



UK Aviation and Non-CO₂ Impacts Position Paper



SUSTAINABLE AVIATION

TABLE OF CONTENTS

- 3. Forward
- 4. Executive Summary
- 6. 1. Introduction
 - 6. 1.1 Background
 - 6. 1.2 The shifting global perspectives on aviation non-CO₂ impacts
 - 11. 1.3 Purpose and objectives of this paper
- 12. 2. Overview of non-CO₂ impacts from aviation
 - 12. 2.1 Outline of non-CO₂ impacts and their formation
 - 12. 2.1.1 Contrails and contrail cirrus
 - 14. 2.1.2 Nitrogen Oxides (NO_x)
 - 14. 2.1.3 Water Vapor (H₂O)
 - 15. 2.1.4 Sulphur oxides (SO_x)
 - 15. 2.1.5 Soot and non-volatile Particulate Matter
 - 16. 2.2 Assessing the scale of non-CO₂ impacts
 - 23. 2.3 Conclusions on available evidence on non-CO₂ impacts
- 25. 3. Overview of mitigation opportunities
 - 27. 3.1 Operational mitigation
 - 27. 3.1.1 In-flight avoidance
 - 28. 3.1.2 Lower flight
 - 29. 3.1.3 Daytime flight only
 - 30. 3.2 Aircraft and engine design
 - 30. 3.2.1 Alternative aircraft engine design
 - 31. 3.2.2 Fuel efficiencies
 - 32. 3.3 Alternative Fuels and modifications to existing fuels
 - 32. 3.3.1 Sustainable Aviation Fuel
 - 33. 3.3.2 Hydrogen and electric flight
 - 34. 3.3.3 Modifying existing fuels including aromatic content
- 35. 4. Overview of previous, current and future work being undertaken by Sustainable Aviation members
 - 35. 4.1 Formation and detection of emissions
 - 37. 4.2 Operational mitigation
 - 40. 4.3 Alternative fuels and modifications to existing fuels
 - 43. 4.4 Aircraft and engine design
 - 44. 4.5 Involvement of SA members in other related organisations
- 45. 5. Sustainable Aviation's position on non-CO₂ impacts and recommendations
- 47. 6. Final words.
- 48. Acronyms
- 49. About Sustainable Aviation

Forward

Aviation's climate impact extends beyond carbon dioxide (CO₂). Since the Intergovernmental Panel on Climate Change's 1999 special report first highlighted the role of non-CO₂ emissions, the scientific community has recognised their significance. However, persistent uncertainties in quantifying these effects have meant they remain largely outside the goals and targets applied to CO₂.

Today, however, the evidence is clear: non-CO₂ emissions such as nitrogen oxides, water vapour, aerosols, and contrail formation contribute substantially to aviation's overall climate impact, accounting for a large share of near-term warming.

The Sustainable Aviation Advisory Board welcomes Sustainable Aviation's recognition that there is a growing consensus that these effects matter and that uncertainty must not be a barrier to action. While the precise magnitude of non-CO₂ impacts remains under investigation, the potential scale of their influence demands a pragmatic approach: accelerating research, validation trials, and mitigation strategies. This is not about waiting for perfect knowledge - it is about acting responsibly now, guided by the best available evidence.

Encouragingly, parts of the aviation industry

are already moving forward. Airlines, manufacturers, and air navigation service providers are collaborating with academia and information providers to trial operational measures such as contrail avoidance and optimised flight planning. These trials are generating valuable data on feasibility, trade-offs, and climate benefits. Similarly, advances in sustainable aviation fuels and combustor technologies offer promising co-benefits, reducing soot and NO_x emissions while cutting lifecycle CO₂. These steps, though partial, represent meaningful progress.

Sustainable Aviation is well placed to coordinate and report on these contributions, ensuring that industry efforts complement government policy and international initiatives. We see a clear role for Sustainable Aviation in convening stakeholders, sharing insights, and supporting the development of best practice for assessing and mitigating non-CO₂ impacts.

We urge Sustainable Aviation to champion innovation, invest in research partnerships, and embed non-CO₂ mitigation into their sustainability strategies.

The SA Advisory Board

The Sustainable Aviation Advisory Board works with Sustainable Aviation's Council to provide independent advice and feedback.

Sustainable Aviation is well placed to coordinate and report on these contributions, ensuring that industry efforts complement government policy and international initiatives.



Executive Summary

Sustainable Aviation is the industry body championing aviation's decarbonisation efforts. It is a coalition of UK airlines, airports, aerospace manufacturers, fuel producers and partners all committed to delivering net zero carbon aviation by 2050, and to minimising the aviation sector's noise and air quality impacts.

For more than 20 years, Sustainable Aviation members have worked together to build a more sustainable future for our industry and ensure that aviation can continue to deliver substantial benefits to the UK and its economy.

The impact of non-CO₂ emissions on climate is a key strategic priority for Sustainable Aviation. The greatest challenge for aviation remains the rapid reduction of CO₂ emissions due to their long lifetime and cumulative nature.

However, Sustainable Aviation recognises the growing consensus that aviation's non-CO₂ emissions can also have a significant impact on the climate yet to a degree that remains to be certain. These non-CO₂ emissions include oxides of nitrogen (NO_x), water vapour, particulates including non-volatile particulate matter (nvPM), carbon monoxide, unburned hydrocarbons, soot, oxides of sulphur (SO_x) and the formation of contrails.

In our [2023 Net Zero Carbon Road-Map](#), we set out a commitment to working with the Government and its Jet Zero Taskforce, and stakeholders to conduct further work on this topic.

Using an objective and evidence-based approach, this paper examines the role of non-CO₂ emissions from aviation on climate

change and the current uncertainties around measuring their impact. It also outlines current knowledge on emerging mitigation opportunities and considers how industry is contributing to research, trials on mitigating non-CO₂ emissions and improving scientific understanding of their formation and impact.

As government continues to refine and improve its policy framework, this paper will provide a valuable input.

NO_x and nvPM emissions are currently regulated at a regional and international level for air quality purposes. The International Civil Aviation Organisation (ICAO) developed and will continue to develop best practices, guidance documents and global Standards and Recommended Practices on non-CO₂ emissions and their effects on local air quality and climate.

The monitoring reporting and verification (MRV) of non-CO₂ emissions in cruise flight has begun in the European Union as part of the Emissions Trading Scheme (ETS). This has the aim of increasing scientific understanding. However, while there is regulation for air quality purposes, there are no compliance mechanisms or obligations at a UK or international level that require the reduction or mitigation of the climatic effects of non-CO₂ emissions.

There are uncertainties around the exact scale of climatic impacts from non-CO₂ and the factors affecting their formation and impact. This leads to current uncertainty about how to best mitigate emissions.

It is evident that non-CO₂ emissions have a significant impact on the global climate, with clear agreement across the scientific community that aviation's non-CO₂ emissions are contributing to further climate change. In recognition of the potential scale of non-CO₂ impacts, Sustainable Aviation and its members are committed to supporting the scientific community in advancing understanding and estimating the contribution of non-CO₂ impacts to climate change.

In parallel to this, Sustainable Aviation recognises that a lack of certainty should not prevent industry from accelerating research and validation trials on mitigating impacts in the interim. This will help ensure that future solutions are effective and operationally viable.

For the last few decades, the UK aviation industry has already led and participated in a variety of research projects and trials to advance industry and scientific understanding of non-CO₂ impacts.

This includes the development of potential solutions to manage and mitigate emissions as well as advancing understanding of the formation and detection of emissions.

Sustainable Aviation welcomes the UK Government's commitment to funding research into aviation non-CO₂ emissions and their impacts, including into technologies for supporting detection and mitigation. We believe this is key to ensuring any industry or regulatory action is fully informed.

To deliver these improvements we will need to continue to work closely and collaboratively across all parts of the aviation industry, with other stakeholders such as government and academia, and at an international level. Sustainable Aviation recognises the role it needs to have in providing industry with the platform to do this. We must also work with government and academia to tackle uncertainties and mitigate non-CO₂ emissions.

Sustainable Aviation feel this work should be aligned with four key principles:

1. Working to address scientific uncertainties by improving the collection of live data through observation and improved sensing and in-flight measurement techniques;
2. Maximising CO₂ and non-CO₂ co-benefits, such as through the deployment of targeted Sustainable Aviation Fuel (SAF) use and Advanced Engine Technologies;
3. Exploring mitigation strategies through trials at appropriate scale to test operational and climate impacts; and
4. Engaging with academia and other experts to enable the development of best practice for the assessment of non-CO₂ emissions and impacts.

1. Introduction

1.1 Background

The aviation sector is a known contributor to climate change, producing around 2.5% of all global energy-related CO₂ emissions in 2023¹. In the UK, aviation accounts for 8% of emissions. Through publication of our Sustainable Aviation Net-Zero Carbon Road-Map in 2020, the UK aviation industry was the first in the world to commit to net zero by 2050. Since then, many airlines and governments have committed to the same goal. In developing our Road-Map², Sustainable Aviation evaluated all the levers required to reduce carbon emissions, achieve net zero and accommodate growth in passenger numbers through to 2050. The Road-Map recognised that non-CO₂ emissions from aviation also have an impact on the climate.

These non-CO₂ emissions include oxides of nitrogen (NO_x), water vapour, particulates including non-volatile particulate matter (nvPM), carbon monoxide, unburned hydrocarbons, soot, oxides of sulphur (SO_x) and the formation of contrails. Through the work of our Air Quality Working Group, Sustainable Aviation supports work to reduce non-CO₂ emissions and improve air quality around airports. This included publishing a report on UK aviation and air quality in 2017³. However, this work did not examine the climate-related impacts of non-CO₂ emissions.

In our Road-Map, we highlighted that the impacts of non-CO₂ emissions on the climate were an important and substantial issue that must be addressed alongside CO₂. We also noted that there are uncertainties around the size, nature, duration and permanency of these impacts which makes them challenging to address in the same format as the Road-Map. We nevertheless committed to working with the Government, Jet Zero Taskforce, and others to conduct further work on this topic. Non-CO₂ impacts from aviation are a strategic priority for the Sustainable Aviation coalition.

1.2 The shifting global perspectives on aviation non-CO₂ impacts

NO_x and nvPM emissions are currently regulated at a regional and international level for air quality purposes, such as through the ICAO Local Air Quality Standards and Recommended Practices⁴. In terms of regulation of non-CO₂ emissions and their climatic impacts, while nitrous oxide (N₂O) is included under the Kyoto Protocol⁵ as a greenhouse gas, other non-CO₂ emissions such as other NO_x, SO_x, contrails and soot are not defined as such.

As a result, while there is regulation for air quality purposes, there are no compliance mechanisms or obligations at a UK or international level that require the reduction or mitigation of the climatic effects of non-CO₂ emissions.

1. International Energy Agency (n.d.) Aviation.

2. Sustainable Aviation (2023) Net Zero Carbon Road-Map.

3. Sustainable Aviation (2018) UK Aviation and Air Quality.

4. International Civil Aviation Organisation (2022) Environmental Report 2022, ICAO Standards and Recommended Practices: Annex 16, Volume II.

5. UNFCCC (1997) Kyoto Protocol To The United Nations Framework Convention On Climate Change.

However, the policy landscape is shifting towards recognising that non-CO₂ emissions are a key contributor to climate change. As a result, there is growing support for the monitoring and reporting of non-CO₂ emissions, as well as research and trials to help prevent and mitigate their impact. An example of this is the EU Monitoring, Reporting, and Verification (MRV) for aviation non-CO₂ emissions, which came into effect in January 2025. An overview of the current treatment and perspectives of non-CO₂ by policymakers and industry at a UK, EU and international level is provided below:

UK

In the UK, there is an increasingly clear recognition of the climate impacts of aviation non-CO₂ emissions. In the Climate Change Committee's (CCC) Seventh Carbon Budget⁶, non-CO₂ emissions are estimated in some studies to account for around two-thirds of aviation's total effective radiative forcing globally - and around twice as much as historical CO₂ emissions from aviation. The CCC has called on for the UK to commit to preventing an increase in the non-greenhouse gas warming impacts of aviation after 2050.

It also called on the UK to strengthen the ambition and effectiveness of ICAO objectives and the Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA) on non-CO₂ effects.

In 2022, the UK Government at the time published its Jet Zero Strategy⁷, which recognised the need to address non-CO₂ impacts and increase understanding of their scale. As part of the Strategy, five delivery plan policies were outlined:

- Continue to work with the scientific community and industry, including through the Jet Zero Council SAF Delivery Group⁸ to increase our understanding and evidence of the non-CO₂ impacts of using SAF blend flights;
- Work closely with atmospheric scientists, other researchers, industry and internationally to better understand the science and potential mitigations of non-CO₂ impacts from aviation;
- Consider the scientific and practical underpinning work needed to determine at what point contrail avoidance trials in the UK may be beneficial;
- Exploring whether and how non-CO₂ impacts could be included in the scope of the UK ETS; and
- Work with the CCC to explore its recommendation for no additional non-CO₂ warming from aviation after 2050 and to develop a methodology to monitor the non-CO₂ impacts from aviation on a regular basis.

6. Climate Change Committee (2025) The Seventh Carbon Budget.

7. Department for Transport (2022) Jet Zero Strategy.

8. NB: this group was established under the previous Government's Jet Zero Council, which has effectively been replaced by the Jet Zero Taskforce (and its associated SAF Task and Finish Group) created by the current UK Government in 2025.

9. International Civil Aviation Organisation (2022) Environmental Report 2022, ICAO Standards and Recommended Practices: Annex 16, Volume II.

