



Consolidating and stepping up aviation's climate ambition: a comprehensive definition of a climate neutral air transport system

Bram Peirlings¹, Ligeia Paletti¹

¹ Royal Netherlands Aerospace Centre, Anthony Fokkerweg 2, 1059 CM Amsterdam, the Netherlands

5 *Correspondence to:* Bram Peirlings (bram.peirlings@nlr.nl)

Abstract. To date, commercial aviation contributed approximately 4% of global anthropogenic climate change through the emission of greenhouse gases during flight and operational non-CO₂ climate effects. Over the last few years, numerous aviation-related organisations have set goals to reduce aviation's climate impact. These goals, however, lack alignment, are poorly or ambiguously defined, or are internally inconsistent. This increases uncertainty about what aviation should work
10 towards, how various stakeholders can contribute, and introduces problems with respect to accountability. In order to address this issue, this paper presents a comprehensive definition of a climate neutral air transport system as an "air transport system of which the climate effects of all its greenhouse gases and non-CO₂ effects throughout the entire life cycle of each element of the system is balanced". The proposed definition spans relevant systems and encompasses all life cycle phases. To achieve a climate neutral air transport system by 2050, all life cycle greenhouse gas emissions and non-CO₂ climate effects
15 remaining after in-sector reduction should be neutralised, as should all remaining non-CO₂ climate forcing from emissions prior to 2050. Clarity on governance is furthermore needed, as the goal and associated targets proposed should be adopted globally.

1 Introduction

Commercial aviation contributes to global anthropogenic climate change through CO₂ and non-CO₂ emissions and their
20 resulting climate effects. In 2019, the last year before COVID-19 and the associated reductions in air transport, CO₂ emissions from the combustion of fossil jet fuel (kerosene) totalled approximately 1 GtCO₂ (IEA, 2024). As a share of total 2019 anthropogenic CO₂ emissions, global aviation has been estimated to contribute 2.5% - a share that had been growing and especially increased since the 2010s (Ritchie, 2020). Although this can be argued to be a relatively small share, aviation CO₂ emissions are unequally distributed over the world's population (Ritchie, 2020; Gössling & Humpe, 2020), and various
25 estimates project aviation's share might rise tenfold by mid-century (Cames et al., 2015; Pidcock & Yeo, 2024; Becken & Pant, 2020).

On top of the warming effect of CO₂ emissions, there are the aforementioned non-CO₂ climate effects of aviation. Awareness of non-CO₂ climate effects of aviation has grown notably over the last few years (e.g. EASA, 2020; Lee et al., 2021; Lee et al., 2023), also with policymakers and, increasingly, the general public. These non-CO₂ effects are caused by



30 various gaseous and particulate emissions, which result in changes of the chemical and physical composition of the
atmosphere at higher altitudes. As scientific understanding about non-CO₂ effects of aviation in general is still less detailed
than understanding about CO₂ emissions (Lee et al., 2021; Lee et al., 2023), and there is ongoing scientific debate on the best
metric to express the non-CO₂ contribution in CO₂-equivalents (or, alternatively, express both contributions in terms of a
change in temperature) (e.g. Faleiros et al., 2026; Megill et al., 2024; Meinshausen & Nicholls, 2022), estimates about the
35 exact relevance of the non-CO₂ contributions vary. Most-cited is the finding that in 2018, aviation non-CO₂ effects
accounted for 66% of the total aviation net effective radiative forcing – meaning that the climate impact of non-CO₂
emissions is twice as large as that of CO₂ emissions alone, and that aviation’s total contribution to effective radiative forcing
is three times as large as the contribution of aviation CO₂ alone (Lee et al., 2021). The most recent estimate on the total (i.e.,
CO₂ and non-CO₂ combined) effect of aviation known to the authors quantified it at 4% of total anthropogenic global
40 warming to date (Klöver et al., 2021). Regardless of the exact current share, aviation has to make its contribution towards
solving global warming from a fundamental fairness perspective, as part of all human activities.

In this context, at the 2022 ILA Berlin Air Show, the Advisory Council for Aviation Research and Innovation in Europe
(ACARE) presented its new vision for the future European aviation, titled ‘Fly the Green Deal’ (ACARE, 2022). Among the
goals for 2050 is to achieve climate neutral aviation, thereby adding onto the list of environmental sustainability goals and
45 ambitions set by the aviation industry, and moving beyond targets that were solely focused on CO₂ emissions (Peerlings,
2020; Van der Sman et al, 2021; IATA, 2021; ATAG, 2021; French Presidency of the Council of the European Union,
2022). Among those, the agreement of a Long-Term Aspirational Goal (LTAG) reached by the International Civil Aviation
Organisation (ICAO) Assembly in October 2022, aiming at net zero CO₂ from international aviation from 2050 (ICAO,
2022), can be seen as a global landmark for the aviation sector.

50 However, there are significant differences between all those visions and targets, especially when reading beyond the titles
and headlines. Moreover, differences exist between aviation-specific goals and targets and the visions (and expectations) of
society at large. This is a problem. Aviation is a global sector and the difference in ambitions across various stakeholders’
groups and at European and world-wide levels increase uncertainty on where the sector should be headed. This uncertainty
allows for individual actors in the sector to set-up their own strategies that might seem to align, but at times are actually in
55 conflict with national and international sustainability strategies and targets.

This paper aims to further establish and contribute to that discussion in three ways. First, a number of goals from both
aviation (Sect. 2) and societal and governmental perspectives (Sect. 3) are investigated and detailed. Highlighting differences
and ambiguities yields to the finding that a clear definition of climate neutral aviation is lacking. To address that gap, such a
definition is proposed in Sect. 4. Third and last, recommendations are made towards targets which would fit the new
60 definition, next to a governance model which could enable the aviation sector to not only target but also achieve the goal of a
climate neutral aviation by 2050 (Sect. 5).



2. Climate goals of the aviation sector

Currently, there are two main strategic documents aiming to guide and thereby influence the European aerospace innovation: ACARE's 'Fly the Green Deal' (FTGD) and the Aviation Research and Innovation Strategy (ARIS) driven by Clean
65 Aviation and SESAR Joint Undertakings.

ACARE's FTGD replaced the 2011 publication 'FlightPath 2050' (FP2050) (ACARE, 2011). FP2050 has guided European aviation research during the 2010s, and FTGD has been conceived to do the same for the next decades. As first overarching goal of the vision, FTGD aims to "by 2050, achieve climate neutral aviation" (ACARE, 2022, p. 15). For a definition of climate neutrality, the document points to the European Climate Law adopted in 2021, in which the European Parliament
70 sets "a binding objective to climate neutrality in the Union by 2050" (European Parliament and Council of the European Union, 2021, Art. 1).

ARIS, developed by the Clean Aviation and SESAR Joint Undertakings and published in 2025 (Clean Aviation Joint Undertaking and SESAR Joint Undertaking, 2025), outlines a vision for the future of European aviation from the perspective of the members of these two joint undertakings, public-private partnerships between the European Commission and the
75 European aeronautics industry focused on aircraft development and air traffic management innovation, respectively. Ambitions and targets for European aviation from 2030 to 2050 are also detailed; for the year 2050, the objectives are (p. 9):

- "Net reduction of greenhouse gas (GHG) emissions from aircraft technologies, compared to 2020 state-of-the-art aircraft, depending on the energy source – in particular, an additional 10-15% relative to 2035 aircraft technologies.
 - Net CO₂ reductions of up to 90% when combined with sustainable aviation fuels (SAF), or achieve zero CO₂ emissions in flight through the use of hydrogen."
- 80

Already prior to the release of FTGD, five key European aviation associations – ACI EUROPE (airports), Airlines for Europe (A4E; airlines), Europe's Regional Airlines Association (ERA; regional airlines), Civil Air Navigation Services Organization (CANSO; air navigation service providers) and the European Aeronautics, Space, Defence and Security
85 Industries Association (ASD; manufacturers) – launched the 'DESTINATION 2050' initiative in February 2021 (Van der Sman et al., 2021; DESTINATION 2050, 2021). Whereas FTGD and ARIS are research focused, DESTINATION 2050 can be seen to represent the more operational aviation industry perspective. DESTINATION 2050 sets a goal of net zero CO₂ emissions by 2050 for flights in and departing from the European Union, the United Kingdom and the European Free Trade Association (Iceland, Liechtenstein, Norway and Switzerland). The International Air Transport Association (IATA; airlines)
90 adopted the same net-zero-CO₂-by-2050 goal at global level at their 77th IATA Annual General Meeting in October 2021 (IATA, 2021) and the Air Transport Action Group (ATAG; entire aviation industry) followed suit one day later (ATAG, 2021). In February 2022, some 40 (mainly European) countries and almost 150 industry stakeholder groups – including the DESTINATION 2050 associations – signed the 'Toulouse Declaration', reaffirming their commitment to the decarbonisation

of aviation by 2050 (French Presidency of the Council of the European Union, 2022). Meanwhile, Airlines for America
95 (A4A) as well as ACI World also adopted goals for net zero CO₂ by 2050 (A4A, 2021; ACI, 2021).

The Toulouse Declaration also explicitly called upon partners to agree to a net zero CO₂ Long Term Aspirational Goal
(LTAG) at the next International Civil Aviation Organization (ICAO) assembly, in October 2022 (French Presidency of the
Council of the European Union, 2022). This goal was indeed adopted but, per the scope of the ICAO, only applies to
international aviation and as such excludes domestic flights (ICAO, 2022). In the nature of ICAO's deliberations, it does not
100 attribute specific obligations or commitments in the form of emissions reduction targets to individual States. Instead, it
recognizes that each State's special circumstances and respective capabilities (e.g., the level of development, maturity of
individual aviation markets, sustainable growth of its international aviation, fair transition, and national priorities of air
transport development) will inform the ability of each State to contribute to the LTAG within its own national timeframe.
Each State will contribute to achieving the goal in a socially, economically and environmentally sustainable manner and in
105 accordance with its national circumstances.

