REPORT

A policy roadmap for aviation non-CO_2 emissions in Europe

There is no single silver bullet for the mitigation of aviation non-CO_2 emissions, and will need to be addressed through a combination of policies. While EU law includes sporadic initiatives on non-CO_2 emissions, a coherent vision and holistic approach for their reduction is lacking.



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Executive summary

Aviation contributes to global warming beyond emitting carbon dioxide (CO_2). Aircraft engines emit other gases and particulate matter that affect the climate, air quality and our health. These lesser known non-CO_2 emissions have a significant impact on the environment, comparable to that of CO_2. Addressing contrails - the largest source of aviation's non-CO_2 emissions - alone would provide Europe with a significant leverage toward meeting global climate goals.

Key data points

3-5%

Implementing contrail avoidance frees up 3–5 percentage points of the global 2025–2050 temperature budget in a 2°C pathway that would otherwise be consumed by aviation.

50 million

People living near the main European airports experience the negative health and air quality impacts of aviation. Changes in the composition of jet fuel is a currently unused lever to address this matter.

3%

A small share - less than 3% of flights - generates 80% of contrail induced warming globally.

Aviation's total environmental footprint is the sum of its CO_2 and non-CO_2 impacts combined. While the EU claims to be seriously committed to addressing the full climate impact of the sector, regulation of and action on non-CO_2 emissions is lagging behind.

We have reached the point where science - at least for certain non-CO_2 forcers - is sufficiently robust, so that the EU can complement research with regulation and start gradually rolling out mitigation solutions. Further delay in taking action can't be justified under the precautionary principle. Evidence shows that even if the mitigation strategy is not perfect at first, the most significant climate risk can be inaction.

Addressing non-CO_2 emissions is necessary to stay on track with the Paris commitment

Mitigating non-CO_2 emissions is not only an opportunity for the aviation sector to reduce its environmental footprint in the short-term, but recent scientific research confirms that it is vital to

stay on track with the temperature goal of the Paris Agreement. CO_2 net zero efforts are crucial, but alone won't be sufficient to achieve the targets.

A three-pronged problem: climate, air quality and health

Beyond their climate impact, non-CO_2 emissions have an adverse effect on air quality and people's health, especially in communities living nearby a major airport. An estimated 50 million people living around the 32 major airports in Europe could experience significant health effects like high blood pressure, diabetes and dementia as a result of ultra fine particles released by aircraft. Addressing those pollutants through changes in jet fuel composition can lead to a double benefit: climate and health.

Solutions exist but need policy support to scale up

Mitigation solutions exist, but they can't be scaled up without a **favourable regulatory framework**. The necessary investments in operationalising contrail avoidance at scale or in R&D - such as developing and deploying tools for air traffic controllers to re-route aircraft for contrail-avoidance or further research into how changes in jet fuel composition can improve air quality - won't be realized without the necessary certainty for stakeholders.

This is why T&E has developed a vision on how combining different policies can enable the scale up of mitigation solutions. In developing this Roadmap, T&E has conducted a series of interviews with various stakeholder groups, such as airlines, Air Navigation Service Providers (ANSPs), policy makers, scientists and NGOs.

Key recommendations

Addressing aviation non-CO_2 emissions requires EU action in five different policy areas:

- **Integrating non-CO_2 emissions into EU climate targets**

The European Climate Law enshrines an economy-wide net zero target by 2050 but restricts its scope to Kyoto-listed greenhouse gases, omitting aviation non-CO_2 emissions. Guided by the precautionary principle, and building on the best available science, the EU must include contrails and non-CO_2 greenhouse gas emissions in climate targets in a phased-in manner, starting with the acknowledgement of the need to address them.

- **Integrating contrails into the EU ETS**

To effectively monitor non-CO_2 emissions and incentivise mitigation for airlines, it is crucial to proceed with the automatic extension of the EU's monitoring and verification tool (the non-CO_2 MRV) to all departing and incoming flights. This would ensure the most warming long-haul flights are in scope and thus inform policy making. In addition, the European Commission's proposed incentive scheme ("contrail allowances") in the EU ETS is a positive step enabling airlines to take action on contrail avoidance. An effective incentive scheme

should support contrail avoidance planning systems and the cost of executing contrail avoidance. In line with the MRV, the scheme should cover all flights arriving to and departing from Europe, and the support should be tailored to match the latest scientific insights on the cost of contrail avoidance.

- **Integrating contrail avoidance in European air traffic management**

Navigational contrail avoidance - re-routing flights to avoid the cold and humid airspaces prone to contrail-forming - is among the fastest and most affordable ways for the sector to mitigate its environmental footprint. In order to scale it up, Europe needs to:

  - Secure funding for medium and large-scale trials, with particular focus on combined trials, in the upcoming Aviation Strategy and in the next Multi-Annual Financial Framework (MFF) via initiatives such as the proposed Clean Aviation Moonshot.
  - Prioritize R&D for deployment of contrail avoidance with particular focus on ATM tooling.
  - Enable European ATM legislation for contrail avoidance. This includes a new Environmental and Climate KPI for Air Navigation Service Providers (ANSPs) that allows for contrail avoidance and expanding the mandate of the Network Manager to include contrail avoidance coordination.

- **Integrating non-CO_2 emissions into RefuelEU**

Changing jet fuel composition is a powerful but currently unused lever to improve air quality, and reduce health and climate impacts of aviation non-CO_2 emissions. As jet fuel remains the main source of fuel for aircraft for the next two decades, the EU should introduce a jet fuel specification as part of the RefuelEU review in 2027 and gradually lower the level of pollutants in the subsequent reviews.

- **Supporting non-CO_2 mitigation with aircraft technology**

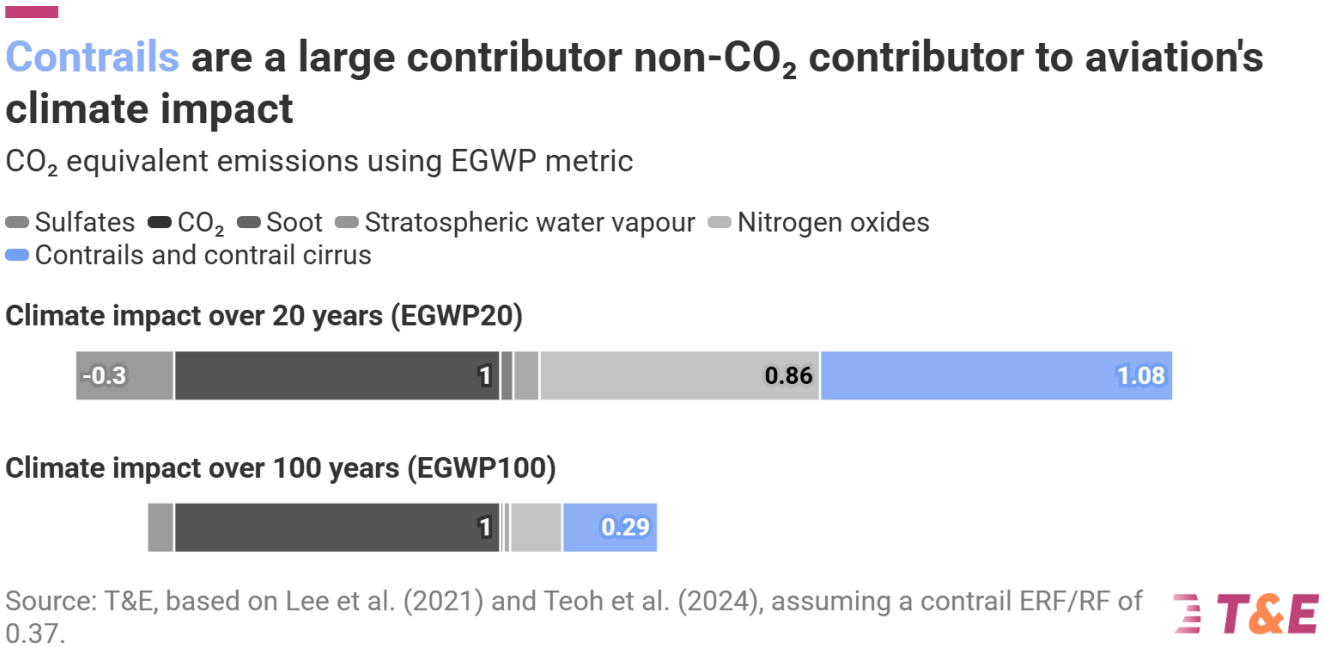
On top of contributing to decarbonisation, disruptive aircraft technologies, such as zero-emission and hybrid propulsion systems, also reduce aviation's non-CO_2 emissions. Therefore, public support for aviation R&D in the next MFF should move from incremental improvements to high risk, high reward technologies that mitigate both carbon and non-CO_2 emissions. The EU should also leverage existing aviation legislation, such as the EU ETS, ReFuelEU or the Air Services Regulation, to create the right market conditions for disruptive aircraft technologies. Finally, NO_x, vPM and nvPM engine emission standards should be strengthened, including the creation of a standard for cruise emissions.

01

Understanding aviation's non-CO_2 climate impacts

Aviation contributes to global warming by emitting carbon dioxide (CO_2) and currently accounts for around 2-3% of annual global CO_2 emissions. On top of that, aircraft engines emit other gases and particulate matter that affect the climate and our health. These are called non-CO_2 emissions. Aviation's non-CO_2 emissions include sulfur oxides, nitrogen oxides, soot, stratospheric water vapour and contrails. Their combined climate impact is of the same order of magnitude as aviation's CO_2. Despite that, they receive less public and policy attention than CO_2 emissions from aviation. The following chapter introduces the science of the different types of non-CO_2 emissions of aviation, with recommendations on how to advance scientific research in specific areas.

1.1 Contrails



Source: T&E, based on Lee et al. (2021) and Teoh et al. (2024), assuming a contrail ERF/RF of 0.37.

Condensation trails (contrails) form behind planes and are the single biggest contributor to aviation's non-CO_2 warming. When an aircraft burns jet fuel, it emits water vapour, soot and other particles at high altitude. Water vapour from the exhaust and the surrounding air freezes onto these particles, forming ice crystals that make up contrails. Most contrails disappear within a few

minutes. However, if a plane flies through regions with very cold and humid air known as ice supersaturated regions (ISSRs) the ice crystals in the contrails can last longer, forming persistent contrails. Over time, they can spread into contrail cirrus, thin high-altitude clouds lasting hours to days. These clouds reflect incoming sunlight (cooling) and trap outgoing infrared radiation (warming). The net effect is warming.