In line with these commitments, the UK Government committed to supporting the advancement of research and collaboration between industry and academia. This includes the commissioning of a Task & Finish Group on contrail avoidance as part of the Jet Zero Taskforce. The aims of the group include mapping all avoidance trials globally and designing and planning a UK-led contrail mitigation trial. It also aims to provide recommendations on a UK Monitoring, Reporting and Verification scheme and humidity sensor development. Outputs are expected in Q1 2026.

The Department for Transport also launched a multi-year non-CO₂ research programme in partnership with the Natural Environment Research Council, Department for Business and Trade and the Aerospace Technology Institute (ATI) in 2023. It aims to further scientific understanding on non-CO₂ impacts as well as potential technologies and solutions for addressing non-CO₂ impacts. ATI's Non-CO₂ Technologies Roadmap⁹ has been used to address the call for technological solutions from industry. Alongside this, the Department for Transport commissioned two research projects in the same year. One focused on a literature review of existing research on aviation's non-CO₂ impacts, which was published in 2025¹⁰. The second was an evaluation of methodologies for measuring aviation's non-CO₂ impacts, and an investigation of the impact of reducing the aromatic content of kerosene on contrail formation¹¹.

EU

The EU has advanced policy within this area through the introduction of a non-CO₂ MRV scheme as part of the EU Emissions Trading System (ETS) in 2025. This reporting requirement is mandatory for all routes from an aerodrome located in the European Economic Area (EEA) departing to another EEA country, Switzerland or the UK. For flights to non-EEA airports, there is a deferral of two years for the mandatory monitoring and reporting requirement.

Sustainable Aviation notes that this EU MRV takes reported non-CO₂ emissions and converts them directly into an assessment of climate impact for a given flight. This process has two important steps, both of which require modelling.

The first is to convert input data on trajectory, aircraft, and engine type and other operational parameters (some of which may have to be assumptions, even at this stage). This collected data is then used to produce an estimate of the non-CO₂ emissions for a given flight, interpolating and extrapolating from things like certified engine landing and take-off cycle (LTO) performance to give the cruise emissions. We support this part of the approach, knowing that whilst work is ongoing to refine the interpolation and extrapolation models required, the input data and subsequent emissions assessment should provide a very valuable database for ongoing scientific study. We would support a UK MRV that attempts to do the same.

9. Aerospace Technology Institute (2024) non-CO₂ Technologies Roadmap Report.

10. KPMG (2025) Literature review of aviation's non-CO₂ climate impacts and evaluation of existing metrics.

11. Pourkashanian et al. (2025) Investigating the Impact of Reducing the Aromatic Content of Kerosene.

The second step in the EU MRV is it must apply a further model, supplied by an external contractor, to convert these assessed flight emissions into an assessment of climate impact. As is well described in other parts of this document, this second step is still very much subject to scientific investigation, with the current provided models by the European Commission, called the Non-CO₂ Aviation Effects Tracking System or “NEATS”, under revision at this time. Sustainable Aviation believes that it is too soon for a UK-MRV to incorporate the equivalent of this second step.

There are a number of concerns which have been raised to the European Commission in relation to the EU MRV. Some airlines have concerns which they raised through International Air Transport Association (IATA)¹² that the methodology proposed by the EU Commission is insufficiently mature to measure non-CO₂ emissions accurately, or to help address their mitigation effectively. A preferred approach would be to initiate the process as an experimental and data-gathering phase in support of evidence-based learning upon which to build an effective MRV for non-CO₂ emissions. Other airlines and industry members have concerns over the limited geographic scope of the MRV and have identified the need for a flexible framework that can be improved with the integration of the latest available science¹³.

The EU has also funded several projects including ‘Climate effects reduced by Innovative Concept of Operations - Needs and Impacts Assessment’ (CICONIA). This seeks to enhance understanding of non-CO₂ emissions, their evolution and climate effects while finding ways to reduce the impacts of non-CO₂ mitigation on flight operations. The European Aviation Safety Agency (EASA) has also become increasingly focussed on non-CO₂ emissions. In 2020, EASA produced an analysis for the European Commission for potential policy measures via the EU ETS¹⁴. Six options were recommended to be considered in greater detail, including:

- A NO_x charge;
- The inclusion of aircraft NO_x emissions in the EU-ETS;
- A reduction in maximum limit of aromatics within fuel specifications to address soot particulates and contrail-cirrus;
- Mandatory use of SAF to address soot particulates and contrail-cirrus;
- Avoidance of ice-supersaturated areas in Air Traffic Movements (ATMs) to address contrail-cirrus; and
- A climate charge.

12. Letter from Willie Walsh, Director General of IATA, to Executive Vice-President Šefčovič, Commissioner Hoekstra and Commissioner Vălean.

13. Letter to the European Commission 06 May 2024 (non-CO₂ MRV).

14. European Commission (2020) ‘Updated analysis of the non-CO₂ climate impacts of aviation and potential policy measures pursuant to EU Emissions Trading System Directive Article 30(4)’.

EASA has more recently established the Aviation Non-CO₂ Experts Network (ANCEN) – a collaborative group between academia, industry, non-governmental organisations (NGOs), regulators and policymakers to support and review work on non-CO₂ emission impact assessments and policy options.

International

Internationally, ICAO's Committee on Aviation Environmental Protection (CAEP) Working Group 2 is looking at operational opportunities to reduce non-CO₂ effects on the climate. This is part of its overall work on environmental issues related to operations at and in the vicinity of airports. This includes contrails and aviation induced cirrus¹⁵. The recent ICAO Resolution A42-21¹⁶ also highlights a new focus on non-CO₂ with requests to enhance the scientific understanding and address uncertainties of aviation's climate impacts, including exploring means to quantify potential climate impacts of non-CO₂ aviation emissions and technological and operational measures to address such impacts.

In parallel to this, in industry, IATA recently published a report¹⁷ outlining the potential impacts of contrails and the need for greater understanding of their formation and effect on the climate. This will enable the development of mitigation strategies. Other industry groups, such as the Air Transport Action Group (ATAG), are prioritising the development of a position on non-CO₂ climate impacts of aviation and providing industry coordination, with a working group established in 2025. In 2024, Chief Technology Officers in the aerospace industry called for government research programmes that enhance the scientific understanding of aviation non-CO₂ effects¹⁸.

15. ICAO (2025) Report on Operational Opportunities to Reduce Climate Effects of Contrails and Other non-CO₂ Emissions.

16. ICAO (2025) Resolution A42-21: Consolidated statement of continuing ICAO policies and practices related to environmental protection - Climate change.

17. IATA (2024) Aviation contrails and their climate effect: Tackling uncertainties and enabling solutions.

18. Joint Statement from Chief Technology Officers Advocating for Advancing Science on Aviation's non-CO₂ Impacts on Climate Change (2024).



1.3 Purpose and objectives of this paper

The purpose of this paper is the following:

- Collate the current state of scientific evidence on the impact of aviation non-CO₂ emissions on the climate;
- Provide an overview of the potential opportunities to mitigate these impacts and current understanding of their potential;
- Demonstrate the part that the UK aviation industry is already playing in advancing understanding of non-CO₂ impacts and their mitigation; and
- Outline Sustainable Aviation's commitment to addressing non-CO₂ in its current and future work programme and the steps we will take to do so.

2. Overview of non-CO₂ impacts from aviation

Sustainable Aviation recognises the industry's environmental impact extends beyond CO₂ emissions. Non-CO₂ impacts such as those from contrails and contrail cirrus, NO_x, water vapour, SO_x, and particulate matter are also contributors to climate change by radiative forcing, which is the difference between the amount of radiant power entering and leaving the Earth's atmosphere.

This section provides an overview of the current scientific understanding of non-CO₂ impacts – including their formation, duration, effect on climate change, and uncertainties. It also explores some of the uncertainties associated with comparing non-CO₂ forcings to CO₂ and provides an overview of Sustainable Aviation's position on the scale of aviation's non-CO₂ impacts, in line with the available evidence.

2.1 Outline of non-CO₂ impacts and their formation

2.1.1 Contrails and contrail cirrus

Condensation trails (contrails) appear as visible line clouds that form behind propeller and jet driven aircraft¹⁹. These artificial clouds are composed of ice crystals, and formation is caused by increases in local relative humidity in the engine exhaust plume. The increases occur as a result of mixing of heat and water vapour via the hot and moist exhaust and the cold ambient air. When ambient atmospheric temperatures are cold enough, the humidity may reach the point of liquid saturation where liquid water droplets can form. At low enough temperatures, these water droplets can freeze and form ice crystals, leading to contrail formation.

When ambient air is dry, ice particles forming in the contrail will disappear within seconds or minutes. However, if ambient humidity is high enough where air is supersaturated with respect to ice, these ice particles can grow through interactions with water vapour molecules in the ambient air. This leads to contrails persisting and, in some cases, evolving into cirrus clouds and increasing global cloudiness.

The Schmidt-Appleman criterion determines the conditions under which a contrail can form²⁰.²¹ Contrails may persist as long as the ambient air surrounding the contrail remains ice supersaturated. Predicting where these ice supersaturated regions (ISSRs) can form is a challenge. Work to explore the factors that influence their formation is ongoing.

Other factors aside from temperature and humidity can influence contrail formation, including engine efficiency and fuel properties. Exhaust plumes contain other aerosols aside from carbon dioxide and water vapour, including small amounts of nitrogen oxides (NO_x), hydrocarbons, carbon monoxide, sulphur oxides (SO_x), soot, metal particles, and some organic materials and charged chem-ions.

19. Schumann (2005) 'Formation, properties and climatic effects of contrails' V. R. Physique 6.

20. U. Schumann, Oberpfaffenhofen (1996), On conditions for contrail formation from aircraft exhausts.

21. Appleman (1953) 'The Formation of Exhaust Condensation Trails by Jet Aircraft' Bulletin of the American Meteorological Society 34.

These particles – soot in particular – can provide a stronger basis for contrail formation, because these particles act as surfaces for the condensation of water²². Further details on how different fuels and fuel properties can influence contrail formation are discussed in later sections.

Contrail cirrus has both cooling and warming effects (Figure 1). During the day, contrail cirrus reflects solar radiation, delivering a cooling effect, but they also reflect terrestrial radiation, leading to a warming effect. At night, contrails exclusively have a warming effect. The overall net radiative effect of contrails is warming.

Figure 1: Source: contrails.org

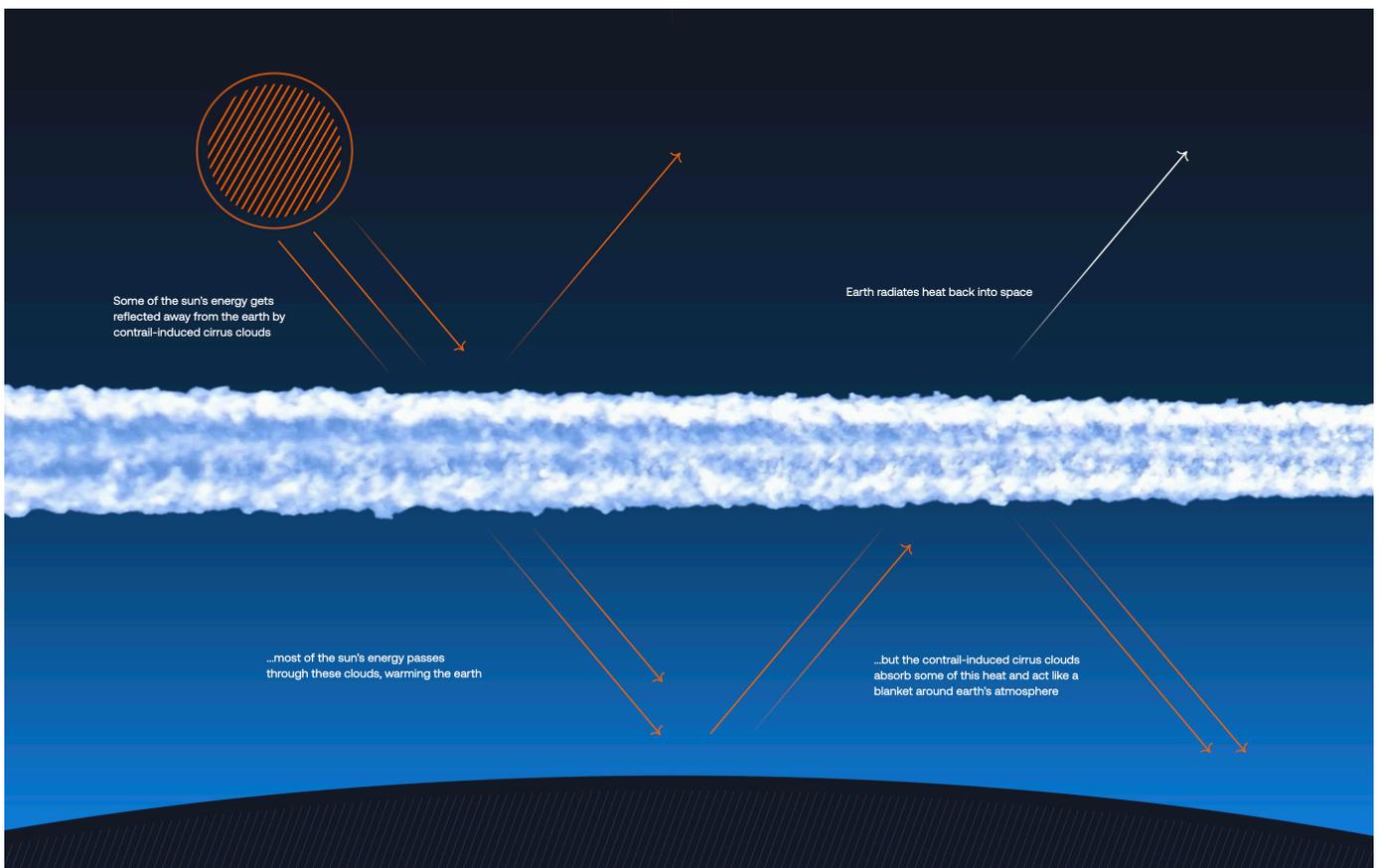


Figure 1 description: This diagram, courtesy of contrails.org, shows the representation of climate impacts from contrails and contrail cirrus.

