehensive Observation Network for Trace gases by Airliner)	2023 - n/a	Ongoing
Partners – industry	**– research institutes**	**– academia**
Airbus; Thales	EUROCONTROL;	
Objectives		
1. network of European research experts to create a common repository of contrail observation data; 2. Make available a common repository of annotated observation data to develop contrail identification and evaluation algorithms		
Key results		
n/a		

Name	Timeline	Status
COOP (Contrail Observation Program)	n/a - n/a	Ongoing
Partners – industry	**– research institutes**	**– academia**
AirFrance; Republique France;	Meteo France;	
Objectives		
1. focus on meteorological model validation (persistence: 10 min);		
Key results		
n/a		

Name	**Timeline**	**Status**
CREATE (Innovative Operations And Climate And Weather Models To Improve Atm Resilience And Reduce Impacts)	01-06-2020 - 30-11-2022	Completed

Partners – industry	**– research institutes**	**– academia**
ARIANET;	ISSNOVA; CIRA; NLR; Ilmatieteen laitos;	Uni. Parthenope; Uni. Politecnica Catalunya;

Objectives
1. achieve innovative procedures in ATM to reduce climate and environmental impact, while becoming more resilient to weather phenomena; 2. study vulnerability of ATM system to weather phenomena; 3. study impact of aviation on the environment both short and long term; 4. study and propose ATM operational changes to improve efficiency of ATM and reduce related environmental impact for both en-route and TMA flight phases, while improving the ATM resilience with respect to weather phenomena; 5. validate proposed ATM operational changes to reduce ATM environmental impact and improve ATM resilience with respect to weather;

Key results
1. CREATE developed programming using trajectory-based operations (TBO) and mapping in four dimensions to deliver a solution; 2. The algorithms CREATE developed allow for real-time adjustments and can be applied to multiple aircraft simultaneously. The optimisation tool reduces environmental impact in the immediate vicinity of airports as well as en route;

Name	**Timeline**	**Status**
DECOR (Demonstrator of eco-responsible trajectory)	n/a - n/a	To start

Partners – industry	**– research institutes**	**– academia**
Thales; Airbus; Air France; ANSP France; and more;		

Objectives
1. simulating and testing at scale, climate-optimized trajectories (including both CO_2 & non-CO_2 effects) with Airlines & ANSP. There is also a dedicated work package to humidity sensors.;

Key results
n/a

Name	**Timeline**	**Status**
D-KULT LUFO VI-2 (Demonstrator climate and environmentally friendly air transport)	n/a - n/a	Ongoing

Partners – industry	**– research institutes**	**– academia**
DFS Deutsche Flugsicherung GmbH; Jeppesen GmbH; PACE GmbH; Lufthansa Technik Deutsche Lufthansa AG; Lufthansa Systems GmbH; Airbus Operations GmbH; European Air Transport Leipzig GmbH (DHL); Federal Association of the German Aviation Industry (BDL);	Eurocontrol; DLR; DWD Deutscher Wetterdienst;	

Objectives
1. provide evidence of the feasibility of eco-efficient flight trajectories, considering non-CO_2 emissions in European and especially in German airspace;

Key results
n/a

Name	**Timeline**	**Status**
ECHOES (Extended Communications in vHF Over Enhanced Satellite segment)	01-03-2022 – 28-02-2025	Ongoing
Partners – industry	**– research institutes**	**– academia**
Startical; Indra Sistemas; Enaire, NAV Portugal ; Mitiga Solutions	DLR;	
Objectives		
1. Performing an environmental impact analysis and a cost-benefit analysis model to quantify the environmental benefits and how the technical performance of the service can be an enabler of disruptive green procedures, such as permanent contrail avoidance or more efficient trajectories		
Key results		
n/a		

Name	**Timeline**	**Status**
ECLIF 1 (Emission and CLimate Impact of alternative Fuel 1)	n/a - 2015	Completed
Partners – industry	**– research institutes**	**– academia**
	NASA; DLR;	
Objectives		
1. evaluate the combustion performance, emission-reduction benefits, and contrail characteristics of alternative jet fuels;		
Key results		
n/a		