In addition to the various groups and organisations just listed, there are numerous other associations, alliances and joint
undertakings. Focussing the discussion on the European continent, almost all individual companies, research organisations
and universities are member of multiple of those associations and alliances. In general, all claim to coherently connect to EU
Green Deal and in large measure to the ACARE's vision. In addition to this, many also have set their own vision regarding
110 climate impact and how that can best be reduced. Unfortunately, those visions and claims are not always aligned. Further
research could help to explain this, but (too) limited understanding of the intricacies of aviation sustainability and climate
impact and fragmented responsibilities seem two major factors contributing to this lack of alignment.

To give just one example, the vision of the Clean Aviation Joint Undertaking (CAJU) is towards climate neutrality in 2050
(Clean Aviation Joint Undertaking, 2024). Though its mission targets a reduction in GHG emissions, its strategic research
115 and innovation agenda (SRIA) only sets quantified targets in terms of net carbon emissions reduction and in relation to
aircraft operation. The importance of including non-CO₂ effects is publicly acknowledged by CAJU as well, but no
quantitative targets are set, given the time difference between the publication of the SRIA and the increased awareness of the
relevance of non-CO₂ effects. Another example would be the ARIS, which proposes "technologies for net zero and absolute
zero emission aircraft" (Clean Aviation Joint Undertaking and SESAR Joint Undertaking, p. 7), but then does not define "net
120 zero" and "absolute zero emission". Although these terms might seem familiar enough to not require to be defined, the ARIS
target quite clearly shows the opposite: its target on "net reduction of GHG emissions" is limited to "aircraft technologies"
and hence excludes changes in fuel, such that the target really seems to be about absolute rather than net GHG emissions.

Additionally, there is the Alliance for Zero Emission Aviation (AZEAA), which has as objective to prepare the entry into
commercial service of hydrogen-powered and electric aircraft (AZEAA, 2021). Whereas battery-electric aircraft indeed have
125 zero in-flight emissions, life cycle impacts seem unaccounted for by this alliance. Similarly, hydrogen-powered aircraft are



indeed without (in-flight) carbon emission, but definitely do emit water vapour and, depending on the propulsion technology, oxides of nitrogen (NO_x).

Focussing on research organisations, the Association of European Research Establishments in Aeronautics (EREA) has not included a formal goal on the climate impact of aviation in its vision study, released in 2021 (EREA, 2021). Nonetheless, as
130 member of ACARE, EREA endorsed ACARE’s FTGD goal of climate neutrality, also in the strategy of the EREA’s Future Sky initiative. Beyond Europe, a spin-off of thirteen research organisations that are members of the International Forum for Aviation Research (IFAR), agreed in 2020 on the Zero Emission Aviation (ZEMA) declaration that stated “the overall goal is to achieve the least possible impact of aviation. That means close to zero emission aviation for the entire product life cycle” (ZEMA, 2020, p. 2). Despite the declaration, no roadmap nor strategy is available on how the signatories of the
135 ZEMA declaration intend to contribute to – let alone fully achieve – this goal.

How individual European research establishments relate back to those overarching goals varies, mainly in line with the climate leadership of individual governments. For example, the vision of the German Aerospace Centre (DLR) seems to be clear from its title “Towards zero-emission aviation”, but the content of the document explains the vision as “research at
140 DLR is paving the way for the air transport system of tomorrow and shaping its transformation to climate-neutral flight” (DLR, 2021, p. 4). “Zero-emission aviation” and “climate-neutral flight”, however, are not the same. As another example, the Royal Netherlands Aerospace Centre (NLR) has “sustainable aerospace” as one of three strategic themes (NLR, 2025), and lists the ambition to make climate neutral aviation possible by 2050. Emphasis is on CO₂ emissions and non-CO₂ effects from a full life cycle perspective, but quantitative targets are not set. At the same time, NLR is also part of the Dutch Roundtable on Sustainable Aviation in which the Dutch aerospace sector in 2020 agreed to reach zero-carbon emission (but
145 not climate neutral) aviation, in this case only by 2070. Moreover, targets differ in the extent to which they allow for (some or all forms of) out-of-sector offsetting (most targets) or do not (e.g. Ministerie van Infrastructuur en Waterstaat, 2020). Lastly, besides the differences and inconsistencies in terms of content, there are differences with respect to the (perceived) priority and commitment: some of the targets set by the various research establishments are closely connected to standing (supra)national policy; others seem to be defined hastily and do not always seem to be a coherent part of an organisation’s
150 strategy.

3. Societal and governmental climate goals

Next to the aviation-specific goals discussed in the previous section, there are the broader societal and governmental targets on reducing environmental impact – global warming especially – that encompass a broader range of industries and (economic) activities. Following the Paris Agreement in 2015, the European Commission in 2019 launched its Green Deal,
155 which was approved in 2020. A key part of it is the European Climate Law, adopted in 2021, which sets a legally binding goal to a climate neutral continent by 2050 (European Parliament and Council of the European Union, 2021). In the context of this paper, the Sustainable and Smart Mobility Strategy of December 2020 is also of relevance (European Commission,



2020). It stipulates the “European Green Deal calls for a 90% reduction in greenhouse gas emissions from transport, in order for the EU to become a climate-neutral economy by 2050” (European Commission, 2020, p. 2).

160 This raises two ambiguities. The first relates to the (possible) discrepancy between the European Climate Law and the Mobility Strategy. If transport GHG have to be reduced by 90% by 2050 while Europe should be a climate neutral continent by that same year, 10% of transport emissions remain unaccounted for. The second is of a more fundamental nature and relates to the definition of climate neutrality. Article 2 of the European Climate Law defines the climate neutrality objective as “Union-wide greenhouse gas emissions and removals regulated in Union law shall be balanced within the Union at the
165 latest by 2050, thus reducing emission to net zero by that date” (European Parliament and Council of the European Union, 2021).

Article 1 of the European Climate Law explicates that the emissions and removals covered by the Climate Law are the ones defined in Regulation (EU) 2018/1999 (European Parliament and Council of the European Union, 2018, Annex V, Part 2): carbon dioxide (CO₂), methane (CH₄), nitrous oxide (N₂O), sulphur hexafluoride (SF₆), nitrogen trifluoride (NF₃),
170 hydrofluorocarbons (HFCs) and perfluorocarbons (PFCs)¹. This list is consistent with the amended Kyoto Protocol (UNFCCC, 1997, 2012), but it is more restrictive than the definition set by the Intergovernmental Panel on Climate Change (IPCC) in its Special Report on 1.5°C Global Warming: “Greenhouse gases are those gaseous constituents of the atmosphere, both natural and anthropogenic, that absorb and emit radiation at specific wavelengths within the spectrum of terrestrial radiation emitted by the Earth’s surface, the atmosphere itself and by clouds” (IPCC, 2018). Other parts of Union
175 legislation are more similar to the IPCC definition. By Art. 1.2(a) of Directive 2009/29/EC (European Parliament and Council of the European Union, 2009), Article 3(c) of Directive 2003/87/EC was for example updated to include in the definition of GHG “other gaseous constituents of the atmosphere, both natural and anthropogenic, that absorb and re-emit infrared radiation” (European Parliament and Council of the European Union, 2009). Neither the European Climate Law nor
180 other Union regulation seem to address the full scope of human activities that is listed in the IPCC definition of climate neutrality, which reads “Concept of a state in which human activities result in no net effect on the climate system. Achieving such a state would require balancing of residual emissions with emission (CO₂) removal as well as accounting for regional or local bio-geophysical effects of human activities that, for example, affect surface albedo or local climate.” (IPCC, 2018).

Besides these higher-level differences, a possibly even more relevant problem in the context of aviation climate effects is that the EU definition of climate neutrality does not capture all relevant (currently known) non-CO₂ climate effects from
185 aviation. By limiting itself to GHG emissions, neither the emission of NO_x at cruise altitude, which interacts with ozone (O₃; warming effect) and methane (CH₄; cooling effect) to have a net-warming effect (Lee et al., 2021), nor the emission of water vapour (H₂O) are included. Even the broader IPCC-definition of GHG emissions seems to exclude warming effects from contrail cirrus (sometimes referred to as aviation-induced cloudiness, AIC), because, even though contrail cirrus starts from water vapour, this water in contrails is in a solid phase – ice – which directly contrasts the definition’s explicit reference to

¹ The EU Emissions Trading Scheme, as it applies to aviation currently, only requires allowances to be surrendered for CO₂ emissions (European Union, 2024), although non-CO₂ effects are included in monitoring and reporting requirements (European Parliament and Council of the European Union, 2023).



190 “gaseous constituents”. Similarly, soot and other (non-gaseous) particulate emissions are excluded from that definition, even
 though, as catalyst for the development of and influence on the climatological effect of contrails (Kärcher, 2018; Voigt et al.,
 2021, Yu et al., 2024; Cantin et al., 2025; Ponsonby et al., 2025), they definitely contribute to the climate impact of aviation
 and need to be addressed in order to achieve the state that the IPCC defines as climate neutrality.

To summarise, Table 1 provides an overview of all the goals mentioned, both from society in general, as well as from the
 195 aviation sector specifically. Whereas all visions target a reduction in (net) emissions, climate impact or environmental
 footprint of aviation, it is stressed that net zero CO₂ is different from climate neutral aviation, which, in turn, is different
 from zero emission aviation.