22. Lán et al. (2020) 'Contrail formation assessment based on aerological data' *Transportation Research Procedia* 51.

2.1.2 Nitrogen oxides (NO_x)

Nitrogen oxide (NO_x) emissions form as a by-product from high temperature and high pressure combustion in aircraft engine combustors (Masiol & Harrison, 2014)²³. The high temperatures and pressures lead to the splitting and subsequent oxidation of atmospheric nitrogen.

At commercial aircraft altitudes, aviation NO_x emissions lead to the production of ozone (O₃) and reactive hydroxyl radical (OH) in the troposphere and lower stratosphere (Khodayari et al., 2014)²⁴. The production of O₃ has a positive effect on radiative forcing and warming^{25, 26} through the absorption of anthropogenic and solar radiation. However, the production of OH leads to the destruction of ambient methane (CH₄). Since CH₄ is a potent greenhouse gas, this decrease in CH₄ is associated with a negative effect on radiative forcing and warming. As CH₄ is also a major precursor to O₃ formation in the free troposphere, its reduction results in a longer-term decrease in O₃ that decays in proportion to the changes in CH₄ over time (Khodayari et al., 2014, and references therein).

Since water vapour is an end-product of CH₄ oxidation, the decrease in CH₄ also results in a decrease in stratospheric water vapour (SWV). The overall increase in ozone and reduction in methane depend on location and time of year, as well as the background atmospheric composition. Although most aircraft emissions occur in the troposphere, in the lower stratosphere the change in SWV may be somewhat offset by direct water vapour (H₂O) emissions by aircraft²⁷.

As a result of these impacts, NO_x emissions lead to a short-term warming effect as well as a longer-term cooling effect. The overall climatic impact of NO_x emissions is therefore often assessed as the 'net NO_x effect' (Lee et al., 2009).

In 2018, NO_x emissions were 2.97 Megatonnes (Mt). This is predicted to rise in line with aviation growth to 15.12Mt by 2070 without any technology or operational improvements, including engine design²⁸. However, if such improvements were implemented, they could confer a reduction of up to 4.66 Mt by 2070.

2.1.3 Water vapour (H₂O)

Water vapour (H₂O) is emitted from aircraft engines as a product of hydrocarbon fuel combustion. H₂O is a greenhouse gas, and the natural hydrological cycle and radiative properties of water are responsible for maintaining earth's habitable temperatures (Lee 2018)²⁹. Emissions of H₂O from aircraft therefore directly increase the concentration of H₂O in the atmosphere, leading to an increase in radiative forcing. Due to lower humidity at higher altitudes, the radiative forcing of H₂O emissions generally increases with the altitude at which they are released^{30, 31}.

23. Masiol & Harrison (2014) 'Aircraft engine exhaust emissions and other airport-related contributions to ambient air pollution: A review' Atmospheric Environment 95.

24. Khodayari, Olsen and Wuebbles (2014) 'Evaluation of aviation NO_x-induced radiative forcings for 2005 and 2050', Atmospheric Environment 91.

25. Wuebbles & Gupta (2007) 'Evaluating the impacts of aviation on climate change', Eos, Transactions American Geophysical Union 88.

26. Lee et al., (2009) 'Aviation and global climate change in the 21st century', Atmospheric Environment 43.

27. Wilcox et al., (2012) 'Radiative forcing due to aviation water vapour emissions', Atmospheric Environment 63.

28. International Civil Aviation Organisation (2025) 'ICAO Environmental Report 2025'.

29. Lee (2018) 'The current state of scientific understanding of the non-CO₂ effects of aviation on climate'.

30. Lim et al., (2015) 'REACT4C: Simplified Mitigation Studies'.

31. Lee et al., (2010) 'Transport impacts on atmosphere and climate: Aviation', Atmospheric Environment 44.

2.1.4 Sulphur oxides (SO_x)

Aviation fuels contain sulphur in trace amounts³². During engine combustion, these trace amounts of sulphur are oxidised to form sulphur dioxide (SO₂)³³, and further oxidised within the atmosphere and engine to sulphuric acid³⁴. These can scatter radiation from the sun, causing a cooling effect³⁵. Sulphates can also affect liquid-phase clouds in the background atmosphere at lower altitudes through acting as cloud condensation nuclei (CCN). This can lead to a cooling effect. Sulphate aerosols can also affect higher level ice clouds, by promoting freezing.

2.1.5 Soot and non-volatile Particulate Matter

Soot emissions encompass non-volatile fine particulate matter composed of black carbon. These can affect air quality and human health as well as climate. Soot emissions are the result of incomplete combustion of aviation kerosene. These particles have a variety of direct and indirect effects on the climate, as broken down below.

Soot particles have a direct warming effect through trapping infrared radiation³⁶.

Soot can also act as condensing nuclei for the formation of contrails, inducing condensation at lower humidities and promoting contrail formation.

The heterogeneous condensation of water on soot leads to a formation of a smaller number of larger ice particles in comparison to the homogeneous condensation in unpolluted air. These larger particles fall out from clouds more readily, leaving clouds with less ice³⁷. This makes clouds including contrail cirrus less reflective and less absorbent of radiation, leading to both cooling and warming effects respectively³⁸.

However, as soot particles age they become coated by sulphuric acid, which hinders their ability to promote ice formation. As a result, the duration of soot emission impacts is likely short-term.

32. IPCC (1999) 'Aviation and the Global Atmosphere'.

33. Brown et al., (1996). Aircraft exhaust sulfur emissions. *Geophys. Res. Lett.* 23 (24), 3603–3606.

34. U. Schumann, Oberpfaffenhofen (1996). On conditions for contrail formation from aircraft exhausts.

35. Lee et al., (2021) 'The contribution of global aviation to anthropogenic climate forcing for 2000 to 2018'. *Atmospheric Environment* 244.

36. Bond et al., (2013) 'Bounding the role of black carbon in the climate system: A scientific assessment'. *Journal of Geophysical Research Atmospheres* 118.

37. Hoose and Möhler (2012) 'Heterogeneous ice nucleation on atmospheric aerosols: a review of results from laboratory experiments'. *Atmos. Chem. Phys.*, 12.

38. Lee et al., (2023) 'Uncertainties in mitigating aviation non-CO₂ emissions for climate and air quality using hydrocarbon fuels'. *Environ. Sci.: Atmos.*, 3.

2.2 Assessing the scale of non-CO₂ impacts

The impact of different activities on global climate, including emissions from aviation, is commonly measured by radiative forcing (RF), which is defined by the IPCC as “[net] changes in the radiation balance of the surface-troposphere system”³⁹.

The climatic impact of aviation in respect of CO₂ emissions is well-studied and quantified. There is a high level of confidence in the estimates for the scale of aviation CO₂ impacts, as outlined in Lee et al. (2021) and ICAO (2016)⁴⁰, with estimates for radiative forcing between 2000 and 2018 ranging from 31 to 34 mW/m². The scale of CO₂ impacts is directly linked to fuel burn, with uncertainties mostly driven by estimations of CO₂ biogeochemical cycling (Lee 2018) and its impacts on the accumulation of CO₂ on an annual basis²⁸.

The section below summarises the current ranges of calculations for the climatic impact of aviation’s non-CO₂ emissions, looking at both radiative forcing and effective radiative forcing factors, duration of impacts, and how well understood the scale of non-CO₂ impacts is in comparison to CO₂.

Radiative forcing of non-CO₂ effects

Alongside radiative forcing, another metric commonly used to compare aviation impacts is effective radiative forcing (ERF). This measurement is defined as “the irradiance change at the top of atmosphere (TOA) following a perturbation to the climate system taking into account any rapid adjustments”⁴¹. These rapid adjustments, which include forcing-driven changes in cloudiness, can alter the global energy balance and eventual climate response. There are uncertainties with the calculation of this method due to the consideration of interactions with different aspects of the climate system, such as cloudiness. These uncertainties are explored further in relation to different emissions within this section.

ICAO’s 2022 Environmental Report cited that the total climatic impact of aviation non-CO₂ emissions is estimated to contribute to almost two-thirds of aviation’s net climate impact.

Table 1, page 17, summarises the ranges of estimates of annual global mean radiative forcing values for non-CO₂ impacts, as well as their effective radiative forcing values, based on recent available literature. It should be noted that estimate ranges have not been adjusted for present aviation activity levels. Where ranges are stated in the literature they have been provided. Where there is a single number, this has been stated.

39. IPCC (2018) Radiative Forcing of Climate Change.

40. ICAO (2016) White Paper on Climate Change Aviation Impacts on Climate: State of the Science.

41. Teoh et al., (2024). Global aviation contrail climate effects from 2019 to 2021. EGU sphere, 2023, pp.1-32.

Table 1: Summary of available estimates on radiative forcing and effective radiative forcing

Description: This table summarises scientific estimates for the climate impact of various aviation emissions. It lists forcing agents (pollutants) in the first column, including CO₂, Contrails, Net NO_x, Sulphur Oxides (SO_x), Water Vapour (H₂O), and Soot/nvPM. The subsequent columns provide data ranges for: Radiative Forcing (RF), Effective Radiative Forcing (ERF), and Efficacy. The final columns cite the year of the study (ranging from 2000 to 2021) and the scientific source.

Forcing agent	RF estimate range (mW m ⁻²)	ERF estimate range (mW m ⁻²)	Efficacy (ERF/RF ratio)	Year/period of focus	Sources
CO ₂	34.3 [31, 38]	34.3 [28, 40]	1	2000-2018	Lee et al., (2021)
Contrails	111.4 [33, 189]	34.3 [28, 40]	0.42	2018	Lee et al., (2021)
	62.1 [34.8, 74.8]	57.4 [17, 98]	0.42	2019	Teoh et al., (2024) ⁴²
	44 [31,49]	26.1		2006	Bier and Burkhardt (2022) ⁴³
			~35%	2006 and 2050	Bickel et al. (2020) ⁴⁴
	[12.4, 51.3]			2006	Brasseur et al., (2016) ⁴⁵
Net NO _x	8.2 [-4.8, 16]		17.5 [0.6, 29]	2018	Lee et al., (2021)
	4.5 [0, 9] per Tg (N) per year			1999-2010	Holmes et al., (2011) ⁴⁶
	6.25			2002	Köhler et al (2013) ⁴⁷
SO _x	-7.4 [-19, -2.6]	-7.4 [-19, -2.6]		2018	Lee et al., (2021)
	[-3.0,-7.0]			2006	Brasseur et al., (2016) ⁴⁴
H ₂ O	2.0 [0.8, 3.2]	2.0 [0.8, 3.2]		2018	Lee et al., (2021)
	0.9 [0.3 – 1.4]			2006	Wilcox et al., (2012) ⁴⁸
Soot and nvPM	0.94 [0.1-4.0]	0.94 [0.1, 4.0]		2018	Lee et al., (2021)

42. Teoh et al., (2024). Global aviation contrail climate effects from 2019 to 2021. EGU sphere, 2023, pp.1-32.

43. Bier & Burkhardt (2022) Impact of Parametrizing Microphysical Processes in the Jet and Vortex Phase on Contrail Cirrus Properties and Radiative Forcing.

44. Bickel et al., (2020) Estimating the Effective Radiative Forcing of Contrail Cirrus.

45. Brasseur et al., (2016) Impact of Aviation on Climate: FAA's Aviation Climate Change Research Initiative (ACCRI) Phase II.

46. Holmes, C.D., Tang, Q., Prather, M.J., 2011. Uncertainties in climate assessment for the case of aviation NO_x. Proceedings of the National Academy of Sciences 108 , 10,997–11,002, doi:10.1073/pnas.1101458108.

47. Köhler et al. (2013) 'Latitudinal variation of the effect of aviation NO_x emissions on atmospheric ozone and methane and related climate metrics'.

48. Wilcox et al., (2012) 'Radiative forcing due to aviation water vapor emissions'.

When considering the effective radiative forcings of non-CO₂ impacts, it can be estimated that annual non-CO₂ forcings could contribute to over double the climate impact caused by the accumulation of aviation CO₂ emissions between 2000 and 2018. However, this figure carries a high range of uncertainty with Lee et al. (2021) estimating the uncertainty for aviation non-CO₂ forcing to be eight times larger than the uncertainty around CO₂ forcing. They arrive at this position when considering individual studies and models and as a result of the uncertainty around the dynamics of the non-CO₂ forcings – including duration, interaction with other climate forcings, and temporal and spatial variation in forcings.

Temporal and spatial variation of non-CO₂ impacts

Approximately 20% of CO₂ emitted persists for millennia⁴⁹, with continued emissions leading to accumulation of CO₂ within the atmosphere, whereas non-CO₂ emissions have a much shorter lifespan (Figure 2).

Figure 2: Global surface temperature change 10 and 100 years after a one-year pulse of present-day emissions. Sources: ICAO (2025)⁵⁰ and IPCC (2021)⁵¹.