Name	**Timeline**	**Status**
ECLIF 3 (Emission and CLimate Impact of alternative Fuel 3)	n/a - n/a	Ongoing
Partners – industry	**– research institutes**	**– academia**
Airbus; Rolls-Royce; Neste;	DLR; NRC Canada	University of Manchester
Objectives		
1. measure emissions of commercial passenger aircraft with 100% SAF on both engines; 2. compare emissions from the use of 100 percent SAF produced with HEFA (hydroprocessed esters and fatty acids) technology against those from conventional aviation fuel and low-sulphur conventional aviation fuel;		
Key results		
1. the research team found SAF releases fewer particulates than conventional kerosene at all tested engine operating conditions, which points to the potential for reduced climate impact and improvement in air quality around airports;		

Name	**Timeline**	**Status**
E-CONTRAIL (Artificial Neural Networks for the Prediction of Contrails and Aviation Induced Cloudiness)	01-06-2023 - 30-11-2025	Ongoing

Partners – industry	**– research institutes**	**– academia**
	BIRA; KMI;	UC3M; KTH;

Objectives
1. conduct a comprehensive study on contrails and aviation-induced cloudiness leveraging state-of-the-art satellite imaginary, exploring their potential impact on the environment; 2. develop an artificial neural network capable of predicting non-CO_2 aviation damage to the environment;

Key results
n/a

Name	**Timeline**	**Status**
EUROCONTROL MUAC Live Trial 2021 (EUROCONTROL MUAC Live Trial 2021)	2021 - 2021	Completed

Partners – industry	**– research institutes**	**– academia**
	DLR; Eurocontrol MUAC;	

Objectives
1. establish and test the procedure that prevents persistent contrails in the MUAC area of responsibility;

Key results
1. ISSR prediction needs improvement; 2. data being processed by DLR and statistical analysis showed that contrails could be avoided;

Name	**Timeline**	**Status**
F4EClim (Flying ATM for Environment Climate)	01-09-2024 - 28-02-2027	Ongoing

Partners – industry	**– research institutes**	**– academia**
	DLR;	TU Delft; UC3M;

Objectives
1. advance aCCFs by integrating weather forecasts and climate science to address uncertainties tied to CO_2, contrails, ozone, methane, and water vapor climate effects; 2. Broaden the scope of aCCFs; 3. explore the development of robust flight planning algorithms to identify eco-efficient aircraft trajectories; 4. Introduction of key performance indicators for stakeholders to implement eco-efficient trajectories

Key results
n/a

Name	Timeline	Status
FASTER-H2 (Fuselage, Rear Fuselage and Empannage with Cabin and Cargo Architecture Solution validation and Technologies for H2 integration)	01-01-2023 - 31-03-2026	Ongoing

Partners – industry	– research institutes	– academia
Airbus Operations; Aernnova Aerospace; Alestis Aerospace; Albany Engineered Composites; Esploro Projects; Fundacion Gaiker; FUNDACION PARA LA INVESTIGACION, DESARROLLO Y APLICACION DE MATERIALES COMPUESTOS; HONEYWELL INTERNATIONAL; Optics11; SOGECLAIR AEROSPACE; Econcore; Acciturri engineering; Leonardo; Airbus Atlantic	DLR; Fraunhofer Gesellschaft zur Förderung der angewandten Forschung; Fundacion centro de tecnologias aeronauticas; INSTITUTO NACIONAL DE TECNICA AEROESPACIAL ESTEBAN TERRADAS; IRT ANTOINE DE SAINT EXUPERY; LGAI TECHNOLOGICAL CENTER; ONERA; NLR; CIRA;	TU Braunschweig; TU Delft; UC3M; TU Hamburg ; DTU; University of Patras

Objectives
1. investigate advanced technologies for designing an integrated fuselage and empennage configuration to reduce production waste and increase material exploitation; 2. New configurations for hydrogen-powered aircraft

Key results
n/a

Name	Timeline	Status
FlyATM4E (Flying Air Traffic Management for the benefit of Environment and climate)	01-06-2020 - 30-11-2022	Completed

Partners – industry	– research institutes	– academia
	DLR;	TU Delft; TU Hamburg; UC3M;

Objectives
1. expand approved climate-assessment methods and optimization of aircraft trajectories in order to identify promising mitigation options suitable to solve the task of reducing overall climate impact of aircraft operation; 2. formulate recommendations how to implement these strategies in meteorological (MET) products and enable not only the understanding of ATM possibilities to reduce aviation's climate impact, but moreover how to implement such eco-efficient routing;