200 **Table 1: Overview of national, regional (mainly European) and worldwide visions related to reducing the climate impact of society
 in general and aviation specifically by various organisations and entities.**

Organisation	Vision and year	Scope (geographical and life cycle)	Publication
<i>National visions</i>			
Dutch Roundtable on Sustainable Aviation	Zero-carbon aviation by 2070	Flights departing from the Netherlands, in-flight emissions	11/2020
<i>Regional (mainly European) visions</i>			
Sustainable and Smart Mobility Strategy	90% reduction in transport greenhouse gas emissions by 2050	Transport sector	12/2020
DESTINATION 2050: ACI EUROPE, A4E, ERA, ASD, ERA	Net zero CO ₂ by 2050	Flights within and departing EU+ (= EU + UK + EFTA), in-flight only	02/2021, updated 02/2025
A4A	Net zero CO ₂ by 2050	United States, in-flight only	03/2021
European Union	Climate neutrality by 2050	Europe, full life cycle	06/2021
Clean Aviation JU	Towards climate neutral aviation by 2050	Worldwide, but focus on Europe. In-flight only	12/2021 09/2024
ARIS	Net CO ₂ reductions of up to 90% when combined with sustainable aviation fuels (SAF), or achieve zero CO ₂ emissions in flight through the use of hydrogen	Europe, in-flight only.	2025
AZEA	Zero emission aviation	Europe, in-flight emissions, noting need for supporting infrastructure	06/2022
ACARE	Climate neutrality by 2050	Europe, in-flight emissions	06/2022
<i>Worldwide visions</i>			
ZEMA	Zero emission aviation	Entire product life cycle	2020
ACI World	Net zero CO ₂ by 2050	-	06/2021
IATA	Net zero CO ₂ by 2050	Worldwide, in-flight emissions	10/2021
ATAG	Net zero CO ₂ by 2050	Worldwide, in-flight emissions	10/2021
ICAO	Net zero CO ₂ by 2050	Worldwide, international aviation only, in-flight emissions	10/2022



4. Achieve climate neutral aviation without agreeing on what climate neutrality is

The overview provided in the previous two sections yields a number of conclusions. First of all, it makes clear that the aviation sector is facing multiple goals and targets in different geographical regions and across different stakeholders' groups. This is particularly confusing given that many times an individual company or organisation is part of different groups with different goals. It also raises the question on how one organisation could seriously commit to any one goal, when subscribing to multiple (and at times conflicting) goals and related targets. Related to that, there are the topics of (policy) clarity and accountability: vagueness about goals and commitments stands in the way of developing longer-term strategies and limits society from being able to hold organisations to these goals and commitments. The lack of a supervisory or regulatory entity, especially one setting (positive or negative) incentives in case targets are (not) met or enshrining targets into binding regulations, likely contributes to such vagueness – and is hence to be avoided. By stressing the very international nature of aviation (which is, in fact, a valid argument, especially from the European perspective), the aviation industry has successfully manoeuvred itself out of national jurisdictions and regulations into the realm of global bodies – where agreements are typically more difficult to reach.

Second, the review of European policy and legislation highlights inconsistencies and shows a lack of clarity. The combination of these two problems culminates in the situation in which ACARE:

1. on one hand, refers to and aligns its vision with the European objective of climate neutrality as defined in the European Climate Law, which was shown not to include non-CO₂ climate effects; and
2. on the other, sets quantitative targets that do cover (a share of) such non-CO₂ effects.

It hence appears that the future visions and interests of the European society at large (represented by, in this case, the European Climate Law) on the one hand, and the future visions and interests of the (European) aviation sector (collectively united under the ACARE mission) on the other, are not aligned.

A clearer definition is thus needed. In a white paper by Delft University of Technology and NLR (TU Delft & NLR, 2021), the aforementioned IPCC definition of climate neutrality (Sect. 3) was used. Although complete, it is a rather generic definition. To make it more specific to aviation, the following alternative definition is proposed instead:

Climate neutral aviation: "Type of aviation of which the climate impact of all CO₂ and non-CO₂ effects is balanced"

Explicit inclusion of "non-CO₂ effects" addresses the "regional and local bio-geophysical effects [...] that [...] affect surface albedo or local climate" missing from GHG-focused definitions. Furthermore, if climate neutral aviation is achieved, aviation activities (part of the larger group of "human activities" referred to be the IPCC) will "result in no net effect on the climate system". Still, this definition leaves unclarities: first, there is unclarity about scope and system boundaries (the 'breadth' of the definition), as the term 'aviation' tends to be used ambiguously. Second, the proposed definition is not explicit about the temporal scale (the 'depth' of the definition) of climate neutrality. These aspects are addressed next.



4.1 Breath: scope and system boundaries

235 The definition of the term ‘aviation’ can be taken from several sources. As of March 2026, Wikipedia cites: “Aviation is the activities surrounding mechanical flight and the aircraft industry. Aircraft includes fixed-wing and rotary-wing types, morphable wings, wing-less lifting bodies, as well as lighter-than-air craft such as hot air balloons and airships.” The Cambridge dictionary quotes: “The activity of flying aircraft, or of designing, producing, and keeping them in good condition” (March 2026). In the authors’ view, and in line with dictionary definition of ‘aviation’, the system boundaries should encompass the entire life cycle of the aviation system, each element within it, from cradle to grave.

240 However, a closer look at the aviation sector goals mentioned previously shows this definition is not universally accepted. FTGD, for example, has as an overarching goal to achieve “climate neutral aviation” (ACARE, 2022, p. 23), but only sets quantified targets related to in-flight emissions – a narrow perspective limited to the operational part of the life cycle. Contrastingly, the explanatory text to this overarching goal, which refers to a “fully climate neutral air mobility system” (ACARE, 2022, p. 23), seems to take an even wider view than the overarching goal itself. Whichever perspective is the one
245 actually meant, remains unclear. The Toulouse Declaration also speaks of “aviation” but, in line with DESTINATION 2050, seems limited to in-flight emissions, too. The target set in DESTINATION 2050 specifically mentions “flights” and is hence clear. Besides that, only ZEMA targets the full life cycle of aviation, as it explicitly defines “zero emission aviation” as
250 itself as “the European aeronautics industry’s commitment to net zero [CO₂]” and refers to DESTINATION 2050 (AZEA, 2021).

The focus on the operational life cycle phase is often supported by research that has shown how the majority of the climate impact of aviation currently indeed comes from in-flight emissions (Liu et al., 2016; Krieg et al., 2012; Chester & Horvath, 2009; Roosien et al., 2024). Although the outcome of such research is solid and undeniable, , these studies seldomly look
255 beyond in-flight impacts, and hence might not be suitable for concluding that other impacts are not (or less) relevant. Indeed, a more comprehensive and complimentary perspective seems necessary when aiming at climate neutrality over the entire life cycle of aviation.

First of all, the approach by which those emissions are calculated (life cycle assessment or LCA) is a method open to significant variability and uncertainty (Keiser et al., 2023). Though codified in ISO standards (ISO 14040 and 14044), a
260 number of decisions and assumptions necessary for performing an LCA are left to the researcher, and are not currently harmonised– although a guidance document was recently put forward (Kan et al., 2025). This is particularly relevant for the boundaries of the analysis. Current aviation LCAs exclude parts of the life cycle of aircraft and other elements of the aviation system. In addition to this, the availability of relevant and reliable data has been identified as a challenge. As such, it is questionable whether existing assessments of other life cycle phases (could) have been thorough enough to draw
265 conclusions on the (low) contribution of such phases to the total climate impact of aviation. Indeed, the extraction and



production of aerospace and infrastructure materials are proven to have high GHG emissions (global steel production accounts for 8% of manmade CO₂ emissions and aluminium for 3% CO₂, IEA, 2020; IEA, 2023), while CO₂ emissions of carbon fibre production are estimated to be at least an order of magnitude higher than those related to steel production (Tapper et al., 2020). Also, the impact of aviation infrastructures, in terms of embodied carbon, has so far not been consistently accounted for in aviation or air transport system LCA studies (one rare example of including the infrastructures in an aviation LCA is by Roosien et al., 2024). Similarly, the impact of disposal of aviation assets varies substantially, but is not accounted for in current estimates of aviation impact on climate or society. The European research project PAMELA found that up to 90% of aircraft parts could be recycled (European Commission, 2021), meaning the materials recovered from aircraft find application in other sectors – and are downcycled. Commercial scalability of those results has unfortunately never materialised, differently than in the cases of end-of-life road vehicles and e-waste. Also, recyclability is not a solution for a climate neutrality aviation, as generating a one-directional resource stream is incompatible with any climate neutrality goal.

Second, the fact that climate effects of aviation activities other than operating flights are most likely covered under Nationally Determined Contributions agreed in the Paris Agreement (as they take place in specific countries) and/or in other sectoral goals and agreements, could be a reason they are seldomly – if ever – considered in aviation LCAs. That does, however, not make these activities any less part of the aviation sector. Third, the relevance of other life cycle phases is only set to increase if the sector manages to successfully reduce or eliminate (net) in-flight emissions and climate effects. Last, knowledge of the emissions of each life cycle of the aircraft or of other aviation assets is necessary in order to enable decisions makers to evaluate which developments substantially contribute to climate neutrality. In conclusion, all those emissions need to be accounted for when aiming at climate neutral aviation.

To resolve the ambiguity related to the term ‘aviation’ and more explicitly address life cycle emissions from the aircraft as well as supporting and related infrastructure, the term ‘climate neutral air transport system’ is proposed. Aiming at a climate neutral air transport system (ATS) is considered clearer and understood to encompass the entire breadth described in this section. This includes all relevant system elements (such as the aircraft, the airport, air traffic management and fuel or energy supply) and the various life cycle phases (ranging from materials extraction to end of life).