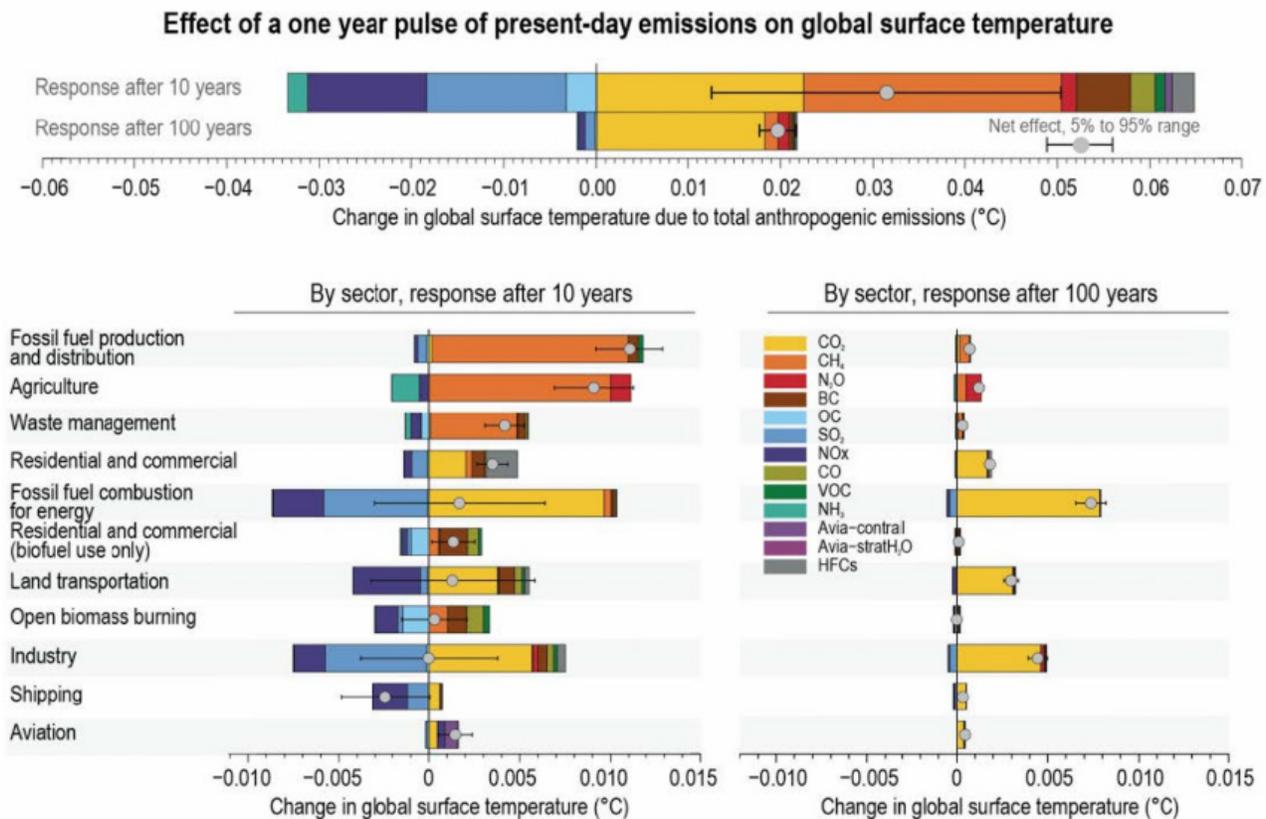


Figure 2 description: The image is a multi-part bar chart comparing the global warming (or cooling) impact of different industrial sectors at two different time horizons: 10 years (left) after the emissions occur and 100 years after (right) a one-year pulse of present-day emissions.

49. Fuglestvedt et al., (2023) A “greenhouse gas balance” for aviation in line with the Paris Agreement.
 50. ICAO (2025) Operational opportunities and challenges for addressing air transport’s non-CO₂ environmental impacts.
 51. IPCC, (2021): Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change.

While the impacts of aviation non-CO₂ effects on the climate are a global issue, there are a number of studies highlighting spatial and temporal variation in climate effects. This includes longitudinal and latitudinal variation as well as variation by altitude.

The typical duration of persistent contrails and contrail cirrus is several hours⁵², with some non-persistent contrails lasting seconds to minutes (Shine and Lee, 2021). Non-persistent contrails have a minimal climate impact. The persistence of contrails is dependent on temperature and ice supersaturation, as well as interactions with other cirrus clouds and nucleating agents. This leads to variations in the duration and persistence of contrails and their climatic impacts across altitudes, seasons and regions (Teoh et al., 2024).⁴¹

Building on Lee et al.'s, (2021) estimate for global annual mean radiative forcing for contrails, Teoh et al. estimated that the contrail net radiative forcing is largest over Europe (876 mW m⁻²) and the USA (414 mW m⁻²) in comparison to a global mean of 62.1 mW m⁻². In contrast to this, the radiative forcing values over East Asia and China were 64 mW m⁻² and 62 mW m⁻² respectively. The study demonstrated that these lower values were due to lower cruise altitudes and limited ice supersaturated regions in the subtropics because of the Hadley Circulation. Petzold et al. (2020)⁵³ also found that ISSRs were more likely to occur during winter and milder winters and storminess, as indicated by a positive North Atlantic Oscillation (NAO) index⁵⁴. NAO is correlated with increased ISSR formation over the North Atlantic flight corridor.

Tropospheric NO_x emissions have a lifespan between several hours and several days^{55, 56} with seasonal variation leading to shorter lifetimes in the summer when photolysis and oxidation are more active, and altitude variations with the lifetime of NO_x reaching several days in the free troposphere due to lower concentrations of hydroxyls⁵⁷. H₂O emissions are also assessed to last for a few days in the troposphere and lower stratosphere but can last for months to years when emitted into the stratosphere.⁵¹

Sulphate aerosols persist for months to years within the stratosphere, with many typically persisting for around 22 months⁵⁸, but have a shorter lifetime in the troposphere⁵⁹. Soot typically persists in the atmosphere for around one week, but this can vary depending on rainfall levels leading to seasonal variation⁶⁰. The impacts of sulphates also have seasonal and regional variations, with enhanced negative radiative forcing over southern high latitudes year-round and during winter for mid latitudes⁶¹.

52. Lee et al., (2023) Uncertainties in mitigating aviation non-CO₂ emissions for climate and air quality using hydrocarbon fuels.

53. Petzold et al., (2020) Ice-supersaturated air masses in the northern mid-latitudes from regular in situ observations by passenger aircraft: vertical distribution, seasonality and tropospheric fingerprint. *Atmospheric Chemistry and Physics*, 2020, 20 (13), pp.8157-8179. [ff10.5194/acp-20-8157-2020](https://doi.org/10.5194/acp-20-8157-2020). [ffhal-04794477f](https://doi.org/10.5194/acp-20-8157-2020).

54. North Atlantic Oscillation (NAO) | National Centers for Environmental Information (NCEI).

55. Ehhalt et al., (1992) Sources and distribution of NO_x in the upper troposphere at northern mid-latitudes.

56. Richter (2010) Nitrogen Oxides in the Troposphere.

57. Shah et al., (2023) Nitrogen oxides in the free troposphere: implications for tropospheric oxidants and the interpretation of satellite NO₂ measurements.

58. ACP - Stratospheric residence time and the lifetime of volcanic stratospheric aerosols.

59. Robock et al., (2009). Benefits, risks, and costs of stratospheric geoengineering. *Geophysical Research Letters*, 36, L19703.

60. Cape et al., (2012) The atmospheric lifetime of black carbon.

61. Moch et al., (2023) Overlooked Long-Term Atmospheric Chemical Feedbacks Alter the Impact of Solar Geoengineering: Implications for Tropospheric Oxidative Capacity.

Over time, changes to the atmosphere such as temperature and humidity, as well as other changes such as NO_x-driven changes to background atmospheric chemical composition may lead to changes in the forcing effects of non-CO₂ emissions⁵¹. In particular, a changing climate may lead to reductions in ISSR formation in the tropics and increases in the Northern Hemisphere by the end of the century⁶². Changes in air traffic over time may also lead to significant increases in contrail formation⁶³.

Exploring metrics for measuring and comparing aviation climate impacts

The uncertainties relating to quantifying non-CO₂ impacts further complicate the ongoing debate on the appropriate emissions equivalency metric. The choice of emissions equivalency metric depends on the application, with each metric capturing a specific aspect of an activity's impact (KPMG, 2025)¹⁰.

For example, radiative forcing only captures the energy imbalance caused by a released gas at a given time, meaning Radiative Forcing (RF) has a number of limitations⁶⁴. Effective radiative forcing is the preferred metric of choice by the Intergovernmental Panel on Climate Change (IPCC) and is the value of RF after atmospheric adjustment. Global Warming Potential (GWP) is a common metric used by policymakers including the Climate Change Committee, and accounts for the RF caused by a 1kg emission of the gas into the atmosphere, integrated over a time period, normalised to the same for CO₂ by dividing each gases' absolute Global Warming Potential (AGWP). Alternatively, Global Temperature-change Potential (GTP) represents the global temperature increase caused by aviation at a specified time-horizon, normalised to CO₂, and has been used in a number of sources.

A recent report commissioned by the Department for Transport compared these metrics and their key features (Table 2, page 21). Building from this, Megill et al.⁶⁵ explored the use of two alternative metrics, Average Temperature Response (ATR) or using an Efficacy-weighted GWP (EGWP) and their benefits.

62. Irvine & Shine (2015) Ice supersaturation and the potential for contrail formation in a changing climate.

63. Bock & Burkhardt (2019) Contrail cirrus radiative forcing for future air traffic.

64. Wuebbles et al., (2007) Evaluating the impacts of aviation on climate change, *Eos T. Am. Geophys. Un.*, 88, 157– 160, <https://doi.org/10.1029/2007EO140001>.

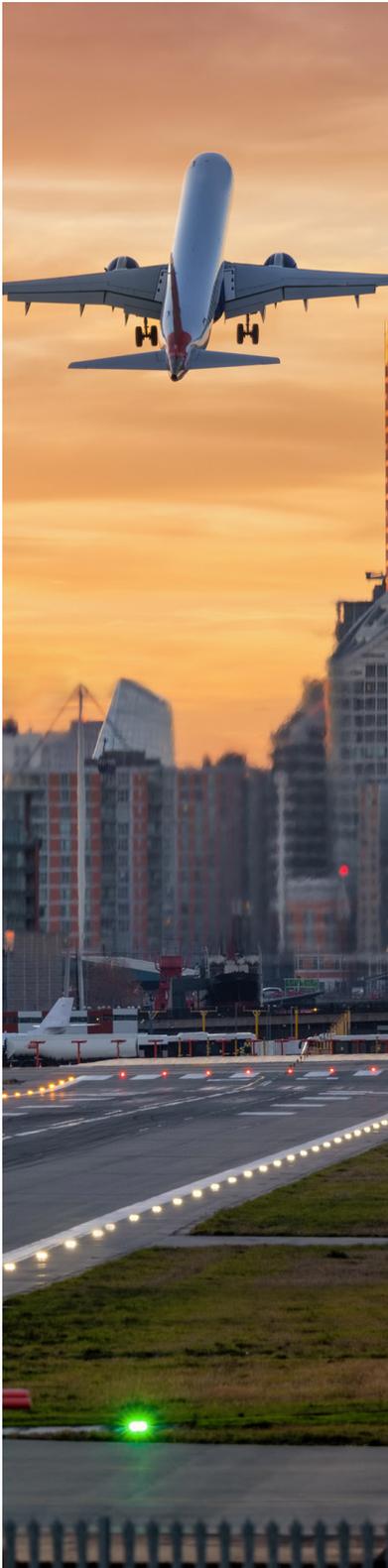
65. Megill et al., (2024) Alternative climate metrics to the Global Warming Potential are more suitable for assessing aviation non-CO₂ effects.

Table 2: Overview of different climate metrics and their key features

Description: This table compares three different methods used to calculate the "carbon footprint" or warming impact of aviation emissions

GWP100, GWP50, GWP20: Pulse based, time-integrated radiative forcing-based metric	
What it captures	The amount of energy added to the climate system from an emission (or other forcing agent) averaged over the time period stated, expressed relative to the same mass of CO ₂ being emitted. When applied to contrails, which cannot be expressed as a mass of emissions, GWP is sometimes defined as radiative forcing per km flown, per flight, or total flights per annum.
Features	Can specify different time periods (it is currently common practice to use 20 years for near term effects or 100 years for longer term effects). Using multiple time horizons helps to capture the fact that the values of GWP20 and GWP100 will vary strongly for short-lived forcings, as they cause strong warming in the short term, but not in the long term. Represents the effect of a pulse/one-off emissions relative to no emission. It does not capture the fact that declining short-lived forcings lead to RF and temperatures declining.
GTP100, GTP50, GTP20: Pulse-based, time horizon temperature change-based metric	
What it captures	The temperature change following the emission at the time horizon, expressed relative to the temperature change if the same mass of CO ₂ was emitted. i.e. if GTP100 is 4, then there is 4x as much warming between the emission and 100 years after from the gas compared to the same mass of CO ₂ being emitted.
Features	Can specify different time periods (commonly 20 years for near term effects or 100 years for longer term effects). Using multiple time horizons helps to capture the fact that the values of GTP20 and GTP100 will vary strongly for short-lived forcings, as they cause strong warming in the short term, but not in the long term. E.g. using GTP20 to will assign a larger CO ₂ -equivalent value to contrails than GTP100. Represents the effect of a pulse/one-off emissions relative to no emission. It does not capture that declining short-lived forcings leads to RF and temperatures declining.
GWP*: Step-pulse based, additional warming-based metric	
What it captures	GWP* bases its equivalence on an approximation of temperature change that occurs from a short-lived pollutant emission. It is denoted a 'step-pulse' metric because it was developed from the observation that a one-off (pulse) CO ₂ emission gives the same trajectory of warming as a step-change in emissions of a short-lived pollutant. It is also referred to as a 'warming equivalent' metric as it effectively 'works backwards' to find the CO ₂ emission that would give the same temperature outcomes.
Features	Approximates the results from a climate model in one equation. Captures the temperature change that an emission causes at specific points in time following the emission. This means that an emission of the same magnitude at different times (e.g. in the pre-industrial time, or in 2050) will have different 'warming equivalent' amounts of CO ₂ . This is a reflection of what would be found by a climate model. It captures the fact that declining short-lived forcings leads to both RF and temperatures declining.
Efficacy-weighted Global Warming Potential (EGWP) and EGWP*	
Features	Weights GWP and GWP* as calculated above by efficacy (the ratio of the climate sensitivity parameter for a given forcing agent to the climate sensitivity parameter for CO ₂ changes ⁶⁶).