Key results
1. making an open-source library available which combines data from numerical weather forecasts with mathematical algorithms to inform users with a spatial and temporal resolved data product on those regions where aviation emissions have a large climate effect; 2. in a European traffic sample, optimisations show that for a modest increase of about 1% in operating costs, a reduction of climate effects in the order of 20-50% can be achieved by assuring efficient implementation among those flights with the highest mitigation potentials;

Name	Timeline	Status
GLOWOPT (Global-Warming-Optimized Aircraft Design)	01-09-2019 - 31-12-2022	Completed

Partners – industry	– research institutes	– academia
		TU Hamburg; TU Delft;

Objectives

1. provide an overview of the state of the art on the scientific background of the relation between aircraft design and operation and its climate impact; 2. derive characteristic aircraft design requirements, primarily payload and range, based on statistical data analysis of the worldwide aircraft fleet and route structure for future entries into Service using a comprehensive air traffic forecast model; 3. develop climate cost functions for the use in the aircraft design optimisation, which reliably represent the climate impact of CO_2, NOx, H2O emissions, as well as contrail-cirrus effects; 4. perform a Multidisciplinary Design Optimization with respect to the climate cost function to find a set of operational parameters, design parameters and aircraft technologies that minimize the climate impact of the aircraft design using an existing MDO environment that applies the developed CCFs as objective function; 5. perform an assessment of the aircraft designs chosen in order to quantify their impact on important metrics such as landing and take-off noise, emissions and cash operating cost;

Key results

1. by the development of aircraft design-related CFAD, GLOWOPT will support the design of new aircraft with significantly reduced climate impact. The amount of CO_2 and NOx emissions will be reduced by using these CFAD in the MDO process, but more importantly, the operating regime of the aircraft is changed such that the location/altitude of the emissions will be shifted to less climate-sensitive regions; 2. GLOWOPT gives the possibility to address the full suite of climate impacts beyond CO_2 emissions in the CS2 Technology Evaluator (TE). This enables assessments within the TE: First, a climate impact assessment of the emission inventories developed within the TE and second, a climate impact assessment of the technologies;

Name	Timeline	Status
GREAT (Greener Air Traffic Operations)	01-01-2020 - 30-06-2023	Completed

Partners – industry	– research institutes	– academia
CETC avionics; KLM; L-UP SAS; HUNGAROCONTROL; Pildo Consulting; CAAC;	DLR; CIRA; CARERI; Nanjing Research Institute of Electronics Engineering;	Civil Aviation Uni. Of China; Nanjing Uni. Of Aeronautics and Astronautics; Uni. Politecnica Madrid;

Objectives

1. decrease fuel consumption and gas emissions during gate-to-gate flight phases; 2. developing and evaluating an environmentally friendly air traffic management operational concept as well as adapted airspace designs and green trajectory optimisation technologies, and by supporting avionic system;

Key results

1. completion of the modelling of the operational and system architecture of greener ATM, followed by a validation of these created models; 2. development of the environmental impact assessment method for GreAT; 3. prototypes of tools, supporting the implementation of these new working methods are already finished and available;

NAME	TIMELINE	STATUS
Green GEAR (Green operations with Geometric altitude, Advanced separation and Route charging Solutions)	01-09-2023 - 28-02-2026	Ongoing

PARTNERS – INDUSTRY	– RESEARCH INSTITUTES	– ACADEMIA
Airbus; Airbus Operation SAS; NATS;	DLR; Eurocontrol; NLR;	Uni. Trieste; Uni. Westminster;

OBJECTIVES
1. investigate the environmental potential of geometric altimetry enabled by satellite navigation, increasing safety and eliminating waste of airspace by removal of the transition layer and supporting more environmentally friendly climb and descent operations; 2. investigate the potential of environmentally driven route charging, with new mechanisms for charging airspace users to incentivise minimum climate impact; 3. look at the potential for increasing capacity through reduced vertical separations enabled by geometric altimetry;

KEY RESULTS
n/a

NAME	TIMELINE	STATUS
H2OPE (Hydrogen Optimized multi-fuel Propulsion system for clean and silEnt aircraft)	01-02-2023 - 31-01-2027	Ongoing