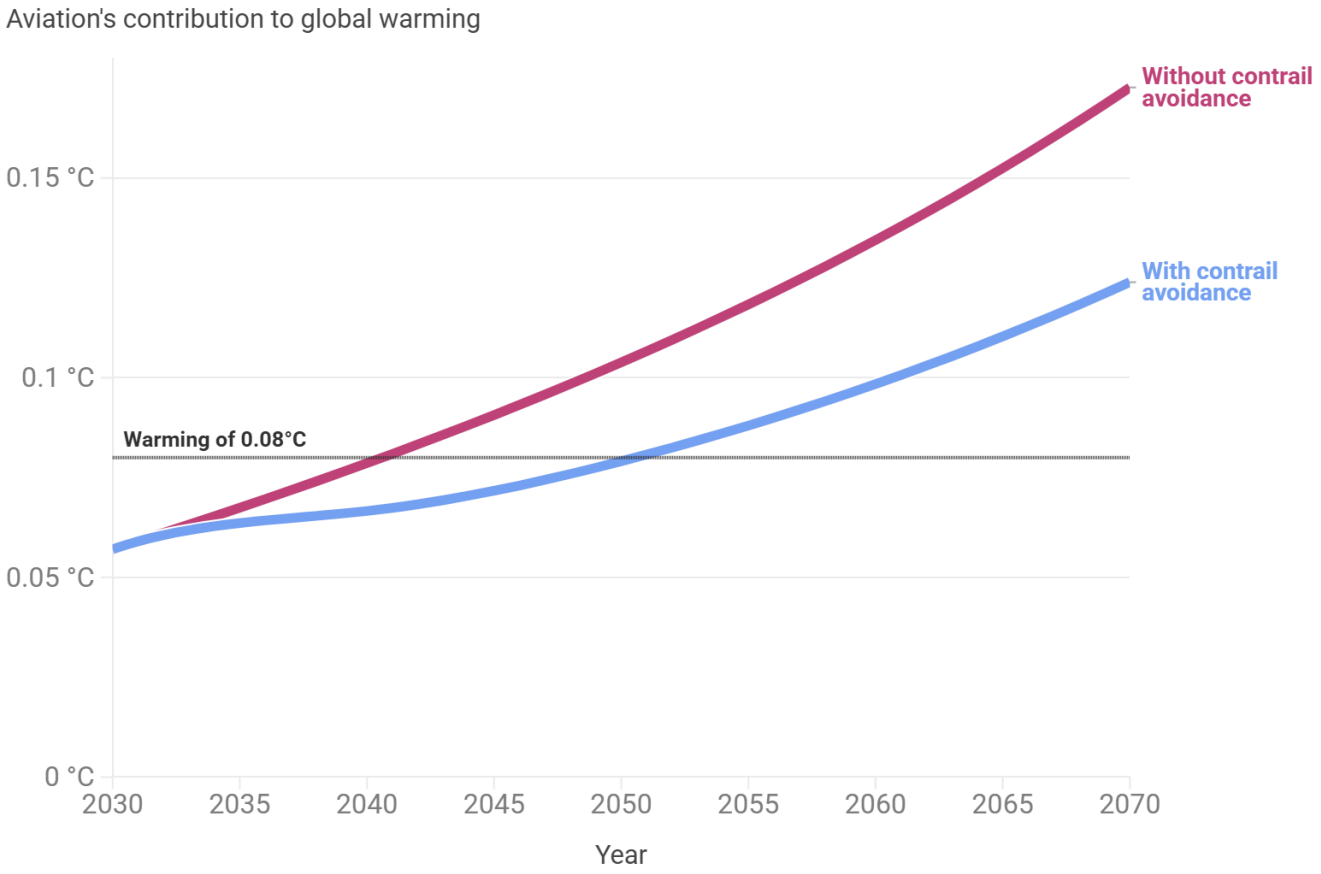
Contrail clouds are short-lived, lasting from minutes to, at most, a day or two. CO_2, on the other hand, remains in the atmosphere for centuries, accumulating as emissions grow and causing long-term warming. Despite their different life spans, the climate impact of both over decades is comparable, due to the outsized impact of contrails during their short life.

Fortunately, contrail warming can be addressed by focusing **on a small share of very warming flights - less than 3% of flights were responsible for 80% of global contrail warming in 2025.**

The atmospheric conditions for contrail formation are well understood: we know that warming strongly depends on when and where aircraft fly. This makes targeted contrail avoidance - avoiding regions where very warming contrails would form - very effective. For well-designed contrail mitigation strategies, the temperature benefit of mitigation could outweigh the additional CO_2 from any extra fuel burned by more than a 100 times. As a result, contrail avoidance is a relatively cheap climate solution, with costs as low as €20/t CO_2e abated

Based on current models, scaling up contrail avoidance from 2030, reaching 50% effectiveness by 2040, could delay aviation-related global warming by ten years. Aviation's contribution to global warming could reach 0.08°C in 2050 rather than in 2040. Starting in 2030, halving contrail warming could prevent around 0.025°C of warming by 2050 and 0.049°C by 2070. This corresponds to roughly 67-225 million tonnes of CO_2-equivalent benefit per year at current traffic levels. In other words, contrail avoidance could free up 3-5 percentage points of the global 2025–2050 temperature budget in a 2°C pathway, which would otherwise be consumed by aviation.

Cutting contrail warming could turn back aviation's climate clock by a decade



Source: T&E (2026), based on Klima Consulting (2026)

Despite the significant progress in understanding contrails science in recent years, some uncertainties remain. Importantly, a T&E study finds that none of these are blockers to deploying avoidance at scale. These uncertainties are linked to the following areas:

1. The impact of soot on contrail formation: Reducing soot emissions generally reduces contrail warming. However, when soot emissions become very low, for example with SAF, hydrogen, or some newer engine designs, other particles emitted or already present in the air can help contrails form instead. This means that there can be substantial contrail formation even when soot emissions are close to zero.
2. How much heat contrails trap: Contrails can warm the climate by trapping heat that would otherwise escape to space, but they can also cool it by reflecting sunlight back into space. Because these two effects partly cancel each other out, even relatively small errors in estimating either one can lead to larger errors in the overall climate impact.
3. How contrails interact with one another: Contrails need water in the air to grow. In busy flight corridors, many contrails can form in the same area and compete for the available water. Once much of that water has been used, any new contrails are likely to be smaller or

disappear more quickly. They may also form in contrail clouds left by earlier flights. This means that if one airline reroutes a flight to avoid creating a contrail, the climate benefit may be smaller than expected if several other aircraft are already creating contrails in the same patch of air.

4. How contrails interact with the atmosphere: Contrails can make the air where they form drier. As the ice crystals in a contrail fall, they take some water with them. This may reduce the formation of natural high clouds that also warm the climate, partly offsetting contrail warming. The size of this effect depends on the weather and remains uncertain because it can only be estimated using computer models, which give different results.

The following table highlights these four key uncertainties surrounding contrail as well as how they impact different contrail mitigation strategies. It highlights that many uncertainties can be mitigated by designing contrail mitigation well. For mitigation measures 2-4 (in the table below), the uncertainty around contrail-atmosphere interactions has a high impact since it affects the net climate benefit of contrail mitigation. However, it **does not invalidate avoidance**: even if contrail interactions with the atmosphere are large, flights producing strong contrail warming still justify rerouting.

How much do uncertainties impact different mitigation strategies

Uncertainty	1. Shift departure times	2. Airline-led pre-tactical avoidance	3. Airspace restrictions	4. Tactical avoidance	5. SAF / Hydrotreated fossil jet fuel
How contrails form	No uncertainties blocking this mitigation strategy	Small impact on effectiveness of this mitigation strategy	Small impact on effectiveness of this mitigation strategy	Small impact on effectiveness of this mitigation strategy	Fine for rich-burn; field testing needed for lean-burn
How much heat do contrails absorb	Start with night flights	Start with night flights	Start with night flights	Start with night flights	Targeted use on night flights
Contrail-contrail interactions	No uncertainties blocking this mitigation strategy	Start in low-traffic areas or coordinate at network level	No uncertainties blocking this mitigation strategy	Start in low-traffic areas or coordinate at network level	No uncertainties blocking this mitigation strategy
Contrail-atmosphere interactions	Impact on effectiveness of this mitigation strategy	Ensure strong net benefit threshold	Ensure strong net benefit threshold	Ensure strong net benefit threshold	Ensure strong net benefit threshold

Uncertainty Impact: None Low Medium High

Source: T&E (2026)

The science is mature enough to act on contrails and introduce legislation if mitigation is designed carefully. The remaining uncertainties do not affect whether contrail avoidance works: targeting the most warming contrails and capping the acceptable extra fuel burn from avoidance maneuvers ensures that contrail avoidance potentially has outsized climate benefits even if contrail warming turns out smaller than currently estimated.

Based on the above, T&E recommends the following action on the remaining uncertainties:

01 Focus research on the uncertainties that most affect whether contrail avoidance delivers a real climate benefit:

Priorities include:

- **Contrail formation:** Follow up on test campaigns (such as ECLIF3 and VOLCAN campaigns) to verify how SAF and hydrotreated fossil kerosene affect contrail formation in newer engines.
- **How much heat do contrails absorb:** Build better observational datasets to improve estimates of contrail warming and cooling.
- **Contrail-contrail interactions:** Improve models of how nearby contrails affect one another when they form in the same area.
- **Contrail-atmosphere interactions:** Run coordinated comparisons of climate models to assess how contrails affect the atmosphere.

While further research into these topics will optimise mitigation strategies over time, they don't limit or delay the possibility of deploying contrail avoidance at scale.

02 Fund contrail avoidance trials to resolve the remaining uncertainties:

Medium-scale trials before 2030, followed by a large-scale contrail avoidance trial in the early 2030s would provide a setting in which contrail-contrail interactions can be observed at realistic traffic densities, and in which mitigation measures can be tested against observed outcomes in different weather conditions. A large-scale trial would require thousands to tens of thousands of flights, sustained for at least a year. It must use transparent methods, a common evaluation framework and open data to verify benefits at scale. It should apply conservative net-climate-benefit thresholds that account for the uncertainty in contrail-atmosphere interactions and any additional CO_2 emissions.

03 Require OEMs to develop and install humidity sensors on commercial aircraft:

Unlike satellites, low-maintenance humidity sensors can directly map regions where contrails form. By gathering high-resolution atmospheric data at cruising altitudes, humidity sensors can support better ISSR forecasting.The priority should be to support the development of certified,

low-maintenance humidity sensors by around 2029, followed by installation on new aircraft and retrofitting of existing aircraft from 2031. Sensors should be installed in a sufficient number of aircraft to achieve wide geographic coverage.

1.2 Nitrogen oxides

Nitrogen oxide (NO_x) emissions are estimated to be the second-biggest contributor to aviation's non-CO_2 warming. At cruise altitude, NO_x enhances ozone formation, a short-lived greenhouse gas. At the same time, NO_x removes methane, which is another potent greenhouse gas, leading to a cooling effect. Studies suggest that currently, the warming from increased ozone outweighs the cooling from methane removal, resulting in a net warming effect. Yet, the net climate impact of nitrogen oxide emissions also depends on the background atmospheric concentration of pollutants. In a possible future scenario with higher methane levels in the atmosphere, the methane-removal effect might lead to a net-cooling effect. Engine design also involves a trade-off: less NO_x generally means more fuel burn. Climate policy on NO_x therefore requires more care than policy on contrails, involving careful trade-offs between the climate and health benefits of NO_x reductions against the additional CO_2 emissions and other climate and health impacts associated with higher fuel consumption. Currently, NO_x is regulated at an international level only during take-off and landing, through ICAO.

At this stage, T&E recommends further research into the climate and health impact of aviation NO_x emissions, including how their warming and cooling effects evolve under different atmospheric conditions. Crucially, technological (e.g. engine technology) and operational mitigation options must be evaluated - accounting for trade-offs with fuel consumption, CO_2 emissions and other pollutants - to inform future regulation of NO_x emissions at cruise altitude.

1.3 Sulfur

Sulfur emissions have a cooling effect by forming particles that reflect sunlight back into space. This effect is small compared to the warming effects of other emissions, such as CO_2 and contrails.

Still, there is another less well understood effect where sulfur emissions can act as seeds for cloud formation, potentially altering the structure and lifespan of low-altitude clouds. This effect is potentially rather large and cooling.This has a direct policy implication: changing the sulfur content of jet fuel, whether through blending low-sulfur SAF or by desulfurising conventional kerosene, may carry material climate uncertainty as it reduces cooling. Further research is required.

1.4 Soot and stratospheric water vapor

Other non-CO_2 emissions, such as soot and stratospheric water vapour also contribute to global warming but to a lesser extent than contrails. Soot's main climate impact is indirect, as it increases contrail formation. Soot emissions will likely decrease through the ongoing adoption of lean-burn engines. Still, as noted above, very low soot levels do not necessarily reduce contrail

formation. Stratospheric water vapour emissions cannot be avoided, but are only a minor concern for current subsonic aircraft. For a possible supersonic aircraft fleet operating at higher altitudes, stratospheric water vapour might have a large climate impact.

1.5 Beyond climate: the air quality impact of aviation's non-CO_2 emissions

Independently of climate, soot, nitrogen oxides and sulfur oxides degrade air quality, particularly around airports.

One of the key pollutants from jet engines is particulate matter (PM), a broad term that encompasses non-volatile particulate matter (soot) as well as volatile particulate matter, which forms from sulfur oxides, nitrogen oxides and unburned hydrocarbons as sulfates, nitrates and organic aerosols. PM also includes ultrafine particles (UFPs), tiny particles less than 100 nanometers in diameter. UFPs are of particular concern because they are emitted in large numbers during take-off and landing, exposing millions of people living near airports. They can penetrate deep into the lungs and enter the bloodstream, potentially causing respiratory symptoms, cardiovascular issues, elevated blood pressure, and even long-term effects like increased mortality and neurological diseases. Studies have shown that aviation emissions are characterized by high concentrations of UFPs, particularly in and around airports. The health impacts of aviation-related UFPs are stark: a CE Delft study commissioned by T&E looking at 32 major European airports estimated that around 50 million people living near these airports could experience significant health effects like high blood pressure, diabetes and dementia. Despite these risks, UFPs remain largely under-researched and unregulated, presenting a significant gap in public health protection. Although the EU Ambient Air Quality Directive (AAQD) requires Member States to set up sampling points at hotspots such as airports for UFPs, no legally binding concentration limits or reduction targets for UFPs are defined.