66. IPCC (2007) Climate Change 2007: Working Group I: The Physical Science Basis and references therein Available at: 2.8.5 Efficacy and Effective Radiative Forcing - AR4 WGI Chapter 2: Changes in Atmospheric Constituents and in Radiative Forcing.



Without prioritising emissions reductions over a specific timeframe, it is challenging to choose the correct metric to compare non-CO₂ and CO₂ forcings, with the likes of GWP100 under-representing the warming generated by short-lived forcings⁶⁷. It is noteworthy that the Committee for Climate Change used a 20-year average to account for the warming from non-CO₂ effects lasting between 10 and 20 years to estimate the total warming equivalent⁶⁸. An alternative is to use temperature-related metrics to compare effects, with Megill et al. (2024) arguing that an average temperature response metric (ATR) or efficacy-weighted GWP (EGWP) would be more suitable.

As outlined in Table 2, these temperature-related metrics rely on establishing the link between emission pulses and the global mean surface temperature increase - and not just the equilibrium temperature response (Yoshimori et al., 2016)⁶⁹ - in order to understand how forcings effect the climate and how that effect varies over time. However, there are significant uncertainties around modelling global temperature responses to non-CO₂ forcings including contrails to determine their ERFs, as highlighted in recent studies.

In contrast to previous work on contrail cirrus ERFs, including those cited in Lee et al. (2021), Bickel et al. (2025)⁷⁰ used alternative global climate models to assess the climate response to contrail cirrus. This involved modelling forcings, feedbacks, and climate sensitivities. In modelled scenarios where contrail cirrus and CO₂ induce the same level of radiative forcing, contrail cirrus has a 45% lower effective radiative forcing than CO₂ and the surface temperature response per unit of effective radiative forcing is also smaller for contrail cirrus than CO₂ at around 40%. Its efficacy (the global mean equilibrium surface temperature increase induced by the contrail cirrus classical RF) is as low as 21% when compared to the CO₂-forced response. The scale of difference in outputs generated by the use of different models suggests that there is still work to be done to gain a full understanding on the interactions of non-CO₂ emissions such as contrails on the climate.

67. Fuglestedt et al., (2010) Transport impacts on atmosphere and climate: Metrics. *Atmos. Environ.* 44, 4648–4677.

68. Climate Change Committee (2025) Methodology Report Box 11.2.

69. Yoshimori (2016) A review of progress towards understanding the transient global mean surface temperature response to radiative perturbation.

70. Bickel et al., (2025) Contrail Cirrus Climate Impact: From Radiative Forcing to Surface Temperature Change.

2.3 Conclusions on available evidence on non-CO₂ impacts

It is evident that non-CO₂ emissions have a significant impact on the global climate, with clear agreement across the scientific community that aviation's non-CO₂ emissions are contributing to further climate change. While there is no consensus yet around the scale of impacts, and how these compare to CO₂ impacts in scale and duration, it is clear that non-CO₂ emissions require additional focus and attention by industry.

Developing an appropriate metric for comparing CO₂ and non-CO₂ emissions will be highly beneficial to aviation. It will help identify the best to mitigate techniques and technologies and catalyse action. Closing the current gaps in knowledge that exist across the duration and scale of climate impacts from non-CO₂ emissions and contrails, as well as the interactions between non-CO₂ emissions, will help enable the development of a metric to compare CO₂ and non-CO₂ effectively.

Sustainable Aviation believe there are a number of priority areas to address in order to advance understanding and help inform comparisons and solve potential trade-offs between CO₂ and non-CO₂ emissions. These include:

- Improving the modelling of non-CO₂ impacts, including the interactions between natural cirrus clouds and contrails⁷¹ and soot-cloud interactions (KPMG, 2025; Lee et al. 2021; Burkhardt et al., 2018);
- Understanding the conditions necessary for contrail persistence and how these conditions can be predicted;
- Improving the collection of observational data to support the identification of contrails and ISSRs;
- Developing improved sensors that can help forecast the conditions necessary for contrail formation; and
- Evaluating the impact of other surface emissions such as surface NO_x, CO, and non-methane volatile organic compounds (NMVOC) on the effect of aviation NO_x and overall tropospheric chemistry (Skowron et al., 2021).

71. D.K. Singh et al., (2024) Understanding the role of contrails and contrail cirrus in climate change: a global perspective.

However, Sustainable Aviation's view is that while these knowledge gaps remain, it is inappropriate to prematurely use CO₂ equivalency metrics in decision making. Reducing these complex, short-lived effects to a single 'CO₂ multiplier' at this current time could be misleading, provide a false sense of accuracy, and lead to detrimental policy trade-offs. Sustainable Aviation strongly recognises the need to address both sources while ensuring neither is prioritised over the other, particularly while further evidence is needed to develop the science.

In recognition of the potential scale of non-CO₂ impacts, Sustainable Aviation is committed to supporting the scientific community in advancing understanding and reducing the current uncertainties shown within modelling non-CO₂ impacts and estimating their contribution to climate change. In parallel to this, Sustainable Aviation recognises that the potential scale of non-CO₂ impacts means that industry should work on mitigating impacts in the interim.

There are a number of opportunities available, which are outlined in Section 3 of this report.



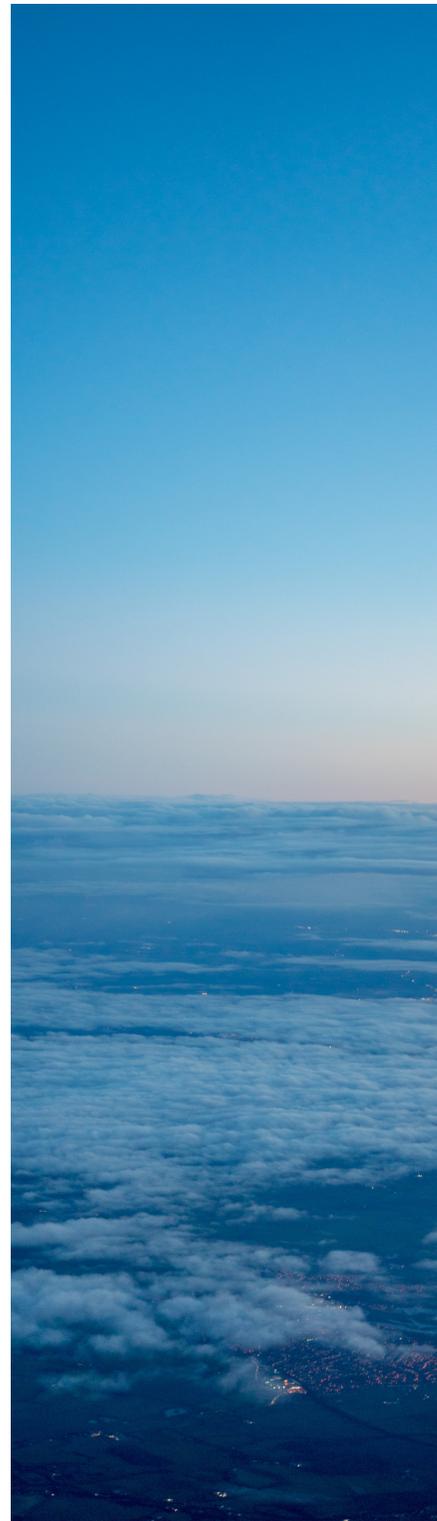
3. Overview of mitigation opportunities

While there is a clear industry and scientific consensus that aviation's non-CO₂ effects likely account for a significant amount of the sector's near-term warming, they are more variable, have a shorter duration, and are subject to more scientific uncertainty than CO₂.⁷²

The impact of greenhouse gas emissions such as CO₂ is the same the same regardless of source or the location of emissions. All this being so, it is clear why CO₂ remains the main pollutant of concern and subject to the most regulation.

As a result, the balance of short-term and long-term impacts from different pollutants makes "what to do" as much about trade-offs and timing as it is about technology.

Table 3, page 26, shows a snapshot on mitigation measures, timescales for these measures, and what the key trade-offs are associated with each.



72. IATA 'Non-CO₂ Aviation Emissions'.

Table 3: Side-by-side snapshot of mitigation opportunities

Description: This is a detailed comparison of seven different strategies for reducing non-CO₂ impacts. The table uses five columns: Strategy, Main Mechanism, Potential Impact, Readiness, and Trade-offs.

Strategy	Main non-CO ₂ mechanism targeted	Potential impact (direction/magnitude)	Readiness and timescale	Key trade-offs and constraints
In-flight avoidance (contrail avoidance)	Spatiotemporal routing to reduce contrails and NO _x climate effects, including avoidance of ice supersaturated regions.	High when targeted; small share of flights causes outsized warming. Estimates of 12–21% climate impact cut on subsets of flights at 0.2–2% cost.	Trials and pilots feasible now; scalable in 1–3 years if forecasting and air traffic movements procedures mature. “Smart” conditional deployment is key.	<ul style="list-style-type: none"> • Risk of extra fuel/CO₂ and/or slower flight times on detours. • Prediction uncertainty. • Airspace capacity limits. • Daily weather dependence. • Operational complexity. • Must guard against CO₂ penalties.
Lower flight (altitude adjustments)	Steep climbs/descents to remain below thin ISSRs.	Moderate when vertical layers are thin.	Operationally feasible today in some cases.	Fuel burn/CO ₂ penalty; controller workload; fleet performance limits.
Daytime flight only	Time-of-day shift to reduce net warming of contrails.	Potential benefit, context dependent.	Policy/slot management challenge; evidence still evolving.	Capacity, equity, noise/curfew constraints; risk of shifting CO ₂ elsewhere.
Aircraft and engine design	Lower NO _x ; reduce soot/nvPM; sensors to avoid contrails.	Medium; NO _x ↓ by ~40–50% with advanced combustors.	2030s entry for major steps.	Cost, certification, maintenance; possible fuel burn trade-offs.
Alternative engine design (e.g., water injection, novel combustors)	Further NO _x cuts; contrail risk modulation.	Medium potential.	2030s for mainstream.	Weight/complexity; water management; CO ₂ penalties if efficiency drops.
Fuel efficiencies (airframe/ops/ATM)	Less fuel → less H ₂ O, NO _x , soot per flight.	Always positive for CO ₂ ; helps non-CO ₂ too.	Continuous; near-term.	Some NO _x -cut tactics can raise CO ₂ (and vice versa).
Sustainable aviation fuel (SAF) in all flights	Lower nvPM/soot; air quality co-benefits.	Meaningful contrail mitigation at higher blends.	Scales 2020s–2030s; blends ≤50% today.	Cost; scarce supply; must ensure high integrity SAF; logistics; unlikely to completely eliminate warming contrails.
Sustainable aviation fuel (SAF) in targeted flights	Lower nvPM/soot; air quality co-benefits on targeted routes with high potential for non-CO ₂ impacts e.g. contrail formation.	Meaningful contrail mitigation without the need for high SAF supply.	2020s.	<ul style="list-style-type: none"> • Likely to mean flights from hub airports are targeted and others miss out on air quality benefit. • Logistical challenges around fuel delivery, storage and loading. • Cost; need to ensure high-integrity SAF. • Unlikely to completely eliminate warming contrails.
Modify aromatics in existing fuels	Direct nvPM/soot reduction at scale.	High near-term leverage.	Could be specified in standards.	Supply, certification seal compatibility, cost, supply; needs policy to move market. Unlikely to completely eliminate warming contrails.
Hydrogen and electric flight	Eliminate in-flight CO ₂ ; change non-CO ₂ profile.	Long-term, potentially large.	2035+ for H ₂ airliners; electric limited to short haul.	New aircraft/infrastructure; NO _x and H ₂ O effects still under study.

3.1 Operational mitigation

3.1.1 In-flight avoidance

- **What it is:** Pre-flight and in-flight trajectory optimisation that weighs CO₂ and non-CO₂ (contrails, NO_x chemistry) based on daily meteorology, which may include tactical altitude or lateral deviations to avoid ice-supersaturated regions (ISSRs) where persistent, warming contrails are likely. ISSRs tend to be horizontally broad at around 100–400 km (Gierens and Spichtinger, 2000)⁷³ but vertically thin with ranges from around 1,000–4,000 ft (Schumann 2012)⁷⁴, so modest level changes can matter; only a small fraction of flights drive much of the warming.
- **Benefits:** Targeted avoidance can yield outsized climate benefit with minimal disruption when predictions are good; live projects (e.g. CICONIA) suggest feasibility in lower traffic density without major ATM disturbance if procedures are in place. For subsets of European flights, climate-optimised planning could cut total climate impact 12.5%–21.3% with operating cost increasing between 0.2%–2.0%. Most benefit comes from contrail mitigation, and effectiveness varies by season/day.