PARTNERS – INDUSTRY	– RESEARCH INSTITUTES	– ACADEMIA
Ergon Research, HIT09	Bauhaus Luftfahrt	TU Delft, Chalmers; Manchester Metropolitan University

OBJECTIVES
1. HOPE will deliver an integrated aircraft propulsion system comprising two multi-fuel ultra-high bypass ratio (UHBR) turbofan engines, a fuel cell based auxiliary propulsion and power unit (FC-APPU) driving an aft boundary layer ingestion (BLI) propulsor based on tube-wing aircraft configuration

KEY RESULTS
n/a

Name	Timeline	Status
HYDEA (HYdrogen DEmonstrator for Aviation)	01-01-2023 - 31-12-2026	Ongoing

Partners – industry	– research institutes	– academia
GE AVIO; Airbus Operation SAS; Safran Aircraft Engines; GE Deutschland; GE Aerospace Poland; GE Marmara Technology Center; ILT Technologies; Ergon Research; Cosvig; Safran Boosters; PFW Aerospace; JPR; ESPA; Jehier; Safran Aerosystems; Safran Electronics & Defence; Fluid Actuation & Control Toulouse; Sogeclair Aerospace SAS; OMB Saleri; Safran Filtration Systems; Safran Electric & Power; Safran Ventilation System; Senior Aerospace Ermeto SAS; ArianeGroup; Siemens Industry Software;	DLR; CETIM; ONERA;	Uni. Degli studi di Firenze; NaU Kai; TU Delft; ETH Zurich;

Objectives
1. strong and time-effective technology maturation plan to develop an H2 propulsion system to secure an Entry Into Service of a zero-CO_2 low-emission aircraft by 2035; 2. aims to address fundamental questions related to the use of hydrogen as an aviation fuel, also including emission studies and technologies, which will serve as an outlook to future engines;

Key results
n/a

Name	Timeline	Status
IAGOS (In-service Aircraft for a Global Observing System)	01-01-2014 - n/a	Ongoing

Partners – industry	– research institutes	– academia
	FZ Julich; CNRS; Max Planck Institute; Meteo France; DLR; TROPOS; KIT;	Uni. Manchester;

Objectives
1. provide high quality data throughout the troposphere and lower stratosphere, and scientific expertise to understand the evolution of atmospheric composition, air quality, and climate; 2. equipping 15-20 aircraft with the aim of feeding the data centre for the scientific community and operational services; 3. providing important measurements in the vertical which surface stations do not provide, and important information in the climate sensitive upper troposphere and lower stratosphere with a high resolution which satellites cannot acquire;

Key results
1. 10 operating aircraft in fleet; 2. open and available data for research; 3. participating in multiple EU programs;

Name	Timeline	Status
Upcoming ICAO report on non-CO_2 **(2025)** ()	n/a - n/a	To start

Partners – industry	– research institutes	– academia
ICAO;		

Objectives
n/a

Key results
n/a

Name	Timeline	Status
IPCC aerosols + non-CO_2 (Fifth Assessment Report of the Intergovernmental Panel on Climate Change: Chapter 7 Clouds&Aerosols)	n/a - 2013	Completed

Partners – industry	– research institutes	– academia
	IPCC;	

Objectives
1. process understanding and considers observations, theory and models to assess how clouds and aerosols contribute and respond to climate change;

Key results
1. persistent contrails from aviation contribute a RF of +0.01 (+0.005 to +0.03) W m–2 for year 2011, and the combined contrail and contrail-cirrus ERF from aviation is assessed to be +0.05 (+0.02 to +0.15) W m–2.;

Name	Timeline	Status
JETSCREEN (JET Fuel SCREENing and Optimization)	01-06-2017 - 31-10-2020	Completed

Partners – industry	– research institutes	– academia
ARTTIC; Airbus Operations; CERFACS; MTU Aero Engines; Safran SA; Safran Aircraft Engines; Safran Aerosystems; Rolls-Royce;	IFP Energies nouvelles; ONERA;	MMU; Politecnico di Milano; Uni. Of Sheffield;

Objectives
1. develop a screening and optimization platform, which integrates distributed design tools and generic experiments to assess the risks and benefits of alternative fuels, and to optimize alternative fuels for a maximum energy per kilogramme of fuel and a reduction of pollutants emissions;