02

Integrating non-CO_2 emissions into EU climate targets

2.1 Introduction

The EU has long been an international leading voice on climate action and catalyst for decarbonisation. With the Green Deal, this ambition was translated into a clear objective: Europe aims to be climate neutral by 2050 - an economy with net-zero greenhouse gas (GHG) emissions, including CO_2.

Building on this vision, the 2050 net zero goal evolved into a legally binding target with the adoption of the European Climate Law in 2021. To track progress and ensure the final goal is met, interim targets have also been set: reducing net GHG emissions by at least 55% by 2030, and by 90% by 2040, compared to 1990 levels.

The overarching climate objective shapes sectoral policies in the EU in different ways. On the one hand, it requires all sectors of the economy and society to play their part. Therefore, amendments in sectoral legislation took place, for instance by including aviation into the EU Emissions Trading System (ETS). On the other hand, consistency with climate-neutrality has become the benchmark for any new proposed legislation: the European Commission is obliged to assess it and provide reasoning in case of non-compliance.

Unfortunately, unlike in the case of CO_2 emissions, there is no such clear long-term vision concerning non-CO_2 emissions. The current EU climate legislation relies on an enclosed list of GHGs, based on the Kyoto Protocol, containing carbon dioxide (CO_2), nitrous oxide (N_2O), hydrofluorocarbons (HFCs), perfluorocarbons (PFCs), sulfur hexafluoride (SF_6), nitrogen trifluoride (NF_3) and methane (CH_4). Non-CO_2 emissions - with the exception of methane - are currently not in scope of the European Climate Law. Instead, they are left to be dealt with by sectoral legislation (if any) without a clear overarching strategy and direction.

Bridging this policy gap requires EU action. In this chapter, we assess EU climate legislation from a non-CO_2 emissions perspective - with reference to the relevant international treaties to which the EU is a contracting party - and then make recommendations for their integration for the aviation sector.

2.2 EU climate legislation

The EU climate architecture is deeply anchored in international law. While the international agreements ratified by the EU generally bind the Union and its Member States, in the area of

climate legislation, there is a specific EU mandate to promote the international measures to combat climate change.This explains how the EU climate legislation was shaped and gained its current form.

Infobox: Relevant international climate treaties on non-CO_2 emissions

The main international climate treaties - such as the Paris Agreement, or its predecessor the Kyoto Protocol - almost exclusively cover so-called long-lived climate forcers and not short-lived climate forcers, like non-CO_2 emissions. The terms 'short-lived climate forcers' and 'non-CO_2 emissions' have a different origin, but a big overlap. Short-lived climate forcer is a scientific category referring to the atmospheric lifetime of the given substance, whereas non-CO_2 emission is a legal notion for emissions beyond CO_2. In the case of aviation we can talk about long-lived climate forcers (e.g. CO_2) and short-lived climate forcers (non-CO_2 emissions, like contrails or aerosols).

According to the Intergovernmental Panel on Climate Change (IPPC) short-lived climate forcers are substances (e.g.: nitrogen oxides, black carbon or particulate matter) that affect the climate either by warming or cooling it, and only persist in the atmosphere from a few hours to a couple of months. They are, in most cases, also air pollutants. Regarding **their climate impact, on a 10-to-20 year time horizon, annual emissions of short-lived climate forcers accounts for as much warming as CO_2**. On longer timeframes though, the impact of cumulative CO_2 emissions' is more prominent.

But why do lawmakers traditionally restrain from including short-lived climate forcers into international agreements? It can be explained by the atmospheric and policy differences between the two groups.

- **Different timescale**: Depending on the time horizon choice the climate impact of short-lived climate forcers is either understated or distorted, making it difficult to integrate them into traditional net zero target setting, where the usual metric is the 100-year Global Warming Potential (GWP100).
- **CO_2 vs non-CO_2?**: Due to their limited atmospheric lifetime, short-lived climate forcers can be reduced much quicker than CO_2, thus potentially diverting attention from long-term decarbonisation.
- **Dual nature**: As short-lived climate forcers are in most cases also air pollutants, legislators tend to regulate them via air quality and health policies rather than climate legislation.
- **Mixed climate signal**: Short-lived climate forcers can have a warming, cooling or a mixed climate impact.

Despite these challenges, the IPCC's recommendation is clear: policy frameworks must integrate decarbonisation with targeted measures for short-lived climate forcers for two main reasons: to avoid near-term warming spikes and to safeguard public health (because of air pollution reasons).

Adopted in 2021, the EU Climate Law enshrines the EU's commitment to the Paris Agreement by setting a binding net reduction target for the covered GHGs by 2050. In doing so, EU legislation mirrors the approach of the Kyoto Protocol - the predecessor to the Paris Agreement - by restricting its scope to a closed list pollutants (carbon dioxide (CO_2), nitrous oxide (N_2O), hydrofluorocarbons (HFCs), perfluorocarbons (PFCs), sulfur hexafluoride (SF_6), nitrogen trifluoride (NF_3), methane (CH_4). The main aviation non-CO_2 emissions are therefore missing.
Interim reduction targets are set for 2030 (at least 55% compared to 1990 levels) and 2040 (90% compared to 1990 levels) and the Climate Law is reviewed every other year to keep track of the progress.

EU Member States, as parties to the Paris Agreement, also have an obligation to contribute to the achievement of the long-term temperature goal of the treaty (holding the increase in the global average temperature below 2°C above pre-industrial levels and to pursue efforts to limit the temperature increase to 1.5°C above pre-industrial levels). As developed nations, they are expected to take the lead by undertaking economy-wide emissions reduction targets. No specific sectoral goals are defined in the treaty. Their efforts are joint and coordinated as the EU submits a single Nationally Determined Contribution (NDC) on behalf of its Member States.

2.3 Policy recommendation

01 Phased-in inclusion of contrails and other aviation non-CO_2 GHG emissions in climate targets

Both the relevant international EU agreements to which the EU is a contracting party to and EU law (EU Climate Law included) refer to the **precautionary approach as a guiding principle in climate action.** In EU law terms, "the precautionary principle may be invoked when a phenomenon may have a dangerous effect, identified by a scientific and objective evaluation, if this evaluation does not allow the risk to be determined with sufficient certainty." In other words, proactive protective action can be taken if there's an environmental risk, even if the risk cannot be precisely quantified. In the case of aviation non-CO2 emissions, the EU ETS Directive specifically refers to the precautionary principle, as a reason why they can't be ignored and EU regulatory measures are needed (in the form of a monitoring scheme and a legislative proposal based on its results by 1 January 2028).

Furthermore, both the Paris Agreement and EU climate legislation require climate action to be

based on the best available science. And the science is absolutely clear that non-CO_2 aviation emissions have a net warming impact of aviation non-CO_2 emissions is comparable to that of CO_2.

The long-term climate targets in the Paris Agreement are defined in temperature and not in an emissions reduction goal. The treaty - unlike the Kyoto Protocol - does not define GHGs by reference to a closed list. It therefore requires parties - EU and its Member States included - to make ambitious efforts to address all GHG emissions. As recent scientific research confirms, in the case of aviation, achieving net-zero CO_2 emissions will not be enough to align the sector with the Paris Agreement. Instead, updated strategies need to include short-lived climate pollutants like contrails.

Finally, as stated in the EU Climate law, all economic sectors need to contribute to the achievement of the climate goals. Therefore, half of aviation emissions can't be ignored regarding the sector's contribution.

Because of the four above-mentioned reasons, and as found in T&E's legal analysis, we suggest that the integration of aviation non-CO_2 emissions into EU climate targets takes place in two phases.

- **Phase one:** Acknowledge non-CO_2 emissions of aviation and establish the need to address them during the 2028 review of the European Climate Law.

- **Phase two**: Set targets for aviation's non-CO_2 emissions reduction in a later review of the Climate law.

The incorporation can be done by amending the European Climate Law to indicate that the binding climate objectives set out in the Regulation do not refer exclusively to the Annex of the Regulation but also to the definition of non-CO_2 aviation effects, included in Article 3(v) of the EU ETS Directive.

Infobox: UK perspective and recommendations

At present, the UK has similar policy gaps in how non CO_2 is treated in climate goals as faced by the EU. Carbon budgets, covered by the Climate Change Act 2008, do not cover contrail warming or aviation's other non-CO_2 emissions, meaning they are not covered by any comprehensive UK target, budget or pricing mechanism. This is recognised by the Jet Zero Taskforce. The UK Government should therefore take several steps to strengthen the policy framework for non-CO_2 emissions:

- **Policy** - the Department for Transport should acknowledge contrails and other non-CO_2 effects in the next Jet Zero strategy update. The Climate Change Committee, the UK's independent advisory board on climate action, should report on non CO_2 issues like contrails and identify where the UK makes progress in its annual progress reports.
- **Data -** once monitoring and reporting data is more readily available, a non CO_2 metric and target should be enforced as part of the UK's central climate legislation. The UK Government should consider whether new primary legislation is required, or whether existing secondary powers within the Climate Change Act can cover this.

03

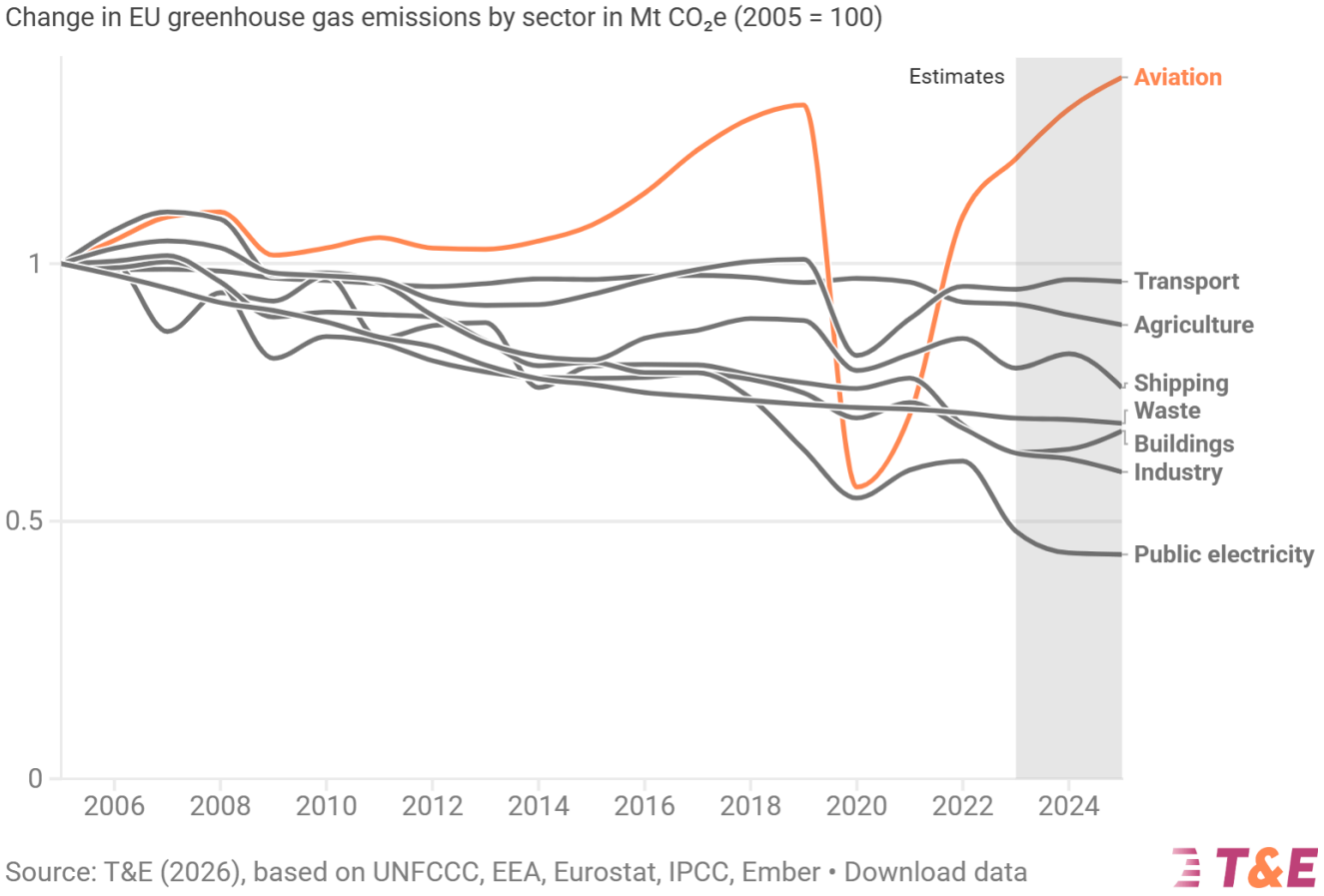
Integrating contrail avoidance in the EU ETS

3.1 Introduction

Aviation is among the fastest-growing contributors to climate change. While greenhouse gas emissions in other sectors are expected to decrease, aviation is still on a growth trajectory.