4.2 Depth: temporal scale of climate neutrality

Besides the ‘breadth’ of the system, there is the ‘depth’ of time. One of the complexities of limiting climate change is the fact that the effects of different GHG (or more in general: climate agents or climate forcers) differ in terms of timescale. Contrail cirrus, for example, disappears after a day at most. During this period, it contributes to climate change, but when it is gone, it no longer has an impact. For CO₂, on the other hand, 15 to 40% of an instantaneous emission will remain in the atmosphere for more than a thousand years, 10 to 25% will remain there for about ten thousand years, and the rest will only be (naturally) removed over a period of multiple hundreds of thousands of years (Masson-Delmotte et al., 2023). As long as

CO₂ molecules are in the atmosphere, they contribute to global warming. Given, thus, the fact that aviation emissions continue to contribute to global warming decades after they were produced, stopping to emit does not clean up past emissions.

This timescale-discussion might seem one of semantics, but Brazzola et al. (2022, p. 763) show, these semantics matter. They propose three possible definitions of climate neutral aviation, evaluate aviation's contribution to temperature change in 2100 and subsequently assess the compatibility of these definitions with the 1.5°C Paris-target, defined as an aviation-caused contribution to global warming of at most 0.04°C compared to pre-industrial levels. In all cases, 2050 is used as the onset date of climate neutral aviation. The three definitions proposed by Brazzola et al. are:

1. Bronze: aviation is climate neutral “compared with its contribution” to global warming in 2050. This realises net zero CO₂ emissions from 2050 and stabilizes non-CO₂ aviation forcing at 2050 levels. As it stabilizes non-CO₂ forcing, this definition is already more ambitious than current industry net zero CO₂ targets. Depending on activity growth (expressed through the Shared Socioeconomic Pathway, SSP), this results in 0.07 (SSP1-2.6) to 0.2°C (SSP5-8.5) warming by 2100 – not compatible with the Paris agreement.
2. Silver: aviation is climate neutral “relative to a world on a 1.5°C trajectory”. This offsets all emissions above a 1.5°C-pathway and therefore is, by definition, compatible with the Paris Agreement. It however does not necessarily achieve net zero CO₂ and/or net zero non-CO₂.
3. Gold: aviation is climate neutral “compared with a world without aviation emissions”. This achieves net zero CO₂ and non-CO₂ by 2050, neutralizes historic non-CO₂ effects remaining in 2050 and leads to a Paris-compatible warming contribution of 0.02 to 0.03°C by 2100.

In all definitions, non-CO₂ emissions are – to the extent required by the definition – neutralised by deploying (additional) CO₂ removal. The point in time at which historic effects should be neutralised is not specified; a certain duration of time should be allowed for this, although a longer period could be argued to delay achieving ‘true’ climate neutrality. Furthermore, CO₂ emitted prior to 2050 is left unmitigated. Following that, the present authors want to propose an even more ambitious definition:

4. Platinum: aviation is climate neutral ‘compared with a world in which aviation emissions never existed’. This achieves net zero CO₂ and non-CO₂ by 2050 and neutralizes all historic CO₂ emissions and non-CO₂ effects remaining in 2050. Although not numerically evaluated, aviation's contribution to temperature change in this case should be 0°C, making it compatible with the Paris Agreement.

Table 2 shows how future and historic CO₂ and non-CO₂ emissions and effects are dealt with under each of the definition. An additional ‘net zero CO₂’ scenario is added for reference.

Table 2: Comparison between net zero CO₂ and various definitions of climate neutrality (based on [50]).

Net emissions from 2050	Remaining effects of emissions prior to 2050	Contribution to
-------------------------	--	-----------------



	CO ₂	Non-CO ₂	CO ₂	Non-CO ₂	warming / compatibility with Paris agreement
Net zero CO₂	0				0.09 – 0.35°C
Bronze	0	Stable at 2050 levels			0.07 – 0.2°C
Silver		Compatible with Paris Agreement / 1.5° C warming			0.04°C
Gold	0	0		Neutralised	0.02 – 0.03°C
Platinum	0	0	Neutralised	Neutralised	~ 0°C

330

Requiring compatibility with the Paris Agreement makes the net zero CO₂ and Bronze targets irrelevant. Silver, even though Paris-compatible, could mean going back on (net zero CO₂) commitments already made and is therefore set aside as well. Platinum, which would substantially go beyond the Paris Agreement goals, could be considered a hypothetical climate ideal, but might not get broad support. As such, Gold is identified as most realistically achievable. That pathway stipulates that past emissions indeed have to be dealt with. Even though Gold’s complete neutralisation of non-CO₂ effects that originated prior to 2050 (mainly NO_x, as contrails are short-lived) in that respect might be argued to do more than what is required by the Paris Agreement, complete neglect of these effects is likely to not meet the Paris goals. On the other hand, by not explicitly neutralising remaining effects of CO₂ emissions prior to 2050, it does not guarantee cumulative CO₂ emissions are limited to a socially accepted share of the global carbon budget (NLR, 2024; Shukla et al., 2022; Lamboll et al., 2023; Forster et al., 2025).

335

340

4.3 Refining the definition

Following the further exploration of scope and system boundaries on one hand, and the temporal dimension of climate change on the other, the previously proposed draft definition can be updated. To explicate that ‘climate neutral aviation’, in the view of the authors, requires a ‘climate neutral air transport system’, the definition is adapted to apply to the latter term as follows:

345

Climate neutral air transport system: “Air transport system of which the climate impact of all its GHGs and other non-CO₂ effects throughout the entire life cycle of each element of the system is balanced”

Besides the broadening to ‘air transport system’, ‘GHG effects’ replaces ‘CO₂ effects’, as other GHG also play a role during especially non-flight phases. Non-CO₂ effects are maintained as a separate element, as these effects do not fit the definition of a GHG.

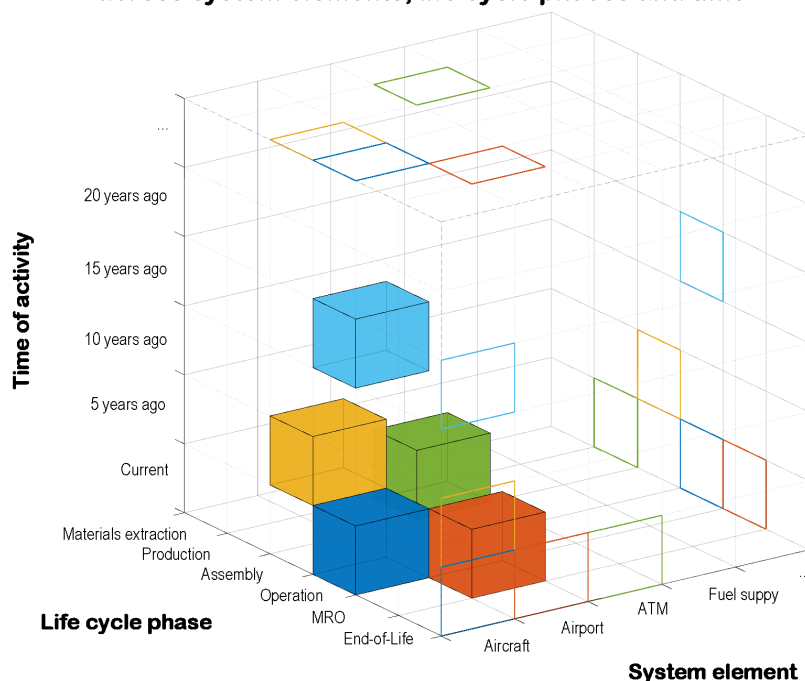
350

Figure 1 presents a graphical version of this definition, stressing that a climate neutral ATS requires climate neutrality across all system elements, life cycle phases and time. In the figure, each of the individual boxes represents a part of the climate impact of the ATS (across system elements, across life cycle phases, and spanning activities across a given period of time). Climate neutrality should be achieved for all these boxes in order to get to a climate neutral ATS. This concerns, for example, the climate impact of aviation operations today (darker blue) and the remaining climate impact of aviation

355

operations 15 years ago (lighter blue), but also the climate impact of maintenance activities to airports today (orange), the climate impact of production of air traffic management (ATM) infrastructure today (green) and the climate impact of aircraft assembly activities 5 years ago (yellow).

A climate neutral air transport system requires climate neutrality across system elements, life cycle phases and time



360

Figure 1: Illustration of ATS elements addressed in the proposed definition of climate neutral aviation

It is important to stress that the proposal made by the authors is a definition, and nothing more. The definition itself does not hold any additional information, regarding whether a climate neutral ATS should even be targeted, or when such a target should be achieved. Similarly, it also does not specify, for example, what (type of) solutions should be acceptable – or desirable, or preferred – means of balancing climate impact. All those considerations are left open to multiple opinions. The opinions of the authors regarding these aspects are discussed in the next section, which applies the definition to outline a path towards a climate neutral ATS, and derives corresponding targets.

365

5. Towards a climate neutral air transport system

Achieving a climate neutral ATS as just defined is not straightforward. This section provides perspectives on three necessary steps: first on governance, second on timelines and geographical scope, and third on (quantitative) targets.

370



5.1 Governance

Individual initiatives cannot solely achieve the climate neutrality goal defined: no single actor or stakeholder can. Nevertheless, the overarching vision must be coherent and consistent across all sector partners, such that all can make their contribution towards that vision. Finally, it should be ensured that all these individual contributions indeed add up to jointly
375 realise the overall goal.

As the goal of climate neutrality is already defined, there is the need for a coordinating, monitoring and steering role – which entity or organisation can indeed take that role is not readily clear. Industrial partners are typically focused on shareholder interests, profitability and shorter-term results. Governments, on the other hand, are at times not involved closely enough with specific topics to set a long-term strategy and develop an associated implementation plan for any sector. Academia is
380 focussed on education and research establishments are also not always sufficiently connected to specific parts of the sector (depending on their specific research focus) and can be heavily influenced by local and national governments. Overall, independent, non-governmental organisations with a research-oriented culture might be most suitable. From the ones discussed in this paper, organisations like ICAO and ACARE come to mind as possible candidates for such a role. The European Union Aviation Safety Agency (EASA) or the European Environmental Agency (EEA) could be alternatives,
385 especially for the monitoring role. If necessary, national or supra-national governments could subsequently take a more enforcing role.