Key results
1. demonstrate that fuels without aromatics – hydrocarbon compounds added to boost performance – can reduce non-volatile particle emissions by up to 80 %; 2. developed tools that can be used to support the design of fuel-optimized aircraft and jet engines as well as for the rapid screening and assessment of new candidate fuels;

Name	Timeline	Status
LTAG ICAO chapter on ops/non-CO_2 (Report on the Feasibility of a Long-Term Aspirational Goal for international civil aviation CO_2 emission reductions)	2020 - 11-10-2021	Completed

Partners – industry	– research institutes	– academia
ICAO;		

Objectives
1. ISG [Impact Science Group] should examine the literature and summarize the amount of carbon dioxide (aka carbon budget) that can be released into the atmosphere while limiting the increase in global mean temperature to 1.5 and 2 degrees Celsius. These carbon budgets can then be compared against the aviation CO_2 scenarios being developed by LTAG-TG; 2. capture the latest information on the impacts of non-CO_2 aviation emissions such that decision makers understand the relative impact of aviation CO_2 emissions and the non-CO_2 emissions on the climate.;

Key results
1. estimated cumulative net global anthropogenic CO_2 emissions from the start of 2020 to limit global warming to 1.5°C is 400 and 500 Gt CO_2 at 67% and 50% probability, respectively.; 2. for a warming limit of 2°C, the remaining allowed carbon emissions are estimated to be 1150 Gt CO_2 at 67% probability and 1350 Gt CO_2 at 50% probability; 3. the uncertainty in these estimates remain large due to non-CO_2 effects, including unrepresented climate feedbacks, historical warming, and the variations in reductions in non-CO_2 emissions;

Name	**Timeline**	**Status**
MEFKON (Measurement-Based Improvement of Humidity Forecasting for Contrail Prevention)	01-06-2023 - 31-05-2026	Ongoing
Partners – industry	**– research institutes**	**– academia**
WxFUSION	DWD;	University Mainz
Objectives		
1. Assessment of the data quality of different humidity sensing systems at en route height (comparison of measurements to first guess). ; 2. Evaluation of NWV prediction improvements on ISSR due to in situ WVM measurements at en route height. ; 3. Evaluation of predictions against satellite images. ; 4. Development of visual display of climate relevant regions.		
Key results		
n/a		

Name	**Timeline**	**Status**
MINIMAL (Minimum environmental impact ultra-efficient cores for aircraft propulsion)	01-09-2022 - 31-08-2026	Ongoing
Partners – industry	**– research institutes**	**– academia**
GKN Aerospace Sweden; MTU Aero Engines; ARTTIC Innovation; Roll-Royce PLC; Reaction Engines;	Bauhaus Luftfahrt;	Chalmers; TU Delft; Cranfield uni.; Aristotelio Panepistimio Thessalonikis;
Objectives		
1. contribute to a radical transformation in air transport by providing disruptive ultra-efficient and low-emission technologies that will, in combination with the aviation ecosystem, sustainably reduce the climate impact of aviation; 2. introduction of climate optimised new propulsion systems based on composite cycle engine technology;		
Key results		
n/a		

Name	**Timeline**	**Status**
MORE & LESS (MDO and REgulations for Low-boom and Environmentally Sustainable Supersonic aviation)	01-01-2021 - 31-12-2024	Ongoing
Partners – industry	**– research institutes**	**– academia**
BOOM technology; Boeing; Reaction Engines Limited; Envisa Sas;	CIRA; CNRS; DLR; ECATS; Fundacion De La Ingenieria Civil De Galicia; INCAS; Institut Franco-Allemand De Recherches De Saint Louis; Von Karman Institute For Fluid Dynamics;	Politecnico Di Torino; TU Delft; TU Hamburg; Lunds Uni.; Panepistimio Patron;
Objectives		
1. thorough and holistic analysis of the environmental impact of supersonic aviation. MORE&LESS aims at maintaining a high level of citizens' and environmental protection at local, regional and global levels, and supports the consequent establishment of regulations and procedures for the future supersonic aviation through solid technical bases;		
Key results		
n/a		

Name	Timeline	Status
MUAC Real time simulation of contrail prevention 2023 (MUAC Real time simulation of contrail prevention 2023)	2023 - n/a	Ongoing