Aviation is the EU's fastest growing source of emissions

Aviation emissions have risen by more than 30% since 2005 - the start of the ETS - while emissions from other sectors have declined



The Emission Trading System (ETS) is one of the key instruments the EU utilizes to address the sector's CO_2 emissions. The EU Emissions Trading System (ETS) puts a price on emissions through a market-based mechanism, ensuring that the Polluter Pays Principle is upheld. In 2012, the system was extended to the aviation sector to ensure **airlines pay for their emissions while also generating revenue to reinvest in the green transition of the sector**. In 2025, airlines

operating in Europe paid nearly €4.1 billion for EU, Swiss and UK ETS allowances (while an estimated €8.5 billion in emissions costs went unpaid, a consequence of the exclusion of long-haul flights).

The EU's non-CO_2 Monitoring, Reporting and Verification (MRV) framework, the world's first mandatory system to measure aviation's non-CO_2 climate impacts, was launched within the EU ETS system in 2025. Due to international and industry pressure, its scope was limited to intra-EEA flights (and flights to the UK and Switzerland) for the first two years, but the full scope will apply automatically from 1 January 2027.

Despite its strengths, the current EU ETS Aviation framework has some critical limitations, the main one being its geographical scope. Both CO_2 pricing and the non-CO_2 MRV only cover intra-EEA flights and flights from the EU to the UK and Switzerland, leaving the most polluting long-haul flights out of scope. As part of the EU ETS framework review, in its proposal from July 2026 the European Commission proposes the extension of scope to 5000km radius (calculated from Frankfurt airport) and an incentive scheme for contrail avoidance for airlines.

The next section of this chapter assesses the non-CO_2 emissions related aspects of the EU ETS and reflects on the Commission's proposal for incentives for contrail avoidance with a view to suggest a policy design that can effectively drive non-CO_2 mitigation.

3.2 Non-CO_2 in the EU ETS

3.2.1. Monitoring of non-CO_2 emissions

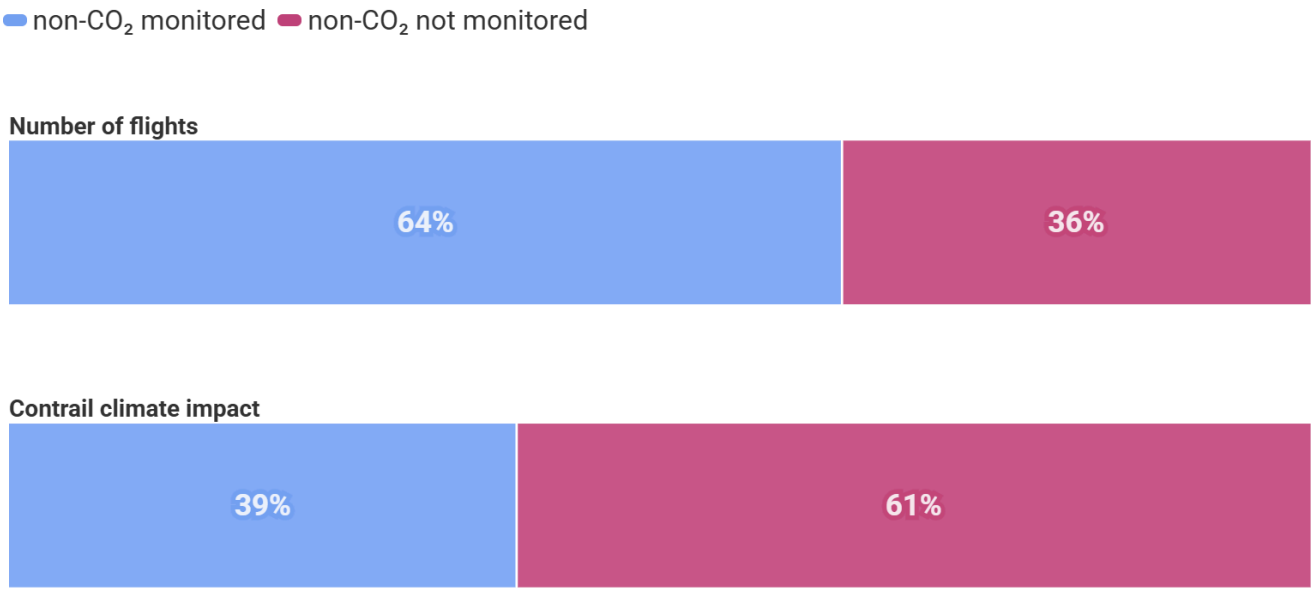
Since January 2025, the EU's non-CO_2 MRV requires airlines to upload flight data (such as trajectories, engine efficiency, and fuel composition) into a dedicated IT platform, called NEATS. The platform then pairs that with weather data and atmospheric models to eventually convert them into net radiative forcing per flight, defined in CO_2 equivalent (CO_2e). Airlines can also opt to report only the flight information within NEATS. NEATS will then extract the relevant data from EUROCONTROL or calculate data based on default values. Once a report is generated by NEATS, airlines are obliged to have their non-CO_2 emission report reviewed and audited by an independent verifier and then submit their results to their respective civil aviation authority.

While NEATS and independent verification ensure reliable monitoring and reporting, the temporary reduction of the MRV scope means it misses many of the flights that warm the climate most. Long-haul flights cause a large share of aviation's climate impact. They spend more time at high altitudes, which makes them especially important for both contrails and NOx, exactly the effects the MRV is meant to capture.

Long-haul flights represent less than 10% of European departures but 40% of contrail warming and contrail warming per kilometre over the North Atlantic is 70% higher than over Europe. Flights from Europe to the United States alone account for an estimated 65 Mt CO_2e of unmonitored non-CO_2 warming, followed by China, the United Arab Emirates, Turkey and Canada.

More than half of contrail climate impact is excluded from the reduced-scope non-CO_2 MRV framework

Share of flights and contrail warming monitored in reduced-scope non-CO_2 MRV, covering intra-EEA flights and flights to Switzerland and the UK



Source: T&E (2026), based on own analysis of Spire Aviation ADS-B data for the year 2025 using pycontrails v0.60.4

3.2.2 Incentives under the EU ETS for contrail action

One of the novelties of the 2026 European Commission's ETS review proposal is the introduction of contrail allowances aiming at incentivising navigational contrail avoidance for airlines. Contrail avoidance is one of the most cost-effective ways to reduce aviation's climate impact, yet the incentivisation of airline action under the framework has been so far missing. According to a T&E study, contrail mitigation starting in 2030, targeting a 50% reduction of contrail warming by 2040, could reduce global warming by about 0.025°C in 2050 and 0.049°C in 2070.

What does the Commission's proposal say? Airlines would receive free ETS allowances for embedding contrail-forecasting models in their flight-planning systems. An operator would receive allowances equivalent to 0.1% of its verified emissions if contrail forecasts are made available to its operations control centre and incorporated into filed flight plans whenever operationally feasible. A further 0.02% would be available where the operator submits additional flight data through NEATS. The incentive would apply to verified emissions within the proposed ETS scope, including the new 5,000 km radius.

Up to 420,000 allowances per year would be available for contrail mitigation, subject to an overall ceiling of three million allowances until 31 December 2033. T&E estimates that the current mechanism could provide annual support of up to approximately €2.5 million for an airline such

as Ryanair and €300,000 for an airline such as TUI. Based on expected participation, around 120,000 of the available 420,000 allowances could be allocated each year, leaving considerable room to strengthen the incentive and support the costs of operational avoidance.

Given the size of the prize - exceptionally cost effective climate warming reduction for aviation in the short-term - it is crucial that the incentive scheme works well and gets airlines onboard for contrail action. Therefore, the proposal must be strengthened by **supporting both contrail avoidance planning (onboarding contrail avoidance tools) and execution (actual contrail avoidance)**. Based on an initial T&E assessment of the potential use of the contrail incentives, **10 million allowances would be sufficient to avoid at least 50% of aviation contrail induced warming effects across all EEA arriving and departing flights.** Ideally, the support would be structured as follows:

- Planning and onboarding of tools: Allowances should be allocated to support the onboarding of contrail avoidance tools and processes on all airlines currently obligated under the EU ETS.This would entail around 230 airlines able to install contrail avoidance systems and develop processes. On top of the Commission proposal to allocate allowances equal to 0.1% of the aircraft operator's annual emissions, our proposal is to add a flat amount of allowances equal to ~€200,000 for all eligible airlines, ensuring small operators with lower ETS emissions would also benefit.. Our analysis shows this support would require around 600,000 allowances annually.
- Execution and avoiding contrails: Based on T&E analysis, 1.4 million allowances annually would be sufficient to support actual avoidance of contrail warming flights. This incentive would cover the airline's operational costs to avoid contrails. T&E calculates that an incentive which covers all additional operational costs for flights that have a certain contrail warming reduction effect would ensure a 50% reduction of contrail induced warming, highlighting the power of the incentive tool. The support to airlines would be provided through a fixed percentage per flight - defined in a delegated act after the reviewed text is adopted - for which they achieve meaningful CO_2e emissions reduction through contrail avoidance. The provided fixed percentage should reflect the operational costs, mainly fuel costs, made by airlines to achieve contrail avoidance.

Contrail allowances **can also serve as a means of incentivising airline-led contrail avoidance trials.** Airline-led trials - the most common approach to navigational contrail avoidance in recent years - support both technological advancement (development and verification of flight planning tools with contrail avoidance functionality) and operational readiness of airlines, so that they are prepared for when contrail avoidances becomes routine activity.

If done well, an incentive scheme under the EU ETS could have a meaningful impact towards reducing contrail warming: it would incentivise airlines to onboard the necessary software whilst reimbursing costs of actual avoidance. **For the first time, a scheme would incentivise contrail avoidance at scale, potentially halving contrail warming in Europe.**

3.3 Policy recommendations

01 Maintain the automatic extension of the non-CO_2 MRV to full scope

T&E emphasises the importance of proceeding with the automatic scope expansion in 2027.The automatic extension of the MRV scheme to the initially extended full scope ensures:

- The ⅔ of non-CO_2 emissions currently not covered - especially the very warming long-haul flights - are included in the mandatory monitoring and reporting scheme in line with the legislators intention.
- The build up of a comprehensive evidence base that can support policy making.