An organisation like ICAO has a substantially larger – global – ‘sphere of influence’, compared to an organisation such as ACARE, which has a more limited (in this case: European) focus. Given the global nature of the ATS, setting goals at a comparable – global – level should be preferred. On the other hand, local initiatives tend to show more ambition and have
390 been able to push technology development (for example, ACARE by informing Clean Sky and Clean Sky 2 programme targets), whereas a large organisation as ICAO has been adopting a more coordinating role (‘following’ the opinions of the members rather the setting the direction). Of course, this is also due to the specific mandate and participants of ICAO (a UN entity), compared to ACARE. Furthermore, although a target monitoring role could fit ICAO, setting ambitious climate targets for aviation might be complicated by the fact that one of the aims of ICAO is to “insure the safe and orderly growth
395 of international civil aviation” (ICAO, 2006, Art. 44.a) – two objectives that might not be (always) compatible with climate neutrality.

At the global level, the United Nations Framework Convention on Climate Change (UNFCCC) might therefore be better suited for this task. The UNFCCC’s Subsidiary Body for Scientific and Technological Advice (SBSTA), for example, is already concerned with emissions from fuel used for international aviation and maintains a working relationship with ICAO
400 (UNFCCC, no date). However, as discussions on that topic could not be concluded in at least the last fourteen SBSTA sessions (UNFCCC, 2025), and as a more refined understanding of the ATS seems beneficial, ACARE overall seems the most suitable organisation to set such a more ambitious goal and perform the necessary monitoring role – at least until the time such ambitions can be adopted at global level.



5.2 Timelines and geographical scope

405 Defining what a climate neutral ATS is helps in target setting, but the latter also requires agreement on timelines and geographical scope. For the former, this paper aligns to the many publications that focus on 2050, in line with the IPCC Special Report on 1.5 °C (IPCC, 2018). Given the international nature of the ATS, the geographical scope of an associated climate neutrality goal should be global as well.

Indeed, this prevents potential waterbed effects (in which climate effects are not reduced, but shifted to other regions) and competitive distortion (SEO & NLR, 2022). Given the previously discussed varying ambition levels around the globe, the authors would feel worldwide agreement on such a goal is unlikely to be reached in a short term. As such, again aligning to ACARE, the remainder of this paper considers an initially feasible scope of a climate neutrality goal to be the European ATS, meaning flights within and departing from European airports, as well as all ground activities related to the operational and all other life cycle phases. Nevertheless, the scope should be increased to a worldwide one as soon as possible.

415 5.3 From goal to targets

In order to measure progress towards achieving a specific goal, more detailed targets are necessary. Furthering the previous section, these targets are developed reasoning back from the year 2050. As a starting point, the quantitative targets from Annex A of FTGD can be used and, for this paper, summarised as follows:

- By 2050, net zero CO₂ emissions has been achieved for all intra-EU flights and those departing the EU;
- 420 • By 2050, new technologies, fuels and operational procedures in service result in:
 - 90% reduction in NO_x emissions and non-volatile particulate matter (nvPM) emissions from all intra-EU flights and those departing the EU relative to the year 2000;
 - 90% reduction in warming contrail cirrus relative to the 2000 baseline. (It is important to remark here that Annex A does not specify a geographical scope on which the targets apply.)

425 A comparison with Table 2 shows achieving the above does not meet the Gold target, as NO_x and nvPM emissions and warming contrail cirrus are reduced by 90% (rather than neutralised completely), and because non-CO₂ effects from emissions prior to 2050 are not addressed. On the other hand, the Gold definition of climate neutrality talks about ‘net’ emissions and effects, whereas for these non-CO₂ effects, FTGD targets gross (in-sector) reductions. This example again stresses the need for detailed targets: requiring neutralisation ‘only’ (as when applying the Gold pathway described by Brazzola et al.) essentially only specifies that the aviation sector is to pay for neutralisation of its emissions, but fails to address who is responsible for realising the emissions reductions and/or negative emissions required to achieve emissions neutrality.

Though recognising that heavy reliance on out-of-sector measures (such as offsetting) is riskier, potentially more expensive (Adler et al., 2023) and could be perceived as unfair (Monios, 2023), no pathway or roadmap has been published (to the knowledge of the authors) that allows aviation to meet net zero CO₂ emission by 2050 (let alone ones in line with

temperature targets set in the Paris Agreement) without at least some out-of-sector measures. As aviation is considered harder (or at least, more costly) to abate (Energy Transitions Committee, 2018), out-of-sector (e.g. carbon removal) action is likely unavoidable (Van der Sman et al., 2021, 2025).

Based on those considerations, the following targets are proposed:

- 440
1. *By 2050, in-sector measures (e.g. new technologies, energy carriers and operational measures) result in a 90% (or larger) reduction in life cycle greenhouse gas emissions and non-CO₂ climate effects (due to, but not limited to, NO_x and non-volatile particulate matter (nvPM) emissions and contrail cirrus) across the European air transport system, relative to the baseline.*
 2. *By 2050, the climate impact of any remaining climate forcing (including life cycle greenhouse gas emissions*
445 *(GHG), NO_x and nvPM emissions, and contrail cirrus) from emissions from 2050 onwards is neutralised.*
 3. *By 2050, the remaining climate impact of non-GHG climate forcing (including NO_x and nvPM emissions and contrail cirrus, excluding CO₂ emissions) from emissions prior to 2050 is neutralised.*

Compared to FTGD, these targets have been clarified and made consistent by changes in a number of areas, thereby also addressing the first of the two ambiguities identified in Sect. 3:

- 450
1. Related to the first target:
 - “Fuels” has been clarified to “energy carriers”, to more clearly put battery-electric alternatives in scope, besides drop-in hydrocarbon alternatives (bio-based or synthetic sustainable aviation fuel, compatible with current aircraft, engines and infrastructure) and non-drop-in gaseous or liquid fuels (mainly: zero-aromatic sustainable aviation fuels and green hydrogen).
 - “Operational procedures” has been widened to “operational measures”, to prevent misinterpretation that only changes in flight procedures (and not in, for example, weight reduction) are considered to contribute to the target.
 - “New technologies, energy carriers and operational measures” has been maintained as an example, but is replaced by the more generic term “in-sector measures”, as there could be other measures within the
455 aviation sector that could contribute to these targets.
 - “Warming contrail cirrus” has been replaced by “contrail cirrus”, as the definition of a climate neutral ATS requires balanced climate impact (different from: no net warming).
 - A “90% reduction” has been changed to a “90% (or larger) reduction” to stimulate further in-sector action.
 - “CO₂” has been broadened to life cycle GHG emissions, in line with the definition of a climate neutral
460 ATS.
 - In-sector reduction targets for GHG, NO_x and nvPM emissions and contrail cirrus have been aligned to 90% (or larger) compared to the baseline in order to ensure in-sector action also in terms of CO₂ reduction.
- 465



- The baseline year 2000 has been removed, as it could be considered to change that to 1990, to better align with Fit for 55 and other targets.

470

- “For all intra-EU flights and those departing the EU” has been expanded to “across the European air transport system”, consistent with the definition of a climate neutral ATS (which spans beyond flights) and the (initial) European focus. The European ATS encompasses all intra-EU flights and those departing the EU.

2. Related to the second target:

475

- A target has been added to neutralise any remaining climate effects from aviation activities in or after the target year. If the first targets are just met, meaning that in-sector measure result in 90% lower climate impact, the second target requires neutralisation of the remaining 10%. This addresses one of the main ambiguities identified, by providing a pragmatic combination of a 90% (or bigger) reduction in the transport sector (as targeted by the Sustainable and Smart Mobility Strategy (European Commission, 2020) and the need to address the remaining 10% (or less).

480

3. Related to the third target

- A target has been added to neutralise any remaining climate effects from aviation activities prior to the target year, per the Gold definition. Given atmospheric lifetimes of NO_x (some 20 years) and contrails (hours to days), current understanding implies that this target comes down to neutralising the climate impact from NO_x emissions between 2030 and 2050.

485

With the proposed definition of climate neutral aviation, clarifying the goal of achieving climate neutral aviation and the detailed targets to get there, the need to refer to the European Climate Law for a definition of climate neutrality is also removed, thereby addressing the second ambiguity identified in Sect. 3. Of course, the updated goal and targets still contribute to the European Climate Law – as would politically be expected.

490

From these targets for 2050, intermediate targets can be derived. Based on the 2030 and 2035 targets set in FTGD, these are shown in Table 3. Appendix A elaborates on differences to the FTGD targets.

Table 3. Intermediate targets towards realising a climate neutral air transport system by 2050.

Year	Target
Today	<ul style="list-style-type: none"> • Confirm one of the current FTGD baseline years (e.g. 2020), or agree to update it in order to better align with e.g. Fit for 55 (using a 1990 baseline). • Quantify baseline levels for all GHG, NO_x and nvPM emissions and contrail cirrus, and other non-CO₂ effects across full life cycle for each part of the ATS. • Agree on criteria related to acceptable means of ‘neutralising’ remaining climate effects. • Explicate the boundaries of “full life cycle”.
2028	<ul style="list-style-type: none"> • Have ready for implementation (i.e., TRL9) mitigation solutions to reduce non-CO₂ climate effects.
2030	<ul style="list-style-type: none"> • Reduce and neutralise remaining full life cycle CO₂ emissions of intra-European flights by 55% compared



	to 1990 levels.
	<ul style="list-style-type: none">• Reduce life cycle GHG emissions and non-CO₂ climate effects by 30% across the ATS, relative to the baseline.• Confirm reduction and neutralisation targets for non-CO₂ climate effects, based on the latest scientific understanding and available mitigation solutions.
2035	<ul style="list-style-type: none">• Reduce life cycle GHG emissions and non-CO₂ climate effects by 40% across the ATS, relative to the baseline.
2040	<ul style="list-style-type: none">• Reduce and neutralise remaining full life cycle CO₂ emissions of intra-European flights by 90% compared to 1990 levels.• Reduce life cycle GHG emissions and non-CO₂ climate effects by 60% across the ATS, relative to the baseline.