Partners – industry	– research institutes	– academia
	DLR; Eurocontrol MUAC;	

Objectives
1. build on the results of trials held in 2021 by carrying out more concentrated trials using real-time simulations to set up working procedures and capacity measures;

Key results
n/a

Name	Timeline	Status
ND MAX/ECLIF 2 (NASA/DLR Multidisciplinary Airborne eXperiments/Emission and CLimate Impact of alternative Fuel 2)	n/a - 2018	Completed

Partners – industry	– research institutes	– academia
Aerodyne; Boeing; FAA;	NASA; DLR; NRC; Max Planck Institute;	Uni. Mainz; Uni. Innsbruck; Uni. Oslo; Missouri S&T;

Objectives
n/a

Key results
1. DLR demonstrated that the use of sustainably produced kerosene can reduce carbon dioxide emissions by 40 percent and soot emissions by up to 70 percent; 2. successfully collected emission and contrail data for the DLR A320 ATRA, which initially used conventional Jet A-1 kerosene fuel and then switched to a blend of kerosene and biofuel, flying under contrail-forming and non-contrail-forming conditions;

Name	Timeline	Status
PRE-TRAILS (Predictive Real-time Emission Technologies Reducing Aircraft Induced Lines in the Sky)	n/a	Ongoing

Partners – industry	– research institutes	– academia
GE Research; RTX Technologies Research Center; Boeing; Northrop Grumman System Corporation	Universities Space Research Association	

Objectives
1. Develop a real-time, in-flight prediction system for aircraft-induced cirrus formed from contrails to provide commercial aircraft operators with information on which flights cause long-lived cirrus clouds; 2. Develop a platform for physics-informed forecasting of aircraft-induced cirrus potential up to 10 minutes ahead of time, using a novel on-board lidar sensor for water vapor; 3. Develop a comprehensive approach for mitigating aircraft-induced cirrus by leveraging satellite observations, deep learning, onboard humidity sensors, and numerical weather prediction models; 4. Develop a real-time, cloud-based aviation contrail prediction and observation system that improves airspace operations through new atmospheric data services and ensemble modeling approaches; 5. Develop a contrail prediction and avoidance system that enables flight crew to proactively respond to regions conducive to long-lived cirrus formation minutes before entering the area

Key results
n/a

NAME	TIMELINE	STATUS
REACT4C (Reducing Emissions from Aviation by Changing Trajectories for the benefit of Climate)	01-01-2010 - 30-04-2014	Completed

PARTNERS – INDUSTRY	– RESEARCH INSTITUTES	– ACADEMIA
Airbus Operations SAS; MET Office;	DLR; CICERO; Eurocontrol;	MMU; Uni. Defli Studi Dell'Aquila; Uni. Of Reading;

OBJECTIVES
1. to explore the feasibility of adopting flight altitudes and flight routes that lead to reduced fuel consumption and emissions, and lessen the environmental impact; 2. to estimate the overall global effect of such ATM measures in terms of climate change;

KEY RESULTS
1. performed a feasibility study on climate-optimized flight planning, addressing inefficiencies of air transport with respect to fuel consumption, emissions and overall climate impact; 2. recommendations on future flight planning, such as practical guidelines for the implementation of environmentally friendly flight routing;

NAME	TIMELINE	STATUS
REFMAP (Reducing Environmental Footprint through transformative Multi-scale Aviation Planning)	01-02-2023 - 31-01-2026	Ongoing

PARTNERS – INDUSTRY	– RESEARCH INSTITUTES	– ACADEMIA
Agentfly Technologies; Future Needs Management Consulting; S&T; Droneprep;	Erevnitiko Panepistimiako Institouto Systimaton Epikoinonion Kai Ypologiston;	KTH; TU Delft; UC3M; Uni. Birmingham; Uni. Salford;

OBJECTIVES
1. quantifying the environmental footprints of air mobility for airliners and unmanned aircraft systems at a multi-scale level, where single trajectories and the flow traffic of multiple vehicles are optimised to minimise their environmental impact in a wide range of communities; 2. investigate how the aviation business models will be affected by the availability of environmental data for each type and route of air vehicle; 3. develop an analytics platform that can process environmental and weather data like wind, noise and emissions (both CO_2 and non-CO_2);