As only a small proportion of flights are thought to significantly contribute the biggest warming impacts, avoidance would not impact substantial numbers of flights. That said, the flights needing to carry out avoidance activity may be more heavily affected^{71,76}. Evidence suggests there is a low cost for substantial climate gain when applied on days/routes with large benefit. Evidence further suggests small portions of flights are responsible for the majority of climate impact. In Europe, it was estimated that about 6–21% of flights are responsible for 80% of contrails climate impact. This is in contrast to NO_x emissions, where 67–71% of flights are responsible for 80% of the corresponding climate effects⁷⁵. In the US, it was estimated that on an average, only 15.1% of daily flights generated contrails⁷⁷.

- **Constraints:** At present there are few reliable forecasts of meteorological conditions and accurate predictions of the potential non-CO₂ impact at the both the pre-flight and in-flight levels. Forecasting of where and when contrails form and persist (and their net radiative effect) remains uncertain. Therefore, the detours risk added fuel burn and CO₂. Planning will be necessary for the additional fuel needed to carry out tactical avoidance. This is a barrier to reliable, effective deployment because implementing an in-flight avoidance system would require clear rules to arbitrate CO₂ vs non-CO₂ impacts. Additionally, the small proportion of flights avoiding the ISSRs would be in the same airspace leading to additional operational safety measures^{71,74}. Operational complexity and training needs are additional factors⁷⁴.

73. Gierens and Spichtinger (2000) "On the size distribution of ice-supersaturated regions in the upper troposphere and lowermost stratosphere," Springer Link, vol. 18, no.

74. Schumann (2012) "A Contrail cirrus prediction model," Geoscientific Model Development, vol. 5, no. <https://doi.org/10.5194/gmd-5-543-2012>, pp. 543–580.

75. Simorgh & Soler (2025) Climate-optimized flight planning can effectively reduce the environmental footprint of aviation in Europe at low operational costs

76. Airbus (2025) How to mitigate contrails and other non-CO₂ emissions | Airbus.

77. Avila et al., (2019) Reducing Global Warming By Airline Contrail Avoidance: A Case Study Of Annual Benefits For The Contiguous United States.

-
- **Timescale and practicality:** Airline trials are underway; broader adoption within 1–3 years is plausible if forecasting, humidity sensing, and operational concepts mature. Flight avoidance will require inputs like real-time weather data for commercial aircraft. More projects funded by academia and government to commercialise higher accuracy water vapour sensors. Only then can they be installed on commercial aircraft and support contrail avoidance systems and verification methodologies. This is in addition to potential ground-based measures such as cameras and artificial intelligence aiding air navigation ISSR avoidance and validation systems complemented by satellite imagery^{71, 75}.
 - **Options for mitigating trade-offs:** Operational mitigation is one of the levers that could be used to reduce short-term climate impact. This can be enabled by having a reliable, agreed and verifiable methodology for applying mitigation and quantifying its benefits and impacts. The main trade off from a climate perspective is with regards to rerouting inducing CO₂ increases and sufficient guardrails should be in place to ensure that one climate impact is not traded for another. Additionally other interdependencies such as safety and capacity concerns, workload for operational staff, flight schedule modifications and passenger experience through potentially longer flight times or delays would need to be assessed. Therefore, it is recommended that this type of action prioritises only high impact flights/segments when integrated with capacity constrained airspace^{74, 75}.

3.1.2 Lower flight

- **What it is:** Flying below thin ISSR layers via steep climbs or descents to prevent persistent contrails⁷¹.
- **Benefits:** Often small altitude changes suffice given thin vertical extent of ISSRs; compatible with targeted, tactical use.
- **Constraints:** This one small change will lead to more drag/fuel burn at non-optimal altitudes, longer flights potentially constricting airspace and introducing performance constraints and increased controller workload⁷⁴.
- **Timescale and practicality:** Near term (within a year) feasible in limited, targeted cases; broader routine use needs ATM procedures and decision support⁷¹.
- **Options for mitigating trade-offs:** Tight CO₂ penalty caps would need to be enforced, and it is likely that this would need to be reserved for high impact use. This would also require a full assessment of sector capacity⁷⁴.

3.1.3 Daytime flight only

- **What it is:** Some contrails cool, some warm with the effect depending on where/when/how long they persist. Scheduling a bias toward daytime to exploit time of-day differences in contrail radiative forcing could reduce the impacts⁷⁵.
- **Benefits:** Potential to reduce net warming if night-time warming contrails are avoided on susceptible routes/seasons. Contrails formed at night tend to trap outgoing longwave radiation, causing net warming. Therefore, shifting flights to daytime could reduce net radiative forcing. Studies by the German aerospace centre DLR and ICAO suggest time-of-day effects are significant but vary by region and season.
- **Constraints:** Operational constraints include airport curfews, slot availability, and passenger demand patterns. There is a risk of congestion and delays during peak daytime hours. There are also equity concerns for regions with limited scheduling flexibility as this could contribute to a capacity crunch in already peaked daytime waves. This would make such scheduling extremely complex. In addition, passenger demand for certain routes is set with optimal arrival times. Changes to this would potentially increase costs and limit route viability^{74, 75}.
- **Timescale and practicality:** This is only conceptual today. It would require detailed analytics and reallocation of slots. Given the intermittent nature of contrail formation, this is a huge undertaking which could have mixed results given that the evidence base and operational concepts are immature. Additionally, the slots at many airports are owned by particular airlines, so reaching agreement to reallocate would be extremely difficult. It could also lead to equity issues, with those airlines who fly in areas less likely to form contrails potentially being given less beneficial slots. Consideration would need to be given to local noise policies and careful network planning to avoid knock-on CO₂ increases. No major airline trials are yet being carried out on this topic, but ICAO and SESAR are evaluating feasibility.
- **Options for mitigating trade-offs:** There is a risk that shifting flights could lead to airspace congestion, which would result in additional holding and fuel burn and thus more CO₂. Additionally, changes could conflict with noise abatement and community impact policies, albeit both positively and negatively. Should timescale and practicality issue be overcome, this mitigation method would have to be combined with routing/altitude optimization to be net beneficial.

3.2 Aircraft and engine design

3.2.1 Alternative aircraft engine design

- **What it targets:** Reduce NO_x and nvPM/soot at source; enable onboard/ground sensors to avoid contrail prone air masses.
- **Benefits:** Advanced combustors (leanburn-, advanced RQL) and water injection can cut NO_x between around 40 and 50%^{71, 78, 79}. Injecting water into the combustor lowers flame temperature, reducing NO_x emissions significantly. Rolls-Royce and Pratt & Whitney have explored water injection in past engine designs. Lean-burn and staged combustors reduce NO_x emissions without water injection. Examples of advanced low-NO_x systems compatible with existing aircraft designs and fuels include Rolls-Royce's ALECSys demonstrator programme and General Electric (GE) Aerospace's Twin Annular Premixing Swirler (TAPS), the latter of which is currently in operation on the GE GEnx engine⁸⁰ and CFM LEAP engine⁸¹. Recent interest is reviving due to increased awareness and prioritisation of climate impact studies. These techniques reduce ozone formation at cruise altitudes, mitigating warming effects.
- **Constraints:** Adds weight and complexity due to water storage and injection systems. Increases fuel burn slightly due to added mass and system operation. There are also maintenance and reliability concerns for long-haul operations. Sensor and climate model maturity still low⁷⁵. Lean-burn and staged combustors have complex combustion dynamics and risk emissions trade-offs. The development and certification costs of this technology are high and may require redesign of engine control systems.
- **Timescale and practicality:** This is technically feasible with potential demonstrations this decade, although retrofitting existing engines is challenging. Instead, technologies could be integrated into future engine designs within five to 10 years if benefits outweigh penalties. ICAO and Clean Aviation are funding feasibility studies into this. It would be expected that rollout of such technologies would form part of rolling upgrades in the 2030s with direct integration into next-gen engines/airframes.
- **Options for mitigating trade-offs:** NO_x reduction needs to be balanced with fuel efficiency and weight penalties⁸². This may be more viable for short-haul or regional aircraft where this problem, particularly in the case of short-haul, is less prevalent. It requires redesign of engine architecture and certification pathways. The priority should be to ensure NO_x cuts don't come with net fuel penalties that erode CO₂ benefits and that we prioritize designs with co-benefits (CO₂ and non-CO₂). Integration into SAF-compatible engines is also essential to ensure long-term compatibility with the shifting fuel market. It will however have long lead times for fleet-wide adoption.

78. Block Novelo et al., (2019). "On-Board Compressor water injection for civil aircraft emission reductions: range performance with fuel burn analysis," Transportation Research part D, vol. 67, pp. 449-463.

79. Liu et al., (2017). "Review of modern low emissions combustion technologies for aero gas turbine engines," Progress in Aerospace sciences, vol. 94, pp. 12-45.

80. GEnx Engine | GE Aerospace.

81. CFM (2016) CFM LEAP-1C integrated propulsion system achieves joint EASA / FAA certification.

82. Prather et al., (2025) Trade-offs in aviation impacts on climate favour non-CO₂ mitigation.

3.2.2 Fuel efficiencies

- **What they are:** combination of current technology and airframe retrofits, new aerodynamics/propulsion efficiency, and improved ATM/ops that cut fuel burn.
- **Benefits:** Always reduces CO₂; may also lower H₂O, soot and NO_x per flight, indirectly affecting contrail impacts and NO_x chemistry impacts.
- **Constraints:** Some tactics that specifically reduce non-CO₂ impacts (e.g. certain thrust derates) can lengthen climb/flight time and raise fuel use and noise.
- **Timescale and practicality:** Ongoing, compounding benefits right now via fleet renewal and operational best practice.
- **Options for mitigating trade-offs:** Where non-CO₂ and CO₂ conflict, some studies advocate prioritising the reduction of non-CO₂ impacts. However, in the overall context of the uncertainty of the impacts of non-CO₂, as mentioned in section 2.2, CO₂ reductions are the surer long-term climate benefit. It is therefore important that we develop robust metrics over appropriate time horizons for future use⁸¹.



3.3 Alternative fuels and modifications to existing fuels

3.3.1 Sustainable Aviation Fuel

- **Mechanism:** SAFs like HEFA, FT-SPK, and Alcohol-to-Jet contain fewer aromatics and sulphur, reducing nvPM/soot and decreasing ice crystal numbers in contrails and therefore their warming potential⁸³. Lifecycle CO₂ is also reduced significantly (by 60–80%) when feedstocks/pathways are high integrity. Additionally, SAF could result in air quality co-benefits around airports.
- **Benefits:** Non-CO₂ and air quality benefits documented in research. Airports/airlines could prioritize SAF where contrail risk is high. Case studies suggest >10% blends may be a threshold for measurable local/non-CO₂ effects (To70, 2024)⁸⁴. Rolls-Royce and Airbus were involved in the ECLIF3 European study using an Airbus A350-900 aircraft with Rolls-Royce Trent XWB-84 engines flying on 100% HEFA-SPK SAF⁸⁵. Compared to conventional Jet A-1, there was a 56% reduction in contrail ice particle number measured. Through further climate simulations, it was estimated that using 100% SAF in all flights could reduce the radiative forcing from contrails by at least 26%.
- **Constraints:** Scarce supply (global SAF production is <1% of jet fuel demand), low blend ratios (≤50% today) and the high cost of SAF are current challenges. The benefits depend more on fuel composition than feedstock type and pathway. Consequently, policies and programmes (such as the UK SAF mandate) that specify fuel types risk maintaining non-CO₂ impacts for longer whilst supply ramps up. Conversely as high blends are needed for stronger non-CO₂ reductions, the UK SAF mandate will enable this sooner. The SAF also requires robust sustainability governance (e.g. CORSIA).
- **Timescale and practicality:** Deployable now through blends. Scaling through from now to 2030s and beyond with supportive policy is already the trajectory - but the policy must be aligned with best climate benefit. Potentially, higher blends or greater supply should be targeted for use on high impact routes as that can amplify non-CO₂ gains while supply is limited.
- **Options for mitigating trade-offs:** SAF is currently more than triple the cost of Jet A-1 and the right policy mechanisms must be in place to ensure that the economic costs of these benefits do not have adverse impacts both on consumers and the environment (should airlines tanker more fuel). We must ensure lifecycle integrity to avoid indirect impacts such as indirect land use change (ILUC) and biodiversity). We must also align climate metrics/monitoring to value non-CO₂ co-benefits appropriately.

83. IATA (2025) The non-CO₂ climate co-benefit of SAF and other fuels with low aromatic and sulfur content.

84. To70 & The Roundtable on Sustainable Biomaterials (2024) Case study on the non-CO₂ impact of sustainable aviation fuels (SAF).

85. Airbus (2024) World's first in-flight study of commercial aircraft using 100% sustainable aviation fuel show significant non-CO₂ emission reductions.