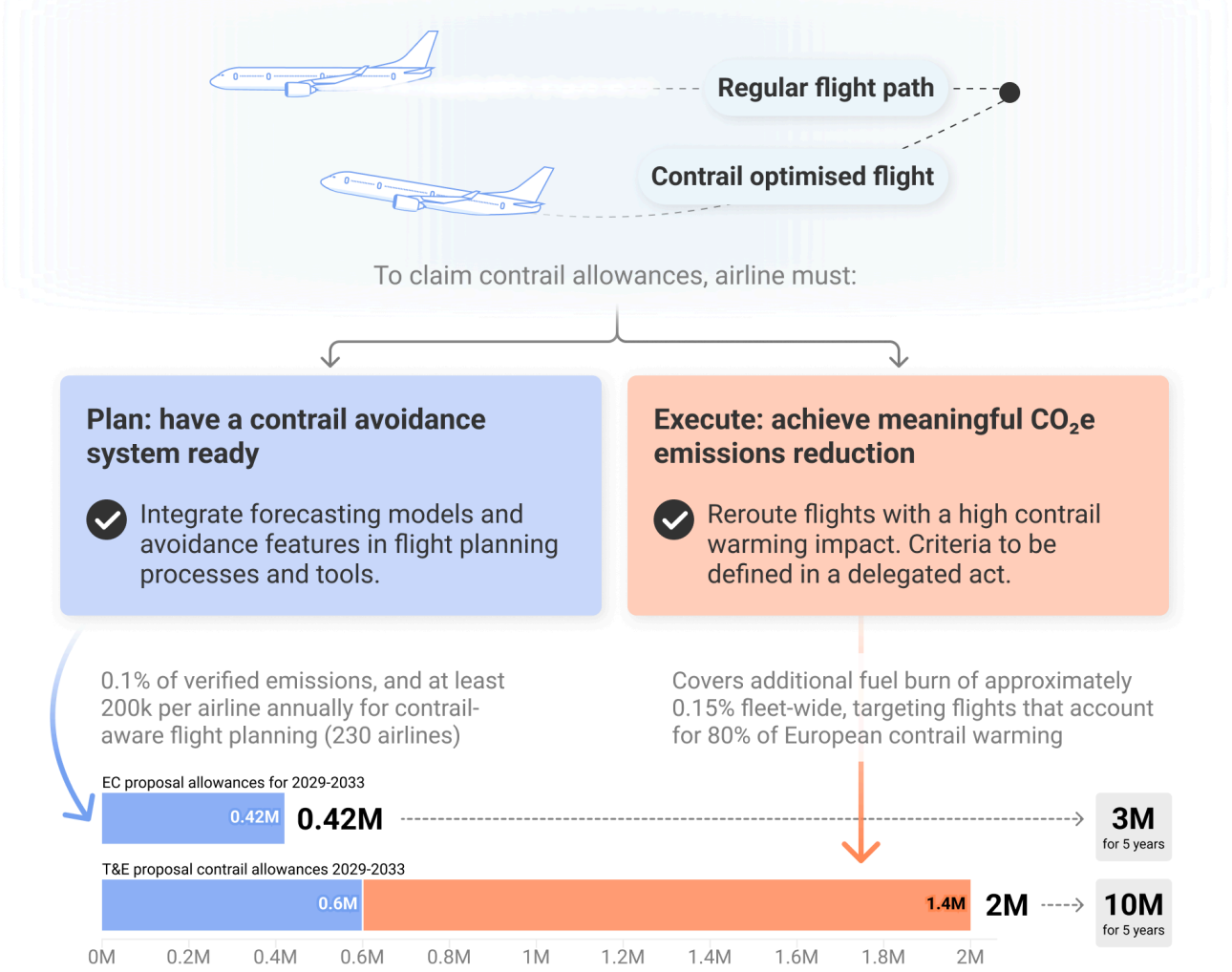
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02 Improve the incentive scheme for contrail avoidance under the EU ETS

While we consider the Commission's contrail allowance proposal a step into the right direction, the current draft presents some shortcomings that need to be fixed so that the incentive scheme is fit for purpose and drives contrail awareness and avoidance at scale.T&E recommends the following adjustment of the scheme:

- **Scope**: we suggest the scope to be expanded to all arriving and departing flights, recognizing that global frameworks, such as CORSIA do not tackle non-CO_2 emissions and that the most promising avoidance routes fall outside the current radius limit. For instance, a very contrail prone area, the North-Atlantic corridor is currently not in the proposed scope of the incentive scheme. A full departure scope for the contrail incentive scheme would ensure that airlines tacking contrails can receive support for the flights with the highest contrail impacts.
- **Amount of allowances**: to drive meaningful mitigation, the amount of allowances should be increased from 3 million to **10 million allowances**. This could incentivize embedding contrail avoidance systems for 230 airlines and would cover the airline's operational costs to avoid contrails. T&E finds that with this adjustment Europe could reduce contrail warming by 50%.
- **Structure of the system**: Support should reward both the installation of systems and procedures to avoid contrails as well as the actual verified operational avoidance of warming contrails. As such we propose a **planning** and **execution** incentive within the mechanism.

T&E recommendations for free ETS allowances for contrail avoidance



Source: T&E (2026) • Assumptions: coverage of all EEA departures and arrivals, 230 eligible airlines, a fuel price of approximately €1,400/t, and annual fuel-consumption growth of 1.1%.

- **Delegated act for the detailed functioning of the scheme**: We suggest that the details of the functioning of the scheme - such as technical specifications regarding weather models and verification systems should be dealt with in a delegated act instead of the main EU ETS text right after the adoption of the former. That would on the one hand provide more time for the legislator to fine tune the system based on the latest EU research and contrail trial results and would allow easier adjustment moving forward in case of new insights.

Infobox: UK perspective and recommendations

At present, the UK ETS only covers domestic and UK-EEA departures, so the highest impact flights from a non-CO_2 perspective, such as those in the North Atlantic corridor, are currently

not covered. In its 2024 consultation on CORSIA, the UK ETS Authority suggested that non-CO_2 measures were being considered for inclusion under the scheme. However, there was limited information on a formal proposal or clear timeline. Non-CO_2 inclusion was not touched on in the consultation on the treatment of SAF under the UK ETS. The UK Government should therefore:

- Start monitoring non-CO2 emissions within the UK ETS as soon a possible. To align with the EU, ensure that any decision covers all UK departing flights.
- Use the upcoming linking of the UK and EU ETS to ensure mutual recognition of non-CO_2 systems, and push for this as part of ongoing negotiations on the ETS linkage.
- Support a UK contrail allowance fund, similar to T&E's recommendation for the EU.

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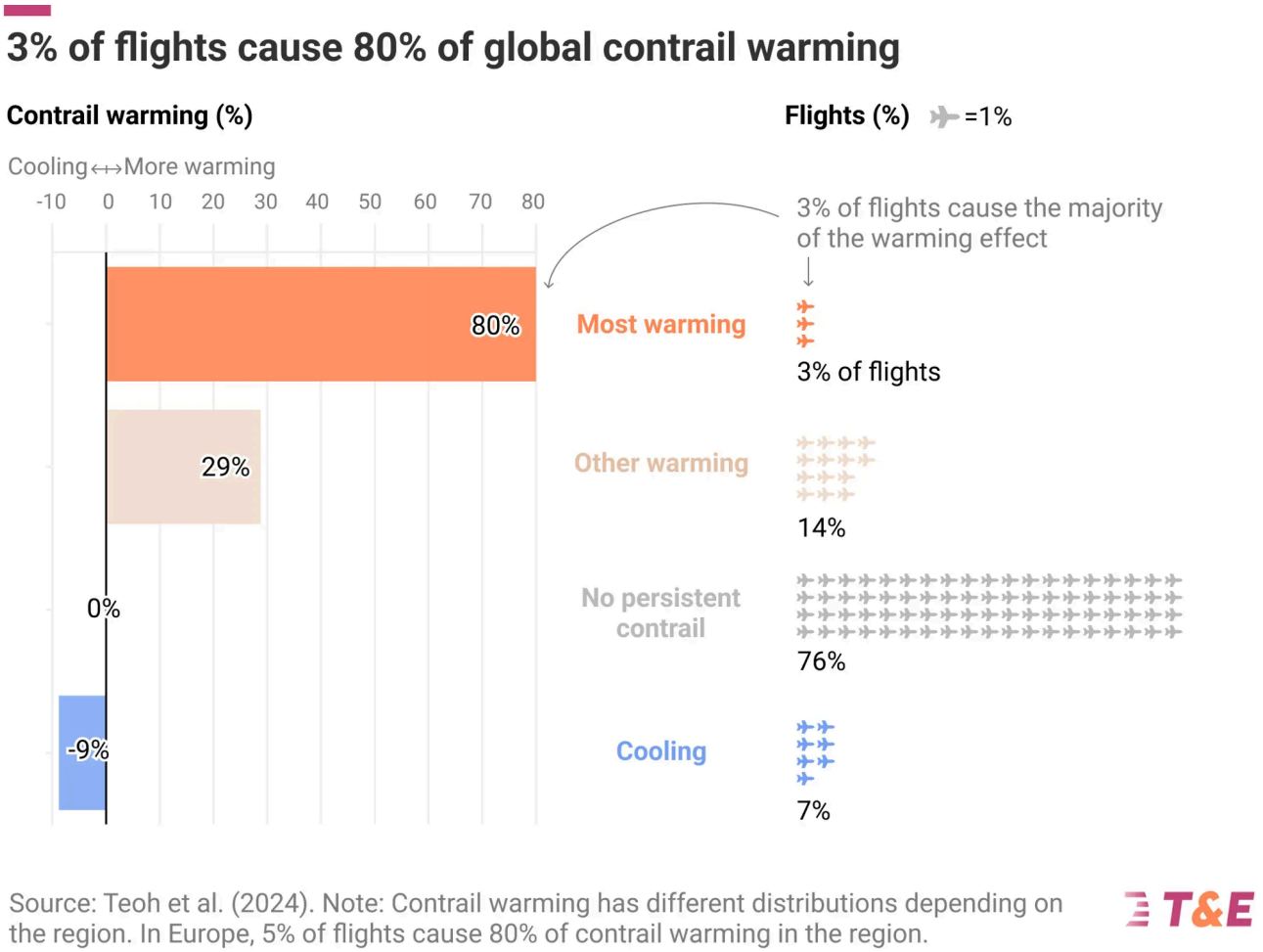
Integrating contrail avoidance in European air traffic management

4.1 Introduction

Navigational contrail avoidance involves rerouting aircraft to avoid cold, humid airspace prone to contrail formation, known as ice-supersaturated regions (ISSRs). It has been researched since the publication of the IPCC's landmark 1999 special report, *Aviation and the Global Atmosphere*.

Since the first half of the 2020s, real-world flight trials have shown that navigational contrail avoidance is feasible and has the potential to mitigate contrail-induced warming. They have also helped identify the operational challenges that must be addressed to realise these climate benefits.

As contrail warming is highly concentrated, a well-designed, targeted avoidance strategy, despite the challenges of integrating contrail avoidance into European ATM, would only have a limited impact on the network as whole.



Source: Teoh et al. (2024). Note: Contrail warming has different distributions depending on the region. In Europe, 5% of flights cause 80% of contrail warming in the region.

This chapter first examines the practical implications of integrating contrail avoidance into European airspace. It then outlines the policies governing European ATM and draws lessons from past contrail trials. Finally, it recommends legislative changes to prepare the ATM system for contrail management by 2032.

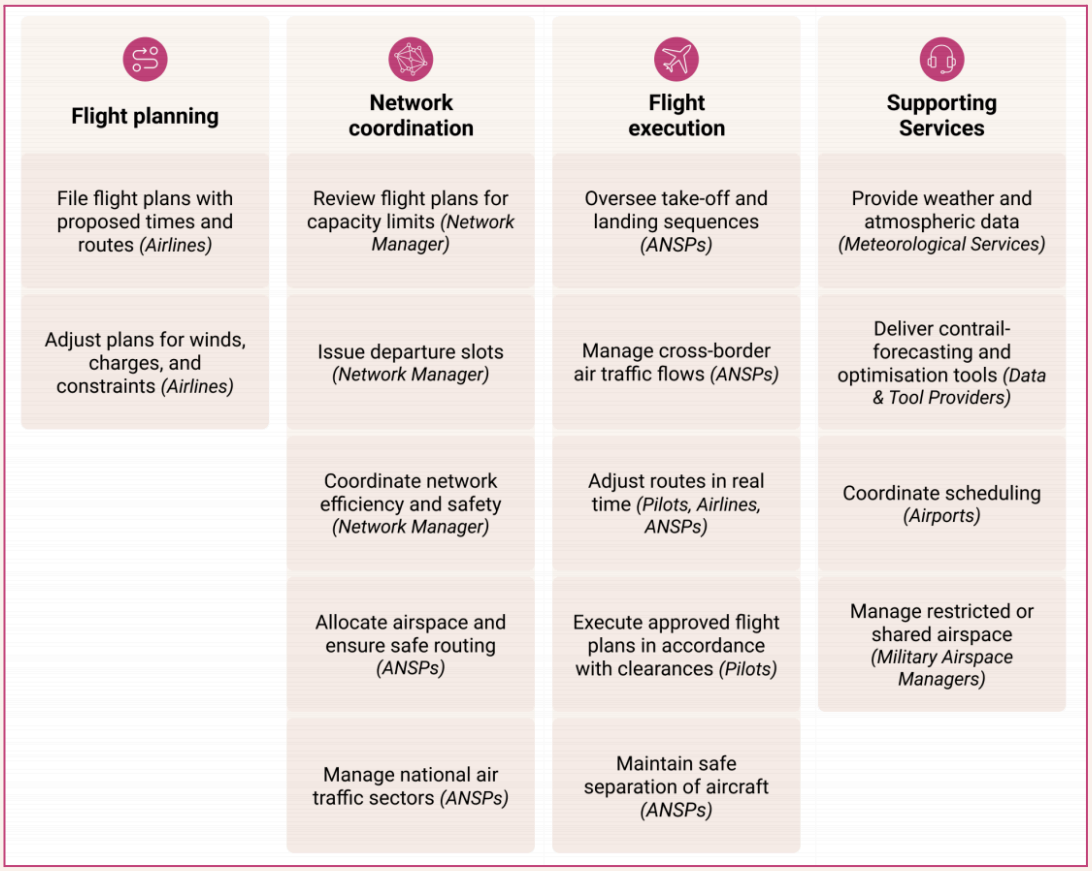
4.2 How does air traffic management work and how will it integrate contrail avoidance?