6 Next steps

495 The aforementioned improvements towards clarity of definition and scope, and the proposed quantitative targets should help reach a climate neutral ATS by 2050 and, through that, make sure the aviation ecosystem contributes to limit and mitigate dangerous climate change. Besides implementing these targets, two aspects have to be addressed:

- Global scale up. As recalled earlier in this article, European research, collaboration, and advocacy and policy work have previously played an undeniable role in increased global ambition when it comes to aviation CO₂ emissions targets, also at global level. As an increasing body of research shows (Lee et al., 2021; Brazzola et al., 2022), ambition should expand beyond CO₂ emissions. For example, through ACARE, but also through its separate members (industry parties, institutions and States), a further push should be made to align global targets with the state of the science. This effort should pay attention to distribute global efforts in a fair manner, recognising some regions are responsible for a larger part of historical emissions and associated climate effects than others.
- Stimulate and keep track of progress towards the goals, for example through ACARE or – following global adoption of these targets – ICAO.

7 Conclusion

Achieving climate neutrality in all sectors is the only long-term, viable solution to mitigate global warming and associated dangerous climate change. Aviation should embrace such ambition as well, aiming to achieve a fully climate neutral ATS. In such a system, all GHG and non-CO₂ effects throughout the entire life cycle of each element of that system should be balanced. To be compatible with a pathway to 1.5 °C global warming, this should be achieved by 2050. GHG and non-CO₂ effects from aviation activities by 2050 should be neutralised from that date, as well as remaining non-CO₂ climate effects from activity prior to 2050. Through increased understanding (of especially non-CO₂ climate effects, by 2028), the development and implementation of mitigation strategies to tackle climate effects (by 2030) and increasing in-sector action to reduce climate effects, a climate neutral ATS in 2050 could be within reach.

It is recognised that no individual stakeholder can bear responsibility for achieving such a goal, or has the individual influence to realise it. As such, there is a clear need for an organisation to keep track of – and ideally stimulate – progress towards such a goal. Progress should happen ‘bottom-up’, i.e., reasoning from the (quantified) targets, but also ‘top-down’, identifying how various initiatives (e.g. DESTINATION 2050, Clean Aviation, AZEA, ZEMA, and others) contribute to the overarching goal and, more importantly, whether leave key topics unaddressed. Given the European policy focus on achieving climate neutrality, that region is considered most likely to adopt the targets proposed here, in which ACARE seems well-positioned to pick up the aforementioned supervising role. Nevertheless, fitting with the global nature of the air transport industry, this goal and associated targets should be adopted globally.

520

525

The need for a clearly defined vision with equally clear targets aligned with national strategies and especially with research evidence, is of absolute importance if the aviation sector wants to succeed at eliminating the harmful impact of its activities on the climate and society, without losing its beneficial impacts on society and economies. Only then, stakeholders can truly collaborate in realising what is necessary.

Appendix A

530

The intermediate targets related to achieving climate neutral air mobility shown in FTGD – Annex A (ACARE, 2022) are the following:

1. Short term (< 2030):
 - a. By 2030, net CO₂ emissions from all intra-EU flights and those departing the EU are reduced by 55% compared to the 1990 baseline (aligned with Fit for 55).
 - b. By 2030, non-CO₂ climate effects are fully understood, managed, monitored and reduction targets are set in line with the latest scientific understanding and available mitigation solutions.
2. Medium term (< 2035):
 - a. By 2035 new technologies, fuels and operational procedures in service result in a 30% reduction in non-CO₂ climate effects of all intra-EU flights and those departing the EU relative to the 1990 baseline.

535

The intermediate targets proposed in this paper deviate in a number of areas, and for the following reasons:

540

- The FTGD-target of reducing net emissions from all intra-EU flights and those departing the EU by 55% compared to 1990 by 2030 (1.a) is considered unrealistic, given for example the analysis by Van der Sman et al. (2021) and current (especially global) net emissions reduction targets. In Van der Sman et al. (2021) it is shown, however, that the target could be realistic for intra-European flights. The intermediate target proposed here is set in line with that.
- The FTGD-target on understanding on non-CO₂ effects (1.b) is replaced by a target in which mitigation strategies should be ready for implementation, as scientific understanding and the development of mitigation strategies occurs in parallel. The FTGD-target in which “reduction targets are set in line with the latest scientific understanding and

545



available mitigation solutions” is changed to the confirmation of such targets, as these are already proposed (both in FTGD and in this present work).

- The medium-term FTGD-target (2.a) is set to 2030 (rather than “before 2035”), aligning with research on carbon budgets for aviation stipulating the need to act quickly (Brazzola et al., 2022), and brought in line with the 2050-targets proposed here. Related, a medium-term reduction target of 40% is set for 2035.
- A 2025 target is added to quantify the relevant baseline values. For nvPM, for example, it is noted that nvPM mass standards were only introduced in 2020 (EASA, EEA & EUROCONTROL, 2025), with nvPM mass and number standards following in 2023 (EASA, EEA & EUROCONTROL, 2025), such that it might be difficult to establish such a historic baseline. Similarly, NO_x (and also nvPM and previously smoke number) standards, only apply to these emissions during the landing and take-off cycle (LTO-cycle), whereas the baselines should span the entire flight. Given the strong dependency of these emissions on the engine thrust setting, it is uncertain to what extent LTO-values (at or near ground level, per definition) are applicable to cruise flight. Whereas EASA notes (EASA, 2020, p. 11 and Sect. 3.4.3) that “cruise NO_x and LTO emissions are generally considered to be related to LTO emission trends”, these emissions are not measured at cruise thrust settings. nvPM emissions at cruise conditions are “not well characterized” and work on estimating nvPM emissions during cruise based on LTO-data is still ongoing (EASA, 2020, Sect. 3.5.3).
- A 2040 reduction target has been added to span the period between 2035 and 2050, based on the recently announced 2040 climate target (European Commission, 2025). In line with the first item in this list, it is set to apply to intra-European flights only.

Code, data, or code and data availability

Not applicable.

Author contributions

Conceptualization, Bram Peerlings and Ligeia Paletti; Data curation, Bram Peerlings and Ligeia Paletti; Formal analysis, Bram Peerlings and Ligeia Paletti; Investigation, Bram Peerlings and Ligeia Paletti; Methodology, Bram Peerlings and Ligeia Paletti; Resources, Bram Peerlings and Ligeia Paletti; Validation, Bram Peerlings and Ligeia Paletti; Visualization, Bram Peerlings; Writing – original draft, Bram Peerlings and Ligeia Paletti; Writing – review & editing, Bram Peerlings and Ligeia Paletti. All authors have read and agreed to the published version of the manuscript.



Competing interests

575 Ligeia Paletti is a member of the editorial board of Journal of Environmentally Compatible Air Transport System.

Disclaimer

Copernicus Publications remains neutral with regard to jurisdictional claims made in the text, published maps, institutional affiliations, or any other geographical representation in this paper. While Copernicus Publications makes every effort to include appropriate place names, the final responsibility lies with the authors. Views expressed in the text are those of the authors and do not necessarily reflect the views of the publisher.

580

Acknowledgements

While the core of the research presented in this publication had been carried out by Ligeia Paletti while still at NLR Netherlands Aerospace Centre, the author wants to thank her current organisation, DLR German Aerospace Center, and in particular the Institute of Maintenance, Repair and Overhaul, for the support during the finalisation of this publication.

585 Financial support

This research received no external funding.

Review statement

The review statement will be added by Copernicus Publications listing the handling editor as well as all contributing referees according to their status anonymous or identified.

590 References

- A4A: Major U.S. airlines commit to net-zero carbon emissions by 2050, <https://www.airlines.org/news/major-u-s-airlines-commit-to-net-zero-carbon-emissions-by-2050/> (last access: 25 February 2026), 2021.
- ACARE: Flightpath 2050 – Europe's vision for aviation: report of the High Level Group on Aviation Research, <https://transport.ec.europa.eu/system/files/2016-09/flightpath2050.pdf> (last access: 1 March 2026), 2011.
- 595 ACARE: Fly the Green Deal – Europe's vision for sustainable aviation, https://www.acare4europe.org/wp-content/uploads/2022/06/20220815_Fly-the-green-deal_LR-1.pdf (last access: 1 March 2026), 2022.