KEY RESULTS
n/a

NAME	TIMELINE	STATUS
RMI Roadmap Contrail mitigation (Contrail Mitigation)	2022 - n/a	Ongoing

PARTNERS – INDUSTRY	– RESEARCH INSTITUTES	– ACADEMIA
Breakthrough Energy; Alaska Airlines; American Airlines; Southwest Airlines; United Airlines; Virgin Atlantic; Airbus; Boeing; Flightkeys; Google Research;	RMI;	Imperial College London;

OBJECTIVES
1. sharing and expanding on the latest science on the climate impact of contrails; 2. developing actionable strategies to avoid warming contrails; 3. analyzing the operational and financial challenges of implementing potential solutions; 4. establishing a roadmap for implementation and validation of contrail mitigation tools;

KEY RESULTS
n/a

Name	**Timeline**	**Status**
SENECA ((LTO) noiSe and EmissioNs of supErsoniC Aircraft)	01-01-2021 - 31-12-2024	Ongoing

Partners – industry	**– research institutes**	**– academia**
Rolls-Royce; MTU Aero Engines; AEDS;	DLR; ONERA; NLR; CIRA;	National Aviation University; MMU; Uni. Southampton; Cranfield Uni.;

Objectives
1. developing deepened understanding and detailed modelling for the emissions, the LTO noise, and the global environmental impact of supersonic aircraft;

Key results
n/a

Name	**Timeline**	**Status**
STARGATE (SusTainable AiRports, the Green heArT of Europe)	01-11-2021 - 31-10-2026	Ongoing

Partners – industry	**– research institutes**	**– academia**
Brussels Airport; TO70; Athens Airport; Budapest Airport; Toulouse Airport; Luxmobility; IES R&D; Sopra Steria; Air Cargo Belgium; DHL Aviation; Vlaams-Brabant; Belgisch Laboratorium Van Elektriciteitsindustrie; Skytanking; Quatra; Brussels Airlines; TUI Airlines Belgium; Societe Nationale Des Chemins De Fer Belges; Ypto; Skeyes; Hydrant Refuelling System; Tractebel Engineering; Integrated Environmental Solutions;	Erasmus UPT; VITO; VIL;	Uni. Hasselt;

Objectives
1. develop, test and implement innovative solutions that make the airport ecosystem more sustainable; 2. optimise terminal operations, for example with the deployment of a Terminal Command Centre, and it will cover other cross-cutting aspects like the minimisation of noise and emissions;

Key results
n/a

Name	Timeline	Status
SWITCH (Sustainable Water-Injecting Turbofan Comprising Hybrid-electrics)	01-01-2023 - 31-12-2025	Ongoing

Partners – industry	– research institutes	– academia
MTU Aero Engines; Airbus Operations; Collins Aerospace Ireland; GKN Aerospace Sweden; Fokker ELMO; Pratt & Whitney Rzeszow; Pratt & Whitney; Hamilton Sundstrand Corporation; Goordrich Control Systems; HS Marston Aerospace Limited	DLR	University Thessaloniki; Chalmers; University Stuttgart

Objectives
1. develop future airliner propulsion systems; 2. Develop a sustainable gas turbine propulsion system, specifically the hybrid water enhanced turbofan

Key results
n/a

Name	Timeline	Status
TEAM_PLAY (Tool Suite for Environmental and Economic Aviation Modelling for Policy Analysis)	01-12-2010 - 31-03-2013	Completed

Partners – industry	– research institutes	– academia
Envisa Sas; Aea Technology; Anotec Consulting; Ingenieurburo Janicke Gbr; Cambridge Environmental Research Consultants Ltd; Safran Aircraft Engines; Airbus Operations Sas; Rolls-Royce; Taks B.V; Limitedskies Limited; Ricardo-Aea Ltd;	DLR; NLR; Totalforsvarets Forskningsinstitut Sweden; Institutul National De Cercetare-Dezvoltare Turbomotoare - Comoti;	MMU; The Chancellor Masters And Scholars Of The University Of Cambridge; Ecole Nationale De L Aviation Civile; National Aviation University;