4.2.1 Roles and responsibilities in air traffic management

Air traffic management (ATM) encompasses the functions, both in the air and on the ground, required to ensure the safe and efficient movement of aircraft throughout a flight. It is a complex activity involving multiple stakeholders, with safety as a non-negotiable requirement. Within that requirement, the system continuously balances competing and interdependent priorities: airspace capacity (meeting traffic demand), efficiency (reducing flight times, fuel burn and costs) and environmental impacts (emissions and noise).

Infobox: Role of different stakeholders in flight planning

Who decides flight routes?



Responsibility for shaping a flight route is shared among several actors at different stages of the flight:

- Before departure, the **airline's operations control** centre plans the flight, selecting the route, flight levels, and timing, with the aim of optimising fuel use, flight time, weather conditions, charges, and airspace restrictions.
- In parallel, the **Network Manager** (i.e. EUROCONTROL) oversees flight plan processing and demand-capacity balancing. It checks the proposed flight plans, addresses potential overloads in specific sectors, and assigns departure slots where needed. The Network Manager may also propose network-level measures such as altitude restrictions or reroutes to maintain overall traffic flow.
- During the flight, **air navigation service providers** (ANSPs) manage the aircraft's movements. Area control centres (ACCs), operated by entities such as NATS (UK), DFS (Germany), DSNA (France), ENAIRE (Spain) or MUAC (Belgium, Netherlands, Luxembourg, and North-West Germany), manage climbing, descending and en-route traffic. Controllers are responsible for maintaining safe separation and may issue tactical instructions like altitude changes.
- **Pilots** are responsible for executing the approved route. Route changes to keep traffic flowing may also request changes mid-flight when conditions such as turbulence, weather or fuel efficiency justify or require a deviation.

- At either end of the journey, **airports** and **local ATC units** manage runway use and sequencing of departures and arrivals.

How is Europe's airspace organised?

Europe's skies are divided into a structured hierarchy designed to ensure the safe and efficient management of air traffic. At the highest level, the airspace is split into Flight Information Regions (FIRs). Each FIR covers a defined portion of national or multinational airspace and is managed by one or several designated ANSP(s). These regions are the basic building blocks of the air traffic control system. In the context of this roadmap, we refer to the ensemble of all EUROCONTROL FIRs as European airspace.

European airspace has particular challenges: high traffic density and fragmentation across 37 ANSPs, each with its own processes and systems. Network-wide operational innovations therefore require carefully designed, phased deployment.

4.2.2 Contrail avoidance approaches

Navigational contrail avoidance adds a layer of operational complexity into the system. Successful implementation depends on close cooperation among ANSPs, airlines and the Network Manager (NM).

Approaches to navigational contrail avoidance differ in two respects: timing and the stakeholder taking the lead. Avoidance can be incorporated into flight planning before departure (pre-tactical) or involve rerouting during the flight (tactical). It can be airline-led, ATM-led or hybrid. So far in contrail trials, a pre-tactical airline-led approach was the most common, for example in the 100 flight D-KULT trial led by Lufthansa, DHL and TUI with the support of the German ANSP.

Lead	Pre-tactical - before the flight departs	Tactical - during flight
Airline-led - Pilot or dispatcher	The dispatcher prepares a flight plan to avoid contrail-forming areas, informs the pilot and submits the plan to the Network Manager (NM) as usual.	The pilot receives real time information to change route to avoid a contrail area, and requests route change to ATC.
ATM-led - ATC, NM or flow manager	The NM integrates contrail areas in their flight planning software, and adjusts flight plans received from dispatchers, who then accept flight plans.	ANSP flow manager restricts airspace in contrail areas, and instructs ATC to avoid those areas. Final decision made based on safety, capacity or economic constraints.

Hybrid - collaborative	The dispatcher prepares a flight plan to avoid contrail areas, and the NM adjusts all flight plans to ensure maximum efficiency at network level.	Both pilot and ATC are informed of the contrail area, and both can request a deviation to avoid it.

4.2.3 Tools and procedures

Scaling up navigational contrail avoidance also requires updating systems - from airline flight-planning software to ANSP traffic-management tools - and procedures, such as flight-level allocation and decision-making protocols.

- **Systems and software:**

To enable contrail avoidance at scale, stakeholders' software must be able to forecast ISSRs and file or adjust flight paths accordingly.

Some providers already offer contrail avoidance functions in airline flight-planning software (e.g. Flightkeys), but contrail avoidance function integration into ATM planning systems is still at an early stage. Existing ANSP tools can visualise ISSRs but do not yet help operators balance rerouting decisions against airspace capacity constraints. During trials, air traffic controllers have relied on manual workarounds to permit rerouting, increasing their workload and operational complexity. Scaling up requires investment in software development and deployment, whether through plug-ins or new tools, as well as training for controllers and flow managers. Moreover, whereas airline flight planning systems are used across multiple airlines, ATM systems are often unique to the ATM organisation. Therefore integration of contrail avoidance systems in ATM requires more adaptations.

- **Protocols:**

ATM protocols - governed by EUROCONTROL and EASA under the SES framework in Europe - are crucial in managing air traffic. They cover different aspects of ATM, from standardizing communication and data-exchange among ANSPs, so that flights can seamlessly cross borders to safety protocols defining rules during emergency situations.

When it comes to navigational contrail avoidance, protocols must provide clear decision-making frameworks so that air traffic controllers know when they can approve contrail avoidance flight plans without compromising safety while weighing trade-offs such as the fuel penalty. Aligned protocols will also ensure that contrail avoidance by different actors (i.e. ATM and airline) are coordinated, and that both stakeholders make similar decisions based on a single source of data.

4.3 European ATM legislation

The main legislative instrument governing ATM in Europe is the Single European Sky (SES) II+ Framework.

Adopted in 2004 and most recently revised in 2025, the SES Framework aims to reduce fragmentation in European airspace by reforming and modernising ATM. More direct flight paths allow airlines to plan routes closer to the shortest distance or most economically efficient trajectory, reducing fuel burn and environmental impacts. The following areas of the SES Framework are relevant to contrails policy:

- **A performance and charging scheme**

The 2009 SES II+ reform introduced a performance scheme that formally assesses the Network Manager and ANSPs. It uses binding key performance indicators (KPIs) across four areas:

- Safety: the primary objective.
- Capacity: the ability to handle air traffic volumes (e.g. measuring delays).
- Cost-efficiency: the cost of air navigation services for users.
- Environment: measured primarily by horizontal flight efficiency (the extent to which the actual flight path deviates from the shortest route).

EU Member States set targets for each key performance area (KPA) in their national performance plans, in line with Union-wide targets defined by the European Commission for multi-year reference periods (RPs). The current period is RP4 (2025–2029). If an ANSP fails to meet its targets, financial, legal or operational enforcement mechanisms may be triggered.

For environmental performance, the main indicator is KEA (key performance environment indicator based on actual trajectory). It measures the extra horizontal distance flown during the en-route phase against the theoretical shortest path, or "great-circle distance", between origin and destination. The system thus treats the shortest route as the most environmentally friendly. It does not distinguish factors within an ANSP's control from external factors. In addition, this two-dimensional measure (latitude and longitude) cannot capture the effects of altitude and time on non-CO_2 emissions. Those factors matter for contrails: their warming effect is greater at night, while daytime contrails can have warming or cooling effects.

The 2025 review of the SES II+ Framework, however, requires the European Commission to develop a new environment and climate metric, acknowledging the limitations of the current KPI. The indicator should "better reflect the impact of air navigation services on the environment and climate, taking into account various climate and environmental elements and their interdependencies." It should be monitored during the current reference period and become a KPI with binding targets in the next period, starting in 2030.

- **Airspace organization and network management**

The SES II+ Framework also seeks to reduce fragmentation along national borders and harmonise European airspace management through network-level initiatives, including the Network Manager function. The Network Manager, currently EUROCONTROL, manages traffic

flows centrally to prevent bottlenecks and optimises the European route structure with a view to reducing flight distances, fuel burn and emissions.

Within EUROCONTROL's role as Network Manager, there is an opportunity to include contrail avoidance. By including contrail avoidance within the tasks for EUROCONTROL, space is provided to EUROCONTROL to develop or support the development of the systems and processes needed, such as decision-supporting tools and protocols for air traffic controllers.

Especially as with the foreseen digitalisation of the European ATM, EUROCONTROL as a Network Manager is evolving into pan-European flight trajectory broker. In this new system the flight trajectory will be calculated by the Network Manager and exchanged with all operational stakeholders, continually updated with ANSP updates and data downlinked from the aircraft. Information relevant for contrail avoidance - for example real time humidity and ISSR data - can be continuously included, and thus provide the basis for a re-routing manoeuvre for contrail avoidance.

- **Research and modernisation**

The SESAR (Single European Sky ATM Research) Joint Undertaking, established in 2007, manages technological and industrial research underpinning the SES II+. Guided by the Digital European Sky framework, it supports ATM modernisation through automation and digital infrastructure. SESAR also conducts research into aviation's non-CO_2 effects, including the CICONIA and CONCERTO flight-trial projects and E-CONTRAIL, which examines the potential use of artificial intelligence in ISSR prediction.

Alongside the Single European Sky and SESAR, another important guiding document is the ATM Masterplan. Updated periodically, it sets out the vision and priorities for ATM modernisation, including the goal of making Europe "the most efficient and environmentally friendly sky to fly in the world by 2045." The 2025 Masterplan includes reducing the total climate impact of ATM, including non-CO_2 effects, and lists priorities for exploratory and industrial research under SESAR.

4.4 Key learnings from past trials and challenges to contrail avoidance

Contrail avoidance trials are live tests or simulations conducted by ANSPs, airlines and researchers to evaluate how trajectory changes affect contrail formation. They are essential for advancing scientific understanding, identifying technological and operational gaps, validating workflows and informing regulatory design.

Effective trials have three distinct roles. **Airline-led trials** develop airlines' contrail avoidance tools and the procedures for dispatchers and pilots. They cost an estimated €0.5–1 million per airline, mainly for staff and fuel, and are sometimes industry-funded. **ANSP-led trials** develop air navigation service providers' tools and procedures. Their estimated cost is up to €4–7 million, largely for tools that each ANSP needs to develop only once; these trials are also sometimes industry-funded. **Combined trials** test coordination among all actors, including the Network

Manager. They can cost up to €10–15 million, reflecting fuel costs and the one-off development of tools for ANSPs and the Network Manager.

Several trials have been conducted in Europe in recent years, including MUAC trials with DLR(2021) and Google (2024-2025), the 100-flight D_KULT trial (2023), the CICONIA trial with contributions from NATS (2024 – ongoing) and the Concerto – Borealis trial (2024).