- ACI: Net zero by 2050: ACI sets global long-term carbon goal for airports, <https://aci.aero/2021/06/08/net-zero-by-2050-aci-sets-global-long-term-carbon-goal-for-airports/> (last access: 22 May 2024), 2021.
- Adler, M., Peerlings, B., Boonekamp, T., van der Sman, E., Lim, M., Jongeling, A., and Pel, S.: The price of net zero: aviation investments towards Destination 2050, SEO Amsterdam Economics, Amsterdam, the Netherlands, 2023.
- Alliance for Zero-Emission Aviation: https://defence-industry-space.ec.europa.eu/eu-aeronautics-industry/alliance-zero-emission-aviation_en (last access: 25 February 2026), 2021.
- ATAG: Commitment to fly net zero, <https://aviationbenefits.org/media/167501/atag-net-zero-2050-declaration.pdf> (last access: 25 February 2026), 2021.
- 600 Becken, S. and Pant, P.: Airline initiatives to reduce climate impact – ways to accelerate action, Griffith University, Australia, <https://amadeus.com/en/resources/white-paper/airline-initiatives-to-reduce-climate-impact> (last access: 13 February 2026), 2020.
- Brazzola, N., Patt, A., and Wohland, J.: Definitions and implications of climate-neutral aviation, *Nat. Clim. Chang.*, 12, 761–767, <https://doi.org/10.1038/s41558-022-01404-7>, 2022.
- 610 Cames, M., Graichen, J., Siemons, A., and Cook, V.: Emission reduction targets for international aviation and shipping, European Parliament, Policy Department A: Economic and Scientific Policy, Brussels, 2015.
- Cantin, S., Chouak, M., and Garnier, F.: Effects of fuel sulfur content and nvPM emissions on contrail formation: a CFD-microphysics study including the role of organic compounds, *J. Aerosol Sci.*, 188, 106612, <https://doi.org/10.1016/j.jaerosci.2025.106612>, 2025.
- 615 Chester, M. V. and Horvath, A.: Environmental assessment of passenger transportation should include infrastructure and supply chains, *Environ. Res. Lett.*, 4, 024008, <https://doi.org/10.1088/1748-9326/4/2/024008>, 2009.
- Clean Aviation Joint Undertaking: Strategic Research and Innovation Agenda, version 2024, <https://clean-aviation.eu/sites/default/files/2024-09/2024-Clean-Aviation-SRIA.pdf> (last access: 1 March 2026), 2024.
- Clean Aviation Joint Undertaking and SESAR Joint Undertaking: Aviation research and innovation strategy: a pathway to competitive and sustainable aviation supporting Europe's sovereignty, <https://aviation-strategy.eu/aris-full-report> (last access: 1 March 2026), 2025.
- 620 DESTINATION 2050: The European aviation sector's climate mission, <https://www.destination2050.eu/commitments/> (last access: 22 May 2024), 2021.
- DLR: Towards zero-emission aviation, <https://www.dlr.de/en/media/publications/brochures/2021/towards-zero-emission-aviation/@@download/file> (last access: 26 February 2026), 2021.
- 625 EASA: Updated analysis of the non-CO2 climate impacts of aviation and potential policy measures pursuant to the EU Emissions Trading System Directive Article 30(4), <https://www.easa.europa.eu/en/document-library/research-reports/report-commission-european-parliament-and-council> (last access: 25 February 2026), 2020.



- EASA, EEA, and EUROCONTROL: European aviation environmental report, European Union Aviation Safety Agency, 630 Cologne, Germany, 2025.
- Energy Transitions Committee: Mission Possible: Reaching net-zero carbon emissions from harder-to-abate sectors, <https://www.energy-transitions.org/publications/mission-possible> (last access: 13 February 2026), 2018.
- EREA: EREA vision study – the future of aviation in 2050, Association of European Research Establishments in Aeronautics, Amsterdam, the Netherlands, 2021.
- 635 European Commission: Process for advanced management of end of life of aircraft, https://webgate.ec.europa.eu/life/publicWebsite/index.cfm?fuseaction=search.dspPage&n_proj_id=2859 (last access: 13 February 2026), 2007.
- European Commission: Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions – sustainable and smart mobility strategy: putting 640 European transport on track for the future, <https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A52020DC0789> (last access: 13 February 2026), 2020.
- European Commission: 2040 climate target, https://climate.ec.europa.eu/eu-action/climate-strategies-targets/2040-climate-target_en (last access: 13 February 2026), 2025.
- European Parliament and Council of the European Union: Directive 2003/87/EC of the European Parliament and of the 645 Council of 13 October 2003 establishing a system for greenhouse gas emission allowance trading within the Union and amending Council Directive 96/61/EC, OJ L 275, 25.10.2003, pp. 32–46: <https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A32003L0087> (last access: 25 February 2026), 2003.
- European Parliament and Council of the European Union: Directive 2009/29/EC of the European Parliament and of the Council of 23 April 2009 amending Directive 2003/87/EC so as to improve and extend the greenhouse gas emission 650 allowance trading scheme of the Community, OJ L 140, 5.6.2009, pp. 63–87, <https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:32009L0029> (last access: 26 February 2026), 2009.
- European Parliament and Council of the European Union: Regulation (EU) 2018/1999 of the European Parliament and of the Council of 11 December 2018 on the Governance of the Energy Union and Climate Action [...], OJ L 328, 21.12.2018, pp. 1–77, <https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32018R1999> (last access: 25 February 2026), 655 2018.
- European Parliament and Council of the European Union: Regulation (EU) 2021/1119 of the European Parliament and of the Council of 30 June 2021 establishing the framework for achieving climate neutrality and amending Regulations (EC) No 401/2009 and (EU) 2018/1999 ('European Climate Law'), OJ L 243, 9.7.2021, pp. 1–17, <https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:32021R1119> (last access: 1 March 2026), 2021.
- 660 European Parliament and Council of the European Union: Directive (EU) 2023/959 of the European Parliament and of the Council of 10 May 2023 amending Directive 2003/87/EC establishing a system for greenhouse gas emission allowance



- trading within the Union and Decision (EU) 2015/1814 concerning the establishment and operation of a market stability reserve for the Union greenhouse gas emission trading system, OJ L 130, 16.5.2023, pp. 134–202, <https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=celex%3A32023L0959> (last access: 12 March 2026), 2023.
- 665 European Union: Consolidated text: Directive 2003/87/EC of the European Parliament and of the Council of 13 October 2003 establishing a system for greenhouse gas emission allowance trading within the Union and amending Council Directive 96/61/EC (consolidated text as of 1 March 2024), <https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A02003L0087-20240301> (last access: 12 March 2026), 2024.
- Faleiros, D. E., Wijn, L., Dietmüller, S., Matthes, S., Marizy, C., and Bergantz, B.: Climate metrics recommendations (CICONIA Deliverable D3.7), in press.
- 670 Forster, P. M., Smith, C., Walsh, T., Lamb, W. F., Lamboll, R., Cassou, C., Hauser, M., Hausfather, Z., Lee, J.-Y., Palmer, M. D., von Schuckmann, K., Slangen, A. B. A., Szopa, S., Trewin, B., Yun, J., Gillett, N. P., Jenkins, S., Matthews, H. D., Raghavan, K., Ribes, A., Rogelj, J., Rosen, D., Zhang, X., Allen, M., Aleluia Reis, L., Andrew, R. M., Betts, R. A., Borger, A., Broersma, J. A., Burgess, S. N., Cheng, L., Friedlingstein, P., Domingues, C. M., Gambarini, M., Gasser, T., Gütschow, J., Ishii, M., Kadow, C., Kennedy, J., Killick, R. E., Krummel, P. B., Liné, A., Monselesan, D. P., Morice, C., Mühle, J., Naik, V., Peters, G. P., Pirani, A., Pongratz, J., Minx, J. C., Rigby, M., Rohde, R., Savita, A., Seneviratne, S. I., Thorne, P., Wells, C., Western, L. M., van der Werf, G. R., Wijffels, S. E., Masson-Delmotte, V., and Zhai, P.: Indicators of Global Climate Change 2024: annual update of key indicators of the state of the climate system and human influence, *Earth Syst. Sci. Data*, 17, 2641–2680, <https://doi.org/10.5194/essd-17-2641-2025>, 2025.
- 680 French Presidency of the Council of the European Union: European aviation summit, <https://web.archive.org/web/20221119041703/https://presidence-francaise.consilium.europa.eu/en/news/european-aviation-summit/> (last access: 19 November 2022), 2022.
- Gössling, S. and Humpe, A.: The global scale, distribution and growth of aviation: implications for climate change, *Glob. Environ. Change*, 65, 102194, <https://doi.org/10.1016/j.gloenvcha.2020.102194>, 2020.
- 685 IATA: Net-zero carbon emissions by 2050, <https://www.iata.org/en/pressroom/pressroom-archive/2021-releases/2021-10-04-03/> (last access: 22 May 2024), 2021.
- ICAO: Convention on International Civil Aviation, Doc. 7300/9, 9th edn., International Civil Aviation Organization, Montreal, Canada, 2006.
- ICAO: States adopt net-zero 2050 global aspirational goal for international flight operations, <https://web.archive.org/web/20250718170900/https://www.icao.int/Newsroom/Pages/States-adopts-netzero-2050-aspirational-goal-for-international-flight-operations.aspx> (last access: 18 July 2025), 2022.
- 690 IEA: Aluminium, <https://www.iea.org/energy-system/industry/aluminium> (last access: 25 February 2026), 2023.
- IEA: Aviation, <https://www.iea.org/energy-system/transport/aviation> (last access: 25 February 2026).