Objectives
1. create a modelling framework to combine and advance European modelling capabilities in order to support the European perspective in the international policy arena; 2. enhance the European modelling capabilities required for policy assessment. These capabilities will be strengthened by creating a common infrastructure allowing for the connection of existing European models (noise, gas emissions, economic and environmental impacts);

Key results
1. researchers successfully harmonised data to enhance modelling capabilities using common interfaces, data formatting guidelines and a central database. As a result, relevant data on aviation and environment can now be used for comparisons and scenario assessments to enable informed short-, medium- and long-term policymaking. A key accomplishment is the interconnectivity achieved between existing stand-alone models and the facility to incorporate other relevant models on a needs basis;

NAME	TIMELINE	STATUS
TULIPS (DemonsTrating lower pollUting soLutions for sustaInable airPorts acrosS Europe)	01-01-2022 - 31-12-2025	Ongoing

PARTNERS – INDUSTRY	– RESEARCH INSTITUTES	– ACADEMIA
Schiphol; Rotterdam Airport; Eindhoven Airport; Cargonaut NL; Schiphol Real Estate; Avinor; Hermes Airports; Catalink; Societa Azionaria Gestione Aeroporto Torino; Wildtriumphs Lda; Egis Villes Et Transports; Egis Concept; Helios Technology Ltd; Egis One 12; Egis Structures Et Environnement; Excess Materials Exchange; KLM; KLM Equipment Services; Mobility Concept; Nobian Industrial Chemicals Bv; Pipistrel Vertical Solutions Doo Podjetje Za Napredne Letalske Resitve; Havenbedrijf Amsterdam N.V.; Skynrg Bv; BAM; Ballard Power Systems Europe As; Ballard Power Systems Inc; DHL Global Forwarding (Netherlands) Bv; Zepp Solutions Bv; D.J. Middelkoop Groep Bv; Bos Logistics Bv; Hycc B.V.;	SINTEF; SINTEF ENERGI; Consorzio Per La Ricerca E La Dimostrazione Sulle Energie Rinnovabili; Fraunhofer Gesellschaft Zur Forderung Der Angewandten Forschung Ev; NLR; TNO; IST-ID;	Politecnico di Torino; MMU; TU Delft; Uni. Antwerpen;

OBJECTIVES
1. accelerate the implementation of innovative and sustainable technologies targeting reduced greenhouse gas emissions at airports; 2. roll out 17 demonstrations of green airport technological, non-technological and social innovations at Amsterdam Airport Schiphol and at the Oslo, Turin and Larnaca airports; 3. measure and quantify the benefits of these technologies and concepts and forecast their impact on EU climate goals;

KEY RESULTS
n/a

NAME	TIMELINE	STATUS
Uplift-CLIM0ART (inflight emission measurement campaign)	2024	Completed

PARTNERS – INDUSTRY	– RESEARCH INSTITUTES	– ACADEMIA
Deutsche Aircraft; Sasol; Pratt&Whitney Canada	DLR;	

OBJECTIVES
1. Investigate the benefits of using 100% zero aromatics Power-to-Liquid proxy fuel (Fischer-Tropsch Synthetic Parrafinic Kerosene, FT-SPK) to reduce climate impact; 2. Measure the emissions of a CS-25 turboprop aircraft in flight with fully synthetic fuels;

KEY RESULTS
1. successful test flight using 100% synthetic zero aromatics fuel on the D328 UpLift flying testbed;

Name	**Timeline**	**Status**
VOLCAN (VOL avec Carburants Alternatifs Nouveaux (Flight with new alternative fuels))	n/a - n/a	Ongoing

Partners – industry	**– research institutes**	**– academia**
Airbus; Safran; Dassault Aviation; French ministry of transport; CORAC;	ONERA; DLR;	

Objectives
1. The VOLCAN evaluations are focused on the emissions of unblended SAF, which – unlike SAF blends that are increasingly being used in aviation today – is not mixed with any conventional aviation fuel;

Key results
n/a

Name	**Timeline**	**Status**
WIMCOT (Where is my condensation trail?)	12-07-2022 - n/a	Ongoing

Partners – industry	**– research institutes**	**– academia**
AirFrance; Republique France;	Meteo France;	

Objectives
1. tool formodeling of persistent contrails risk zones; 2. integrate an optimization chain air traffic to control the impact of environmental aspects of aeronautics;

Key results
n/a

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