3.3.2 Hydrogen and electric flight

- **Mechanisms:** Eliminate in-flight CO₂. Shifts non-CO₂ profile with no soot from H₂ and altered NO_x and water vapour dynamics and battery electric removing both CO₂ and non-CO₂ in-flight. However, battery electric is range-limited^{86, 87}.
- **Benefits:** Hydrogen aircraft (combustion or fuel cell) promise zero in-flight CO₂ and much lower soot. Alongside this, studies indicate potential non-CO₂ advantages versus kerosene if NO_x and contrails are managed, and large-scale concepts target entry by the mid-2030s^{86, 88}.
- **Constraints:** Hydrogen combustion can still produce NO_x⁸⁷; increased H₂O and stratospheric water vapour effects also need careful assessment. Contrails are still likely to occur and are expected to form over a much wider range of atmospheric conditions than for kerosene, with differing microphysics. Hydrogen leakage also has atmospheric chemistry implications. The use of hydrogen would fully eliminate NO_x emissions when used in a fuel cell to power an electric aircraft - and could considerably reduce them if hydrogen is used in a jet engine. Battery electric propulsion would eliminate all CO₂ and non-CO₂ emissions, but scaling batteries remains challenging. It is likely that they will only be deployed for sub-regional aircraft. Such aircraft fly at altitudes where contrails are not formed.
- **Timescale and practicality:** Sustainable Aviation's Net-Zero Carbon Road-Map outlines that electric aircraft are expected to enter service in 2028, but range remains limited to sub-regional routes for the foreseeable future. It also outlines that commercial narrow body H₂ aircraft are likely to enter service in 2035, although major infrastructure upgrades and aircraft redesign is required⁸⁶.
- **Options for mitigating trade-offs:** Introducing hydrogen to aircraft and airports will require significant capital investment into aircraft and airport systems including fuelling infrastructure. It is important that formation of NO_x and contrails are managed via combustor design and operations to deliver the maximum climate benefit. It is also important to ensure sufficient green H₂ supply to avoid upstream emissions⁸⁶.

86. Forster et al., (2023) non-CO₂ impacts of hydrogen: A summary report for the Aviation Environment Federation.

87. IATA (2025) Hydrogen for aviation: A future decarbonization solution for air travel?.

88. ICAO (2022) Hydrogen power – boldly going to the heart of climate-neutral aviation.

3.3.3 Modifying existing fuels including aromatic content

- **Mechanism:** Lower aromatics (especially naphthalene) directly reduce nvPM/soot and contrail ice crystals.⁸⁴ Several studies link the presence of aromatics to black carbon formation⁸².
- **Benefits:** Could deliver sector-wide non-CO₂ benefits without waiting for SAF to scale if embedded in jet fuel specifications. There are also slight energy density benefits, thus reducing fuel burn. Shell and TotalEnergies are exploring low-aromatic blends for aviation and its compatibility with existing engines and infrastructure. Strong lever on contrails via soot reduction; feasible through tighter specifications on conventional jet fuel (e.g., low naphthalene).
- **Constraints:** Potential seal swelling/compatibility concerns need to be addressed as aromatics are needed for lubrication and seal swelling in older engines⁸⁹. This could lead to a risk of leakage. Refinery reconfiguration and cost would also have to be taken into account. This would require regulatory standards and incentives to move the market as fuel specification changes require industry-wide coordination.
- **Timescale and practicality:** Standards changes are achievable on a two-to-five year policy timeline if stakeholders align. It could also complement SAF ramp-up.
- **Options for mitigating trade-offs:** Composition changes need to be balanced with engine/airframe certification constraints. Low aromatic, low-sulphur blends that maintain safety margins should be prioritised. It will be important to quantify the trade off with CO₂ as lifecycle carbon is increased through hydro-treating processes. It will also be important to address any impacts of low aromatic fuels on fuel storage and transport infrastructure.

89. CS Now (2022) Future aviation fuels: Work package C3: interactions between mitigation.

4. Overview of previous, current and future work being undertaken by Sustainable Aviation members

In recognition of the climatic impacts of non-CO₂, member organisations of Sustainable Aviation, including airlines, aerospace manufacturers, air navigation service providers (ANSPs) and airports have been involved in the advancement of industry and scientific understanding of non-CO₂ impacts for the last few decades. This includes the development of potential solutions to manage and mitigate emissions as well as advancing understanding on the formation and detection of emissions.

This section outlines a number of case studies of members' work as well as members' involvement in cross-industry organisations and projects focussed on non-CO₂ impacts, including EU-ANCEN, CICONIA, PACIFIC, A4Climate and CAEP.

4.1 Formation, detection and impact of emissions and contrails

To support the validation and verification of mitigation measures, as well as factors influencing the formation of contrails, further work is needed to develop observation and detection capabilities for contrails and other non-CO₂ emissions. This includes the development of sensing techniques, ground and space observation capabilities, forecasting of humidity and ISSR formation. Aerospace manufacturers have led the way in supporting studies and trials to accelerate research and development in these key areas.



4.1.1 Case Study 1: Airborne humidity sensing studies led by Airbus

The accuracy of ISSR prediction suffers from the lack of humidity measures in the upper troposphere and lower stratosphere. Airborne humidity sensing at cruise altitude could fill this gap, but no sensor on the market is fully satisfactory for this purpose.

Airbus contributes by testing and comparing various sensing technologies, whether commercial or from the lab, in realistic conditions, thanks to its flight test aircraft. In parallel, studies are conducted in the frame of Airbus-led SESAR CICONIA that aim to define the requirements for a future cruise-altitude humidity-sensing capability.

4.1.2 Case Study 2: Developing an approach to estimating in-flight nvPM emissions

Within the work of ICAO CAEP, MEEM (nvPM Mission Emissions Estimation Methodology) has been developed and published⁹⁰. The key capability of MEEM is to enable an estimation of nvPM emissions at cruise from published certification data obtained from ground-based measurements. To improve the prediction accuracy the method has been revised and modifications proposed (MEEM2). MEEM2 is currently in discussion in ICAO CAEP/14 groups and publications are in preparation.

4.1.3 Case Study 3: Prototyping of ground and space contrail observation capabilities by Airbus

Mitigating contrails relies on being able to predict their formation, evolution and impact with sufficient accuracy. But contrails are a complex multi-scale phenomenon that is quite difficult to simulate. Models exist but need to improve and be validated by observation. To that end, Airbus is developing contrail observation and image processing capabilities at various scales: from ground, airborne, and space cameras.

4.1.4 Case Study 4: Climate impact assessments of emissions

Airbus collaborates with the German aerospace research centre DLR in order to improve the ability of their climate impact models, such as OpenAirClim, to take into account non-CO₂ effects, particularly contrails.

90. Ahrens, D., Méry, Y., Guénard, A., and Miake-Lye, R. C. (December 8, 2022). "A New Approach to Estimate Particulate Matter Emissions From Ground Certification Data: The nvPM Mission Emissions Estimation Methodology." ASME. J. Eng. Gas Turbines Power. March 2023; 145(3): 031019.

4.2 Operational mitigation

Industry has a significant role in supporting research into operational mitigations, such as in-flight avoidance, lower altitude flight, and optimised flight planning. This includes leading and participating in trials, understanding the operational and practical impacts of measures and providing flight data to support modelling into mitigation. Sustainable Aviation members have participated in such trials with varying scales of size over a number of years.

4.2.1 Climate effects reduced by Innovative Concept of Operations - Needs and Impacts Assessment (CICONIA)

The CICONIA project, funded by Horizon Europe and UK Research and Innovation (UKRI) and coordinated by Airbus, is an ongoing project which aims to improve the use of weather-forecasting to mitigate non-CO₂ emissions. It has a particular focus on contrails. The project also aims to improve climate impact assessments and test the feasibility of embedding mitigation strategies into tactical operations. Through trials and simulations, CICONIA aims to investigate multiple strategies for flights to minimise or avoid the formation of persistent contrails, especially in oceanic airspace. A number of Sustainable Aviation members are involved in the project and corresponding trials alongside Airbus, including Boeing, NATS, and easyJet.

The project commenced in 2023 and is set to continue until 2026.

At this time, the scientific work packages have resulted in findings advancing our understanding of climate-sensitive regions, leading to improved models able to forecast supersaturation in particular more accurately than before. In addition, significant progress has been made on metrics for avoidance decision-making which combine the probability of contrail creation with the likely impact in an overall climate risk indicator.

From an operational concept perspective, three possible solutions have been identified. They depend on the stakeholder taking charge and their mode of operation, which in turn will be dependent on the nature of the regulations or incentives created by policy-makers.

For short haul airline operations, it is expected that all mitigation decision-making and planning, prompted by provision of prediction data by the MET providers, can be handled on the ground and integrated into the flight planning process. Quite mature tools already exist for flight planning. The assumption is that air traffic control (ATC) operations should be able to facilitate the filed flight plan, particularly when informed of the contrail mitigation objective.

In the case of long-haul operations, while mitigation of contrails close to the origin might be achieved by on-the-ground flight planning, again informed by MET data, the long duration of the mission might lead to updated prediction data being available.



This could then be relayed to the aircraft which may then tactically request a profile alteration from ATC.

Finally, some ANSPs may decide to take a leading role for contrail mitigation to provide more global benefit on top of airline-led action. As the flights are executed, MET information will be ingested by ATC entities, and following a process of analysis to determine suitability, advisories are proposed to aircraft for vertical deviation of +/-2000ft.

The process is supported using controller support tools to identify which aircraft can be requested to deviate and so reduce warming contrails.

While several validation exercises, particularly live flight trials, are still outstanding, others have already finished. They include large studies to identify the effect of different cost indices, aircraft types, and avoidance strategies on climate impact and fuel use.

In addition, multiple desktop and shadow mode exercises have reconfirmed previous results of the minor fuel impacts of most contrail mitigation manoeuvres.

Furthermore, multi-stakeholder workshops have investigated the likely impact of scaled-up non-CO₂ mitigation on ATC operations and have concluded that contrail mitigation is operationally feasible in some circumstances, but not all. It is dependent on workload, traffic density, and complexity, as well as the size of the contrail sensitive area to be avoided.

4.2.2 TUIFly & German 100Flights trial

In Germany, TUI have organised a growing number of contrail avoidance flights as part of key trials, including the German 100Flights trial in 2024. The key aim of the trial was to understand the impact of in-flight avoidance and other operational mitigation strategies on airline operations. This involved collecting data through trials on the benefits and limitations of mitigation as well as the key operational requirements and complexities encountered. The trial also sought to establish the additional fuel burn and associated CO₂ emissions and flight time changes caused by mitigation, and the success of mitigation strategies in limiting contrail formation.

The trials demonstrated the operational feasibility of contrail avoidance. When comparing avoidance and observation flights, it was estimated that contrail avoidance led to a 1-2% change in flight time, which was classified to be within range of usual operations. Using DLR's climate effects modelling, it was estimated that avoidance led to a 60-70% reduction in the total climate effect (CO_{2e} of CO₂ and contrails using GWP metrics).

4.2.3 A4Climate

Looking ahead, TUI will perform >400 operational contrail mitigation flights as part of the A4Climate (Advancing Aeronautics and Aerosol research to Accelerate CLIMATE neutral aviation) project commencing in 2025⁹¹.

This project will run until 2029 with flights expected to be run within the next two years. The aim of the avoidance flights will be to further advance knowledge on mitigation options through collating data on trajectories and weather conditions to improve climate impact and cost assessments, as well as provide a testbed for current flight optimization tools and improve their operational application.

As part of A4Climate, other work packages will be undertaken including improving understanding of the risks and costs of contrail management, assessing the impact of aerosol effects on the radiative properties of high and low clouds, and the impact of lower soot content on contrail ice nucleation.

91. A4Climate, Advancing Aeronautics and Aerosol Research to Accelerate Climate-Neutral Aviation.

4.2.4 Virgin Atlantic Contrail Forecasting

At the heart of this initiative is a data-driven model that predicts contrail-prone conditions by analysing real-time meteorological data, in-flight feedback, and pilot observations. Integrated into CAE's flight planning tools, the model enables dispatchers and pilots to make informed decisions that reduce the likelihood of contrail formation – without compromising fuel efficiency or safety. Instead of enforcing rigid re-routing, the system allows for dynamic adjustments that balance environmental impact with operational feasibility. Crucially, pilots play an active role by submitting post-flight e-forms that capture atmospheric conditions, creating a continuous feedback loop that sharpens the model's predictive accuracy.

This approach not only supports real-time decision-making but also contributes to long-term industry learning. By refining the model with real-world operational data, Virgin Atlantic is developing a scalable, replicable tool that complements traditional emissions-reduction strategies and reinforces the airline's broader commitment to holistic climate action.

The initiative is reflective of the research needed to drive our understanding of contrails whilst highlighting the power of cross-sector collaboration in delivering practical, scalable solutions – bridging operational efficiency with leading-edge climate science.

4.3 Alternative fuels and modifications to existing fuels

As part of ongoing work to reduce the overall climatic impacts of flying, including CO₂ and non-CO₂ impacts, the potential of alternative low and zero carbon fuels and modifications to existing fuels to address non-CO₂ impacts is being explored by a number of Sustainable Aviation members. This includes studying the impact of SAF on non-CO₂ impacts and formation of contrail cirrus through modelling and trials, the impact of fuel content such as reduced aromatics and additives, and the potential for hydrogen to reduce contrail formation.

4.3.1 Impact of sustainable aviation fuel on non-CO₂ impacts and contrail cirrus formation ECLIF3 – contrail formation studies

The ECLIF3 project involved Airbus, DLR, Rolls-Royce, Neste, NRC Canada, and University of Manchester. The project conducted ground emissions tests and flight emissions tests of a latest generation turbofan engine. They used a variety of operating conditions and thrust settings, comparing emissions when burning 100% SAF versus emissions when burning fossil kerosene in the same engine under similar conditions.