These trials offer insights into the challenges the ATM system must overcome for network-wide deployment and indicate the next steps for scaling up contrail avoidance. The following challenges have been identified:

- **ISSR dimensions are overestimated**: Trials confirm that ISSRs are typically very thin vertically, so vertical deviations of only two to four flight levels (2000-4000 feet) are generally sufficient to avoid the most warming contrails.
- **Capacity challenges**: From an ATM perspective, tactical (in-flight) contrail avoidance can create conflicts with **airspace capacity** and increase **controllers' workload**. Blocking or vacating flight levels to keep aircraft out of ISSRs can sharply reduce capacity: MUAC trials showed a drop of up to 20% during off-peak traffic. Trials suggest that pre-tactical avoidance, planned up to three hours before departure, is more manageable.
- **System limitations and the need for automation**: Airlines and air traffic controllers also face system limitations and procedural bottlenecks in flight planning and execution. Major legacy airline flight planning platforms still lack contrail avoidance functionalities. On the ANSP side, without automation of contrail prediction tools, deviation propositions and their seamless integration in ATC tools controllers are left with manual workaround solutions that increase workload. For instance, in the most recent Google -MUAC Trial, the Air Traffic Control Center had to develop a parallel system to their daily used live system in order to be able to enable re-routing for contrail avoidance. More automation and integrated decision support tools could help ease the burden.
- **Need for a single source of data**: stakeholders need to speak the same language, use compatible data and models to be able to cooperate.

4.5 Policy recommendations

Based on current scientific knowledge, past contrail avoidance trials and interviews with key stakeholders, we recommend that future ATM policy and funding focus on:

- Securing further medium- and large-scale trials, progressing from lower- to higher-traffic areas and periods;
- Investing in research and development (R&D) to close the remaining technological gaps; and
- Updating European ATM legislation to enable navigational contrail avoidance at scale.

01 Secure funding for medium and large-scale trials, with particular focus on combined trials, in the upcoming Aviation Strategy.

T&E proposes prioritising public support for combined trials involving airlines, ANSPs and the Network Manager. Each trial should involve hundreds of flights, as in the CICONIA project.

These trials can help addressing the remaining operational bottlenecks related to ANSP tooling, airspace and controller capacity and data sharing by:

- Developing and testing the essential tools and processes: e.g. validating ISSR forecasting systems and air traffic controller decision-support tools and design harmonised flight-planning procedures among all stakeholders;
- Establishing a single source of truth: creating a shared database used by airlines, ANSPs and the Network Manager (e.g. on weather forecast) to ensure a seamless, network-wide coordination; and
- Mitigating airspace capacity and workload constraints by identifying solutions to scale up contrail avoidance from low- to higher traffic areas and advise on contrail avoidance roll-out strategies.

In the short-term, funding for such trials remains limited. Although the Innovation Fund is a potential avenue, its burdensome application process prevented successful trial funding so far. Alternatively, public-private partnerships could be an option. In the longer-term, the Multi-Annual Financial Framework (MFF) should prioritize trial funding - via initiatives such as the proposed Clean Aviation Moonshot - to align with the upcoming 2027 EU Aviation and Aeronautics Strategy, which aims to focus "on ways to support the sector's green and digital transformation, boost investments in innovative, AI and clean technologies".

To prepare European airspace for contrail avoidance in selected low-traffic areas, seasons and times of day by 2032, the European Commission should use its forthcoming Aviation Strategy to:

- **From 2026 to 2029:** to provide €100 million for 10–15 medium-sized trials, prioritising those involving airlines, ANSPs and the Network Manager together. Each should cover at least several hundred flights. Part of the funding should support the one-off development of ATM tools and procedures, laying the groundwork for larger trials and deployment.
- **From 2029 to 2032 and beyond**, to launch large-scale trials involving thousands of flights across all seasons. These should test operational procedures, address remaining scientific gaps and resemble routine deployment as closely as possible.

02 Prioritize R&D for deployment of contrail avoidance with particular focus on tooling.

Navigational contrail avoidance still has R&D needs. Among them - as identified by the final report of the joint EASA–EUROCONTROL Aviation Environmental Reporting Working Group (AVENIR) and underlined by trials - is the necessity of a tool for ANSPs to support air traffic controller's decision-making in contrail avoidance situations. AVENIR refers to them as **automated ATC conflict-detection tools** (to prevent safety conflicts when planes change altitude).

Such tools are not yet available, but the digital transformation of the European ATM - guided by the ATM Masterplan - presents a great opportunity to focus on the industrial research required for their development. This is also in line with the latest 2025 review of the roadmap that states that "reducing the total impact of ATM on the climate, including non-CO_2 emissions (e.g. the effect of contrails) is to be addressed in phase D of the implementation, starting from 2026." Once the tool is developed, deployment can start.

The deployment of new technologies under ATM Masterplan happens in packages, for instance through Common Project 1 and 2 (CP1-2) frameworks. Funded by the Connecting Europe Facility and launched by the SESAR Joint Undertaking, these packages aim to create the technical foundation for a more digital, modern ATM. Unfortunately, the draft proposal of the CP2 framework presented to stakeholders in the summer of 2026 does not contain any reference to neither the development nor the deployment of such a tool. As the rollout of CP2 is until the mid-2030s, this would cause a significant delay in the deployment of navigational contrail avoidance in Europe.

Therefore T&E recommends that both the development (industrial research) and the deployment of an ATM tool with contrail avoidance capabilities is prioritised in the SESAR research programmes and in Common Project 2.

03 Enable European ATM legislation for contrail avoidance.

Scaling up contrail avoidance requires more than large-scale trials and R&D investment: it also needs an enabling regulatory framework. Two priorities are to revise how the SES II+ performance scheme assesses ANSPs' environmental performance and to expand the Network Manager's mandate to cover contrail avoidance coordination.

- **Develop a new Environment and Climate KPI for ANSPs under the SES II+ Performance scheme that allows for contrail avoidance**

The 2025 review of the SES Framework requires a more suitable environment and climate KPI to be developed for implementation from 2030 (RP5). Stakeholders appear to agree that the current indicator is unfit for purpose, as surveys conducted by the consultant preparing the assessment report for the European Commission confirm. However, few proposals set out what the new indicator should measure.

The Performance Review Body (PRB) in its 2025 Position Paper proposes a trajectory-comparing approach. They suggest comparing actual flight paths with standard or fuel-optimized routes to see how much extra fuel is burned due to air traffic control decisions and flight restrictions. This exercise could help identify the root causes behind suboptimal flight trajectories and link the extra fuel burnt to the responsible stakeholder. The PRB recommends two phases: an initial pre-departure indicator at the start of RP5 (2030), assessing fuel inefficiency before departure, followed by a fully developed real-time trajectory-tracking framework from 2034. It also suggests integrating a broader non-CO_2 metric as the assessment shifts from pre-tactical to tactical.

While this approach is an important step in moving from the shortest route concept to fuel optimised trajectories, it remains very CO_2 focused: the PRB states that "until it is possible to quantify the additional climate impacts of a flight, the trajectory that achieves optimum fuel efficiency will be considered the best available proxy for environmental sustainability." It therefore leaves non-CO_2 effects out of the assessment and does not meet policymakers' stated intention to reflect ATM's climate impact in the new indicator.

We recognise the potential CO_2 reductions from the PRB's approach and the difficulty of developing a new environment and climate KPI. Nevertheless, the new criterion must avoid penalising ANSPs for enabling contrail avoidance, which can carry a small fuel penalty.

In the short term, T&E therefore proposes a new environment and climate KPI based on fuel-optimised trajectories, with flexibility for contrail avoidance. Building on the PRB proposal, it would add a "green tag": extra fuel burned during verified contrail avoidance manoeuvres would be recorded in ATM systems and credited back to the ANSP, so it would not count as a trajectory inefficiency in its performance assessment. By RP6 though (2035 onwards) the environment and climate KPI must be further developed so that it includes a non-CO_2 metric.

The new environment and climate KPI must also be balanced against capacity (air traffic flow management delays) and cost-efficiency KPIs so that ANSPs have an incentive to approve deviations. Starting in areas and periods of low traffic would make these trade-offs easier to manage without causing network-wide congestion.

- **Expand the mandate of the newly appointed Network Manager to contrail avoidance coordination**

The Network Manager, currently EUROCONTROL, already has a broad mandate to optimise European airspace, including the coordination of traffic flows, central flight-plan validation and network-wide airspace design. Because contrail-forming regions often cross borders and standardised processes are needed, the Network Manager is well placed to coordinate contrail avoidance centrally. Beyond that as the future trajectory-broker with the ATM digitalization, the NM would be able to centrally coordinate contrail-avoidance in the European airspace.

The SES II+ Framework already refers to "environmentally- and climate-optimised flight trajectories" in describing the Network Manager's role, but does not define the term. Scientific literature describes a climate-optimised, or green, trajectory as a flight plan designed to reduce the total warming impact of a flight, combining CO_2 and non-CO_2 effects. Because non-CO_2

effects depend strongly on atmospheric conditions, including humidity, as well as season, time of day and altitude, climate-optimised route planning must take these factors into account.

As a first step towards the Network Manager facilitating those trajectories, there must be a shared concept and agreed definition of a climate optimised trajectory in order for all stakeholders in the ecosystem to be able to seamlessly cooperate. That would also entail agreement on the trade-off between CO_2 and non-CO_2. As a next step, the agreed legal definition of a climate-optimised trajectory must be codified in the SES II+ Implementing Rules.

Finally, developing the necessary decision-making protocols for air traffic controllers and ensuring the network-wide coordination of ANSPs are also crucial elements of contrail avoidance at scale and it is only possible through the central position and traffic flow management of the Network Manager.

T&E recommends that, when the new Network Manager is appointed in 2029, the European Commission expand its mandate to: (i) lead work on defining a climate-optimised trajectory; (ii) develop processes and protocols for contrail avoidance; and (iii) coordinate stakeholders' contrail-related actions across the network.

4.6 Conclusion

If these policies are adopted, European ATM could have the tools, processes and regulatory framework needed to support phased, network-wide deployment of navigational contrail avoidance by the mid-2030s. Deployment could begin in lower-traffic areas, seasons and times of day: 75% of warming contrails are generated by flights in autumn and winter during the late afternoon and evening, when traffic is lower. This could deliver substantial climate benefits without severely affecting traffic or other ATM KPIs. According to current models, scaling up avoidance from 2030 and reaching 50% effectiveness by 2040 could delay aviation-related global warming by ten years.

Infobox: UK perspective and recommendations

The UK does not have a direct equivalent to a Network Manager, with one regulated ANSP (NATS) and the Civil Aviation Authority (CAA), which sets performance and price control. However, similar levers to the ones stated above can be pulled to ensure air traffic management effectively considers non CO_2 issues. There are several steps that could be taken in the UK:

- Ensure that the CAA and NATS build non CO_2 metrics into the next NATS price control. As set out by the AIA, there is limited time to influence the next pricing window as it

closes in late 2027. NATS has previously said that it is developing new environmental metrics, but further progress needs to be shown.

- Build on Operation Blue Skies, of which the Department for Transport provides £2.65m via the Aerospace Technology Institute. Provide funded follow-on trials in different regions from 2028, and assess trial exemptions such as night noise curfew breaches.
- Air traffic management operations on non CO_2 needs clear management and accountability. We believe this should be the Department for Transport or the CAA. This needs to be formalised effectively through a governance framework developed by the UK Government.

05

Integrating non-CO_2 emissions into RefuelEU

5.1 Introduction

Fuel policy is at the heart of reducing aviation's climate impact. In recent years, as part of the Fit for 55 Package, the EU has made important progress by mandating an increasing share of Sustainable Aviation Fuels (SAFs) in aviation fuel in the RefuelEU Regulation. The Regulation also includes a reporting requirement on the chemical composition of jet fuel but it is not the core focus of the text, in spite of the fact that fossil jet fuel will remain the primary source of fuel used in aircraft for the next two decades.

Jet fuel consists of a mix of many different types of molecules, made mostly of carbon and hydrogen, plus some impurities. From an air pollution and climate perspective, two compounds are of particular relevance, aromatics and sulfur:

- Aromatics: These are ring-shaped carbon molecules in the fuel. When burned, they do not break down cleanly, making them the primary source of non-volatile particulate matter (nvPM) - the solid soot and black smoke visible behind an engine. One type of aromatic stands out: Naphthalene. When burned, it produces high numbers of nvPM.
- Sulfur: This naturally occurring impurity burns inside the engine to form sulfur oxide gases. As these gases cool down in the atmosphere, they react to form volatile particulate matter, which are microscopic liquid droplets that contribute to air pollution and cloud formation.