- IEA: Iron and steel technology roadmap: towards more sustainable steelmaking, <https://www.iea.org/reports/iron-and-steel-technology-roadmap> (last access: 25 February 2026), 2020.
- IPCC: Global Warming of 1.5°C. An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty, edited by: Masson-Delmotte, V., Zhai, P., Pörtner, H.-O., Roberts, D., Skea, J., Shukla, P. R., Pirani, A., Moufouma-Okia, W., Péan, C., Pidcock, R., Connors, S., Matthews, J. B. R., Chen, Y., Zhou, X., Gomis, M. I., Lonnoy, E., Maycock, T., Tignor, M., and Waterfield, T., Cambridge University Press, Cambridge, UK and New York, NY, USA, 2018.
- Kan, D. M., Scheers, E., Paletti, L., Rahn, A., Bachman, J., Albano, J., Höller, M., Diniz, S., and Kroos, K.: Life cycle assessment in the air transport system, Royal Netherlands Aerospace Centre and German Aerospace Centre, <https://hdl.handle.net/10921/1792>, 2025.
- Kärcher, B.: Formation and radiative forcing of contrail cirrus, *Nat. Commun.*, 9, 1824, <https://doi.org/10.1038/s41467-018-04068-0>, 2018.
- Keiser, D., Schnoor, L., Pupkes, B., and Freitag, M.: Life cycle assessment in aviation: a systematic literature review of applications, methodological approaches and challenges, *J. Air Transp. Manage.*, 110, 102418, <https://doi.org/10.1016/j.jairtraman.2023.102418>, 2023.
- Klöwer, M., Allen, M. R., Lee, D. S., Proud, S. R., Gallagher, L., and Skowron, A.: Quantifying aviation's contribution to global warming, *Environ. Res. Lett.*, 16, 104027, <https://doi.org/10.1088/1748-9326/ac286e>, 2021.
- Krieg, H., Ilg, R., Brethauer, L., and Loske, F.: Environmental impact assessment of aircraft operation: a key for greening the aviation sector, *J. Aerosp. Sci. Technol. Syst.*, 91, 73–78, 2012.
- Lamboll, R. D., Nicholls, Z. R. J., Smith, C. J., Kikstra, J. S., Byers, E., and Rogelj, J.: Assessing the size and uncertainty of remaining carbon budgets, *Nat. Clim. Chang.*, 13, 1360–1367, <https://doi.org/10.1038/s41558-023-01848-5>, 2023.
- Lee, D. S., Fahey, D. W., Skowron, A., Allen, M. R., Burkhardt, U., Chen, Q., Doherty, S. J., Freeman, S., Forster, P. M., Fuglestvedt, J., Gettelman, A., De León, R. R., Lim, L. L., Lund, M. T., Millar, R. J., Owen, B., Penner, J. E., Pitari, G., Prather, M. J., Sausen, R., and Wilcox, L. J.: The contribution of global aviation to anthropogenic climate forcing for 2000 to 2018, *Atmos. Environ.*, 244, 117834, <https://doi.org/10.1016/j.atmosenv.2020.117834>, 2021.
- Lee, D. S., Allen, M. R., Cumpsty, N., Owen, B., Shine, K. P., and Skowron, A.: Uncertainties in mitigating aviation non-CO₂ emissions for climate and air quality using hydrocarbon fuels, *Environ. Sci.: Atmos.*, 3, 1693–1740, <https://doi.org/10.1039/d3ea00091e>, 2023.
- Liu, H., Xu, Y., Stockwell, N., Rodgers, M., and Guensler, R.: A comparative life cycle energy and emissions analysis for intercity passenger transportation in the U.S. by aviation, intercity bus, and automobile, *Transp. Res. D Trans. Environ.*, 48, 267–283, <https://doi.org/10.1016/j.trd.2016.08.027>, 2016.



- Megill, L., Deck, K., and Grewe, V.: Alternative climate metrics to the Global Warming Potential are more suitable for assessing aviation non-CO₂ effects, *Commun. Earth Environ.*, 5, 249, <https://doi.org/10.1038/s43247-024-01423-6>, 2024.
- Meinshausen, M. and Nicholls, Z.: GWP* is a model, not a metric, *Environ. Res. Lett.*, 17, 041002, <https://doi.org/10.1088/1748-9326/ac5930>, 2022.
- 730 Ministerie van Infrastructuur en Waterstaat: Verantwoord vliegen naar 2050 – Luchtvaartnota 2020–2050, Ministerie van Infrastructuur en Waterstaat/Government of the Netherlands, The Hague, the Netherlands, 2020.
- Monios, J.: The moral limits of market-based mechanisms: an application to the international maritime sector, *J. Bus. Ethics*, 187, 283–299, <https://doi.org/10.1007/s10551-022-05256-1>, 2023.
- NLR: CO₂ reduction targets for Amsterdam Airport Schiphol based on remaining IPCC CO₂ budgets up to 2050, Royal Schiphol Group, Amsterdam, the Netherlands, https://assets.ctfassets.net/biom0eqyyi6b/4HLetoMGTKDE3NTPP51mHe/d3578d6486e44b41c7c9b7e45753473d/CO2_reduction_targets_for_AAS_based_on_remaining_IPCC_CO2_budgets_up_to_2050.pdf 2024.
- NLR: NLR strategic plan: 2026–2029, Royal Netherlands Aerospace Centre, Amsterdam, the Netherlands, https://www.nlr.org/wp-content/uploads/2025/12/NLR-Strategieplan-2026-2029_november_v02_UK.pdf, 2025.
- 740 Peerlings, B.: Terug naar de toekomst: op naar een duurzame luchtvaart, Royal Netherlands Aerospace Centre, <https://www.nlr.org/nl/newsroom/blog/terug-naar-de-toekomst-op-naar-een-duurzame-luchtvaart/> (last access: 14 February 2026), 11 May 2020.
- Pidcock, R. and Yeo, S.: Analysis: aviation could consume a quarter of 1.5C carbon budget by 2050, <https://www.carbonbrief.org/aviation-consume-quarter-carbon-budget> (last access: 13 February 2026), 2016.
- 745 Ponsonby, J., Teoh, R., Kärcher, B., and Stettler, M. E. J.: An updated microphysical model for particle activation in contrails: the role of volatile plume particles, *Atmos. Chem. Phys.*, 25, 18617–18637, <https://doi.org/10.5194/acp-25-18617-2025>, 2025.
- Ritchie, H.: Global inequalities in CO₂ emissions from aviation, <https://ourworldindata.org/breakdown-co2-aviation> (last access: 13 February 2026), 2020.
- 750 Ritchie, H.: What share of global CO₂ emissions come from aviation?, <https://ourworldindata.org/global-aviation-emissions> (last access: 14 February 2026), 2024.
- Roosien, R. J., Lim, M. N. A., Petermeijer, S. M., and Lammen, W. F.: Multi-modal life cycle assessment of journeys by aircraft, train or passenger car, *Aerospace*, 11, 98, <https://doi.org/10.3390/aerospace11010098>, 2024.
- SEO and NLR: Aviation Fit for 55: ticket prices, demand and carbon leakage, SEO Amsterdam Economics, Amsterdam, the Netherlands, 2022.
- Shukla, P. R., Skea, J., Reisinger, A., Slade, R., Fradera, R., Pathak, M., Al Khourdajie, A., Belkacemi, M., van Diemen, R., Hasija, A., Lisboa, G., Luz, S., Malley, J., McCollum, D., Some, S., and Vyas, P.: Summary for policymakers, in: *Climate Change 2022: Mitigation of Climate Change. Contribution of Working Group III to the Sixth Assessment Report of the*



- Intergovernmental Panel on Climate Change, edited by: Shukla, P. R., Skea, J., Slade, R., Al Khourdajie, A., van Diemen, R., McCollum, D., Pathak, M., Some, S., Vyas, P., Fradera, R., Belkacemi, M., Hasija, A., Lisboa, G., Luz, S., and Malley, J., Cambridge University Press, Cambridge, UK and New York, NY, USA, <https://doi.org/10.1017/9781009157926.001>, 2022.
- 760 Tapper, R. J., Longana, M. L., Norton, A., Potter, K. D., and Hamerton, I.: An evaluation of life cycle assessment and its application to the closed-loop recycling of carbon fibre reinforced polymers, *Compos. Part B Eng.*, 184, 107665, 2020.
- 765 <https://doi.org/10.1016/j.compositesb.2019.107665>, 2020.
- TU Delft and NLR: Towards a sustainable air transport system, Delft University of Technology, Delft, the Netherlands, https://filelist.tudelft.nl/News/2021/02_Februari/LR/Whitepaper_NLR_TUDelft.pdf, 2021.
- UNFCCC: Kyoto Protocol to the United Nations Framework Convention on Climate Change, United Nations Framework Convention on Climate Change, Kyoto, Japan, 1997.
- 770 UNFCCC: Doha Amendment to the Kyoto Protocol, United Nations Framework Convention on Climate Change, Doha, Qatar, 2012.
- UNFCCC: Emissions from fuels used for international aviation and maritime transport, <https://unfccc.int/topics/mitigation/workstreams/emissions-from-international-transport-bunker-fuels> (last access: 11 March 2026).
- UNFCCC: Chronological development under the SBSTA ‘bunkers’, United Nations Framework Convention on Climate Change, <https://unfccc.int/documents/201340>, 2025.
- 775 Van der Sman, E. S., Peerlings, B., Kos, J., Lieshout, R., Boonekamp, T.: Destination 2050: A Route To Net Zero European Aviation. Royal Netherlands Aerospace Centre, Amsterdam, the Netherlands, <http://hdl.handle.net/10921/1555>, 2021.
- Van der Sman, E. S., Peerlings, B., Söffing, L. A., Brouwer, R. W. H., Adler, M. W., Jongeling, A., Behrens, C., Kieffer, M.: DESTINATION 2050 - ROADMAP. Royal Netherlands Aerospace Centre, Amsterdam, the Netherlands, <https://hdl.handle.net/10921/1700>, 2025.
- 780 Voigt, C., Kleine, J., Sauer, D., Moore, R. H., Bräuer, T., Le Clercq, P., Kaufmann, S., Scheibe, M., Jurkat-Witschas, T., Aigner, M., Bauder, U., Boose, Y., Borrmann, S., Crosbie, E., Diskin, G. S., DiGangi, J., Hahn, V., Heckl, C., Huber, F., Nowak, J. B., Rapp, M., Rauch, B., Robinson, C., Schripp, T., Shook, M., Winstead, E., Ziemba, L., Schlager, H., and Anderson, B. E.: Cleaner burning aviation fuels can reduce contrail cloudiness, *Commun. Earth Environ.*, 2, 114, 2021.
- 785 <https://doi.org/10.1038/s43247-021-00174-y>, 2021.
- Yu, F., Kärcher, B., and Anderson, B. E.: Revisiting contrail ice formation: impact of primary soot particle sizes and contribution of volatile particles, *Environ. Sci. Technol.*, 58, 17650–17660, <https://doi.org/10.1021/acs.est.4c04340>, 2024.
- ZEMA: Zero Emission Aviation. A statement from aviation research organizations from 13 different countries - the ZEMA Group, <https://www.dlr.de/en/media/publications/miscellaneous/2020/statement-zero-emission-aviation> (last access: 25 February 2026), 2020.
- 790