Results of the ECLIF3 contrail measurements are detailed in a 2024 paper⁹² which states:

- “Apparent ice emission indices of 100 % HEFA-SPK (hydro-processed esters and fatty acids–synthetic paraffinic kerosene) were measured and compared to Jet A-1 fuel contrails at similar engine and ambient ice-supersaturated conditions within a single flight.”
- “A 56 % reduction in ice particle numbers per mass of burned fuel was measured for 100 % HEFA-SPK compared to Jet A-1 under engine cruise conditions.”
- “Our results indicate that higher hydrogen content fuels ... may lead to reduced climate forcing from contrails.”

VOLCAN

The VOLCAN (“VOL avec Carburants Alternatifs Nouveaux”) ground and flight-test measurement campaigns took place from 2021 to 2023. On ground and in-flight emissions, as well as contrails properties, were measured using Airbus A319neo and A321neo test aircraft powered by CFM LEAP-1A engines, burning 100% fossil Jet A-1, 100% HEFA SPK and blends. The LEAP-1A engine has a staged combustion chamber featuring “lean burn” low particulate emissions technology. To single out its impact, testing was done with this capability on but also deactivated by engine software change. This is known as “forced rich burn”. Results of the campaign are detailed in a 2025 paper⁹³:

- Lean Burn reduces nvPM cruise emissions by three orders of magnitudes in flight, with all tested fuels, compared to classical combustor technology.
- The nvPM reduction trend with SAF seen in ECLIF3 is confirmed in forced rich burn.
- In flight, total particulate matters (tPM), including volatile ones (vPM), were measured at a similar level as with forced rich burn.
- Similar levels of contrail ice particle number were measured in lean burn (soot poor) and rich burn (soot rich) mode.

Precursors for this ice formation in soot poor conditions are not yet identified: potential candidates are volatile particles consisting of sulfuric acid, nitric acid, unburnt hydrocarbons, or engine oil.

92. Markl et al. (2024) Powering aircraft with 100 % sustainable aviation fuel reduces ice crystals in contrails.

93. Voigt, C et al (2025) Substantial aircraft contrail formation at low soot emission levels, preprint.

Flight100

Virgin Atlantic's Flight100 in 2023, the first commercial flight fuelled by 100% SAF, reported reductions of 40% in the generation of particulates compared to Jet A-1⁹⁴. Further work to simulate contrail formations from the flight using the SAF blend suggested that the blend used could contribute to a reduction in persistent contrail formation⁹⁵. A similar trial was performed in 2023 by Boeing as part of its EcoDemonstrator studies in partnership with NASA and United Airlines⁹⁶, which compared contrail formation as the aircraft switched from 100% SAF in one fuel tank to conventional jet fuel in the other - in order to study the impact of SAF on the characteristics of contrails⁹⁷.

QRITOS

Looking ahead, several Sustainable Aviation members, including Rolls-Royce, British Airways, and Heathrow, are involved in the recently-announced QRITOS (Quantifying Reduction in Thermal Contrails by Optimising SAF) project⁹⁸. QRITOS aims to demonstrate smart SAF allocation strategy in a real-world airport environment and airline operation. Environmental impact is assessed through modelling and verified through satellite observations.

The goal is to maximise the climate benefit of SAF deployment by allocating SAF blend to flights most likely to produce an observable reduction in contrail warming impact. To support these objectives, the project will design and test a logistical framework to enable the flight trial and develop contrail modelling and data-processing capabilities. Concluding in April 2027, the two-year project will also enhance forecasting methods, advance understanding and modelling of contrail formation, and develop verification methods based on satellite data.

4.3.1 Impact of fuel content on non-CO₂ impacts and contrail cirrus formation

PACIFIC

PACIFIC (Particle emissions, Air Quality and Climate Impacts related to Fuel Composition and Engine Cycle) will cover the testing of an unprecedented set of fuels at lab and rig test levels and down select some of them for testing at engine/aircraft levels. Using advanced measurement and analytical methods will enable the learnings of those experiments to be transferred into simulations of contrails and their climate impact. It will further enable an assessment of mitigation measures and potential policy implications.

PACIFIC will pave the way towards new guidelines for future fuel specifications (drop-in and non-drop-in 100% SAF, fossil Jet fuel) with the objective of minimising climate and local air quality impacts and providing important inputs to future modelling and testing work. Members of Sustainable Aviation, including Rolls-Royce and Airbus, are involved in the project.

94. Virgin Atlantic (2024) Flight100 Technical Readout.

95. Teoh et al. (2024) Virgin Atlantic Net Zero Flight: Final Report.

96. Boeing (2023) Boeing, NASA, United Airlines To Test SAF Benefits with Air-to-Air Flights - Oct 12, 2023.

97. Boeing (2023) 737-10, DC-8 team up to test sustainable fuel.

98. Rolls-Royce (2025) Rolls-Royce leads UK project to demonstrate smarter use of Sustainable Aviation Fuel.

4.3.2 Measuring contrails in hydrogen flight

To evaluate the potential of hydrogen-powered aircraft in reducing contrail formation, Airbus have led a joint project alongside Perlan and the DLR to measure the contrails of a hydrogen turbojet in flight⁹⁹. The Blue Condor project uses Arcus gliders developed by Perlan, with one modified to accommodate a hydrogen engine and the other equipped with a conventional kerosene jet engine.

Alongside measuring contrail formation with instruments installed on a tow chase plane to measure the microphysical properties of the contrails resulting from hydrogen burn, the research team also conducted emission measurements of nitrogen oxides and possible aerosol particle formation at lower altitudes. The team have also conducted engine test runs on the ground to provide additional information on the emissions of the hydrogen engine at various power settings. As of April 2025, seven test flights have been conducted, of which four resulted in the formation of contrails from the hydrogen engine. The data is currently being evaluated in detail and will be published in a scientific paper.

4.4 Aircraft and engine design

Aircraft and engine design, including cleaner engine technologies for greater fuel efficiency and different propulsion systems, are being developed and studied in detail by aerospace manufacturers including Rolls-Royce.

The Rolls-Royce UltraFan is targeting to be 25 per cent more fuel efficient than the original Trent 700. It is a key element of the Rolls-Royce sustainability strategy as part of its commitment to continue to improve gas turbine performance and efficiency. In combination with the reduced fuel burn (and CO₂), advanced combustion technology is being developed to achieve up to 40% NO_x reduction and significant improvements for nvPM emissions.

99. DLR (2025) World-first in-flight measurements of contrails from hydrogen propulsion.

4.5 Involvement of SA members in other related organisations

Alongside involvement in trials and other projects, a number of Sustainable Aviation member organisations are involved in working groups and other organisations focussed on driving collective action, discussion and knowledge-sharing on non-CO₂ impacts of aviation.

This involvement is shown below:

Working Group/organisation	Aims	Active years	SA Member involved
The Aviation non-CO ₂ Expert Network (ANCEN)	To provide objective, timely, common, and credible technical advice on non-CO ₂ emissions.	2024 - Present	Rolls-Royce IAG Airbus NATS
Jet Zero Taskforce Contrail Avoidance Task & Finish Group	To review contrail mitigation measures and support the implementation of a potential UK-led contrail avoidance roadmap trial, if approved.	2025	Airbus Boeing TUI IAG NATS Rolls-Royce
Committee on Aviation Environmental Protection (CAEP) and associated working groups	Technical committee of ICAO. Assists ICAO in formulating new policies and adopting new Standards and Recommended Practices (SARPs) related to aircraft noise and emissions, and more generally to aviation environmental impact.	1983 - Present	Rolls-Royce Airbus Boeing (as advisor to ICCAIA) NATS
CTO Forum non-CO ₂ Effects Working Group		2024 - Present	Airbus Boeing Rolls-Royce

5. Sustainable Aviation's position on non-CO₂ impacts and recommendations

Aviation's climate impact extends beyond carbon dioxide, with non-CO₂ effects accounting for a substantial portion of its total warming influence. While significant scientific uncertainties persist regarding the precise magnitude and mechanisms of non-CO₂ effects, particularly for contrails and NO_x, this uncertainty should not impede proactive research and validation of mitigation strategies.

Instead, a pragmatic approach is needed, including funding for research and industry action. We must actively pursue the generation of the data and insights necessary to refine scientific understanding.

Analysis highlights that effective near-term mitigation is achievable without significantly increasing CO₂ emissions. Operational strategies, particularly contrail avoidance, show significant potential for climate benefits. However, it is vital that we have mature, verifiable approaches to delivering operational strategies. This includes mature forecasting and sensor technologies as well as a clear framework for estimating the CO₂ and non-CO₂ impacts associated with mitigating actions. This will ensure they deliver a true net climate benefit and avoid counter-productive CO₂ penalties.

The widespread adoption of Sustainable Aviation Fuels, while primarily a CO₂ reduction strategy, could offer crucial co-benefits by reducing soot emissions and altering contrail properties, making SAF a holistic climate solution. Furthermore, advancements in engine combustor technologies show promise for significant NO_x reductions. However, it is important to note that both of these solutions are unlikely fully to eliminate contrail formation.

Looking ahead, a concerted, globally-coordinated effort is essential. This includes continued, targeted investment in atmospheric research to reduce uncertainties, especially concerning aerosol-cloud interactions and the evolving net effect of NO_x. Crucially, global harmonisation of methodologies and policies, potentially led by ICAO, is necessary to avoid fragmented approaches and ensure equitable, effective mitigation worldwide.

Finally, the development of emerging propulsion technologies, notably hydrogen and electric aircraft, could fundamentally transform aviation's climate footprint in the long term, though their specific non-CO₂ implications require dedicated and thorough investigation.

To deliver these improvements we will need to continue to work collaboratively across all parts of the aviation industry. We also need to work closely with other stakeholders, particularly government and academia, as well as at an international level. Sustainable Aviation recognises our role in providing industry with the platform to do this. We are also committed to working with government and academia to tackle uncertainties and work towards mitigating non-CO₂ emissions.

Sustainable Aviation will align our future work with four key principles:

- begin to address scientific uncertainties by improving the collection of live data through observation and improved sensor technologies and in-flight measurement techniques;
- maximising CO₂ and non-CO₂ co-benefits, such as through the deployment of targeted SAF use and advanced engine technologies;
- exploring mitigation strategies through trials at appropriate scale to test operational and climate impacts; and
- engaging with academia and other experts to enable the development of best practice for the assessment of non-CO₂ emissions and impacts.



6. Final words

The paper has looked at the most up to date and relevant scientific evidence on non-CO₂ to provide the most recent understanding on the topic. It is an issue of significant importance to the aviation sector and a growing field of academic research. The evidence base and literature has accelerated rapidly in recent years. It is vital that the sector and strategic partners such as government and academia can make recommendations and decisions about next steps based on the most up-to-date analysis.

The paper highlights the latest insights into emerging mitigation options and examines the role of industry in advancing research and trials aimed at reducing non-CO₂ emissions and deepening scientific understanding of their origins and effects. By working collaboratively on trialling mitigation techniques, we hope to be able to increase our input into this evidence base in the near future. As government continues to evolve its policy framework, we believe this paper, and the suggested actions from it, will enable practical decisions about mitigation options based on robust data and serve as a meaningful contribution to that process.



Acronyms

Description: This table provides a list of acronyms used throughout this publication and its term and definition.

Acronym	Term and definition
ANCEN	Aviation non-CO ₂ Experts Network
ANSP	Air Navigation Service Provider
ATAG	Air Transport Action Group
ATI	Aerospace Technology Institute
ATM	Air Traffic Movement
CAEP	Committee on Aviation Environmental Protection
CCC	Committee for Climate Change
CCN	Cloud condensation nuclei
CH ₄	Methane
CICONIA	Climate effects reduced by Innovative Concept of Operations - Needs and Impacts Assessment
CO	Carbon monoxide
CO ₂	Carbon dioxide
CORSIA	Carbon Offsetting and Reduction Scheme for International Aviation
DLR	Deutsches Zentrum für Luft- und Raumfahrt (German Aerospace Center)
EASA	European Aviation Safety Agency
EEA	European Economic Area
ERF	Effective Radiative Forcing
ETS	Emissions Trading System
HEFA	Hydroprocessing Esters and Fatty Acids
H ₂	Hydrogen
H ₂ O	Water vapour
IATA	International Air Transport Association
ICAO	International Civil Aviation Organisation
ILUC	Indirect land use change
IPCC	Intergovernmental Panel on Climate Change
ISSR	Ice supersaturated regions
MRV	Monitoring, reporting and verification
NGO	Non-government organisation
NO _x	Nitrogen oxide
nvPM	Non-volatile particulate matter
O ₃	Ozone
OH	Hydroxyl radical
PM ₁₀	Particulate matter smaller than 10 micrometres in diameter
RF	Radiative forcing
RQL	Rich-Quench-Lean
SAF	Sustainable Aviation Fuel
SESAR	Single European Sky ATM Research
SO _x	Sulphur oxide
SO ₂	Sulphur dioxide

About Sustainable Aviation

Sustainable Aviation is the industry body championing aviation's decarbonisation efforts.

We're a coalition of UK airlines, airports, aerospace manufacturers, fuel producers and partners all committed to delivering carbon net zero aviation by 2050, and to minimising the impact of aviation noise.

We have a long term strategy which sets out the collective approach of UK aviation to tackling the challenge of ensuring a cleaner, quieter, smarter future for our industry.

We are focused on finding collaborative ways of improving our environmental performance and creating a balanced debate to ensure sustainable growth of our industry, which is crucial to the health of the UK's economy.

For more information visit www.sustainableaviation.co.uk





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