The link between the composition of aviation fuel - specifically aromatics and sulfur content - and non-CO_2 emissions has been scientifically well established leading to both climate and air quality consequences.

As far as climate is concerned, studies show that lowering the level of aromatics in fuel leads to decrease in soot particle emissions. This generally reduces contrail warming. Recent research also connected the fuel's higher hydrogen content to preferable outcomes for climate, with lower emissions of non-volatile particles leading to reduced contrail formation. However, when soot emissions become very low, for example with SAF, hydrogen, or some newer engine designs, other particles emitted or already present in the air can help contrails form instead. This means that there can be substantial contrail formation even when soot emissions are close to zero.

Lowering sulfur content of jet fuel also has a range of climate effects. On the one hand, a likely reduction in contrail formation, which adds up to the effect described above. On the other hand, a decrease in cooling sulphate aerosols, whose emissions are directly related to sulfur

concentrations in jet fuel. Finally, a possible reduction in low level cloud formation. It remains unclear whether the overall effect of decreasing sulfur in jet fuel will result in a cooling or warming effect.

But more importantly, burning cleaner jet fuel also results in better air quality and health co-benefits on the ground. Lower aromatic, naphthalene and sulfur content directly reduce emissions of ultrafine particles (UFPs), which are linked to various illnesses such as respiratory issues, high blood pressure, diabetes, and cardiovascular diseases among the population living near airports.

Unlike kerosene, unblended SAFs are mostly low, or completely free, of aromatic compounds, so increasing their use carries the side benefits described in the previous paragraphs. However, as fossil jet fuel will remain the primary source of fuel used in aircraft for the next two decades, addressing the chemical properties of conventional jet fuel offers a powerful lever for regulators to deliver environmental benefits and reduce non-CO_2 emissions in the near-term in this hard-to-abate sector.

Infobox: Available technological solutions to lower aromatics and sulfur content in fuels

From a technical standpoint, "cleaner kerosene" with a higher hydrogen, and lower sulfur and aromatic content can be produced through three primary pathways:

- **Hydroprocessing:** A refinery process that adds hydrogen to jet fuel. This process reduces sulfur content, and turns aromatic compounds into molecules with hydrogen-to-carbon ratio, with better combustion properties, which reduce the particle emissions when burnt. Several technoeconomic analyses from the US and the EU have estimated that the costs of hydroprocessing jet fuel to reduce sulfur, aromatics and naphthalene could be less than 5 cents per litre.

- **Co-processing with biomass or synthetic crude:** A refinery process where renewable feedstocks (biomass or non-fossil synthetic crude) are simultaneously processed alongside conventional fossil crude oil (or its refined fractions) within existing petroleum refinery units.

- **SAF blending:** The physical process of mixing pure, unblended SAFs with conventional fossil-based jet fuel (Jet A or Jet A-1) to produce a safe, finished fuel that can be loaded directly into aircraft.

5.2 European jet fuel legislation

The current EU aviation fuel legislation - anchored in ReFuelEU and the Renewable Energy Directive (RED) - focuses almost entirely on lifecycle CO_2 intensity. Lifecycle CO_2 intensity is crucial for the long-term decarbonisation of the sector, but due to the low aromatics and sulfur levels in pure SAFs, increasing SAF-blend mandates will also have a certain mitigating impact on non-CO_2 warming, as shown by the table below.

Changes in average aromatics,sulfur and naphthalene levels as a result of the RefuelEU SAF-blend mandate implementation

	Blend					Pure SAF			Pure fossil		
Year	SAF %	Fossil %	A (% vol)	N (% vol)	S (ppm)	A (% vol)	N (% vol)	S (ppm)	A (% vol)	N (% vol)	S (ppm)
2024	0.60%	99.40%	17.09%	0.71%	360	0	0	0	17.19%	0.71%	362.17
2025	2%	98%	16.85%	0.70%	354.93	0	0	0	17.19%	0.71%	362.17
2030	6%	94%	16.16%	0.67%	340.44	0	0	0	17.19%	0.71%	362.17
2035	20%	80%	13.75%	0.57%	289.74	0	0	0	17.19%	0.71%	362.17
2040	34%	66%	11.35%	0.47%	239.03	0	0	0	17.19%	0.71%	362.17
2045	42%	58%	9.97%	0.41%	210.06	0	0	0	17.19%	0.71%	362.17
2050	70%	30%	5.16%	0.21%	108.65	0	0	0	17.19%	0.71%	362.17

The analysis assumes purely paraffinic SAF with no aromatics, naphthalene and sulfur; and a fossil jet fuel with the same composition as the one reported under ReFuelEU by jet fuel suppliers for the year 2024.

As the shares of SAF in the blend increase, the average level of aromatics and sulfur in the blend of SAF and jet fuel are expected to decrease. For example, by 2035, under the projected 20% SAF-blend mandate, the aromatic content in the fuel blend is expected to decrease to 13.75% from the 2024 baseline of 17.09%, while sulfur levels will drop to 289.74 ppm from 360 ppm. This reduction illustrates how scaling SAF adoption directly lowers the concentrations of key compounds linked to particle emissions, contrail formation, and aviation's non-CO_2 climate warming effects.

Nevertheless, neglecting the chemical properties of traditional fossil fuels means that regulators are missing an opportunity to achieve further environmental gains in mitigating non-CO_2 warming effects and realizing air quality and health co-benefits.

This is especially the case as the RefuelEU Regulation mandates the Commission to assess possible measures to optimise fuel content of aviation fuels and present its findings to the European Parliament and the Council by 1 January 2027 at the latest (either as part of the report on RefuelEU application or as a standalone one).

5.3 International jet fuel standards

The composition of jet fuel is defined by international standards. The most important are ASTM D1655, for Jet A and Jet A1, and ASTM D7566 for aviation fuel containing synthetised hydrocarbons (SAF). Those standards set the range limits of aromatics (max. 25%, min. 8% only in D7566), naphthalene (max. 3%), and sulfur (max. 3000 parts per million) in fuel. It is important to note, that while the ASTM standard sets the maximum - and in the case of aromatics in SAF the minimum - amounts for the specific compounds, the batches of jet fuel used today vary heavily in their composition. For instance, aromatic content in conventional kerosene, according to a recent study from the University of Sheffield generally ranges between 15–22%. The sulfur content of available jet fuel tends also to be lower, according to EASA's research between 176-293 ppm in Europe and 576-867 ppm in the US. The most recent European data, published in the ReFuelEU Aviation Annual Technical Report, found that the average reported composition for the EU's jet fuel in 2024 was 17.09% for aromatics, 0.71% for naphthalene, and 360 ppm for sulfur.

Recognizing the connection between fuel composition and aviation non-CO_2 emissions and the necessity for "cleaner kerosene" and based on a request from the European Parliament, the European Union Aviation Safety Agency (EASA) has launched a pilot project in 2024 to examine the feasibility of lowering the aromatics and sulfur content of conventional jet fuels via an EU-level standard. The European body for jet fuel standards and safety certification pilot project has since transformed into the European Jet Fuel Standard Project and is still ongoing. The findings of the project feed into the preparatory work of the RefuelEU Review.

5.4 Policy recommendation

Having established that fuel composition is a critical lever for mitigating non-CO_2 climate and health impacts, T&E recommends the following policy pathway to integrate these requirements into the existing regulatory framework.

01 Introduce an EU jet fuel specification:

Under RefuelEU's Monitoring, Verification and Reporting Scheme (MRV) (Article 10) fuel suppliers are already mandated to report annually the following characteristics of the jet fuel: aromatics, naphthalenes, sulfur content, and energy content by batch as well as the hydrogen to carbon ratio.

In the near term - via the RefuelEU review announced for 2027 - regulation can proceed by capping aromatics while targeting hydrogen levels around current market averages (17.09% for aromatics and 360 ppm for sulfur).

That would limit both the administrative burden and the cost of compliance for stakeholders. Concerning the administrative burden, the fuel specification would build on the existing RefuelEU reporting requirement for fuel suppliers. The cost of compliance would remain low, as reaching the market average level of aromatics would require zero to little treatment of the fuel at the beginning.

In addition, anchoring this specification in the 2027 RefuelEU review establishes a crucial regulatory precedent, ensuring the EU takes full ownership of its jet fuel environmental standard. **In the longer term the foreseen subsequent reviews of the Regulation would allow for gradually adjusting the fuel specification in parallel with the maturation of science and the entry to market of new aircraft that are able to operate on 100% SAF.**

As highlighted by EASA in its initial findings on lower compositional limits report, the elements of the specification would be threefold, (i) the introduction of a minimum hydrogen threshold, (ii) reducing the upper limit of sulfur content and (iii) setting a new, lower limit for aromatics within the international standards.These changes would lead to the reduction of harmful particle and sulfur oxide emissions, thus better climate and health outcomes.

There are two challenges needed to be addressed concerning a possible new EU fuel specification. The so-called SAF-blend wall and the international aspects.

As for the SAF-blend wall, the policy design of the new jet fuel specification must account for the minimum aromatics level and other requirements defined by the ASTM standard, including cold temperature properties and lubricity. This would ensure the correct functioning of aircraft and engine systems, such as the swelling of engine seals. Indeed, engine seals need fuel to make them slightly swell so they completely plug gaps and prevent leaks in the engine. Aromatics in kerosene make this happen, but SAFs are usually low-aromatics and without those compounds old rubber seals can shrink and harden, which creates tiny gaps where fuel can leak out.
With the current, low SAF-blend mandate in Europe this is not a problem now, but can become one as SAF-blend mandates increase. That being said, major OEMs and aircraft manufacturers have already announced plans to bring aircraft to the market flying 100% SAF by 2030. In December 2021, United Airlines' Boeing 737 Max aircraft already flew from Chicago to Washington with 100 passengers with a 100% SAF in one of its engines.

To avoid the SAF-blend wall, the EU can gradually adapt the fuel specification in parallel with the review of aircraft design and continue research and development in order to resolve the seal problem.

Due to the international nature of aviation and fuel standards, the question of taking action at regional or global level naturally arises. In the short-term EU action - e.g. introducing a new jet fuel quality standard - is desirable, and as in many cases of environmental regulation EU leadership can inspire action at the international level. It is even more important to do so, because the

RefuelEU review in 2027 provides the legislative vehicle to proceed with the launch of a regional fuel specification.

European action can be followed by action taken at the global level. In ICAO, it is the Committee on Aviation Environmental Protection (CAEP) and its responsible working groups that are in charge of formulating international standards. However ICAO does not have the competence to set fuel standards - unlike engine and aircraft emissions standards. Currently, two CAEP Working Groups (3 and 5) are assessing certain aspects of jet fuel composition and their environmental impact and will present their report to the CAEP meeting in February 2028. After that the ICAO can decide to make recommendations to international standard setting bodies, such as the ASTM International, but new fuel standards are to be set by the latter, making the timeline of a new fuel standard hard to guess. As the ASTM functions in a bottom-up model, a champion from industry, known as a technical contact or task group lead is required to drive the process that can lead to an eventual ballot and thus the revision of the standard.

Infobox: UK perspective and recommendations

The primary piece of jet fuel legislation in the UK is the SAF Mandate, which focuses specifically on the lifecycle CO_2 emissions of fuels. The UK currently has no policy on fuel composition and the Jet Zero non-CO_2 research programme is yet to provide regulatory outcomes.

The UK has developed its own separate fuel standard, that sits alongside the globally recognised ASTM standard. DEF STAN 91-091 was issued by the UK Ministry of Defence in 1994 and was designed to be more flexible in response to the more challenging operational environments faced by military aviation.

Whilst both the DEF STAN 91-091 and ASTM D1655 define kerosene globally and engines can run on either standard, DEF STAN 9-091 is generally stricter on issues like particular controls and acidity limits. The aviation industry uses a “joint checklist” that combines the most stringent requirements of each standard, which allows aircraft to uplift fuel anywhere in the world. Further steps could be taken in the UK, however:

- The DEF STAN 91–091 standard could be reviewed for a lower aromatics and sulphur limit and a minimum hydrogen content.
- Reporting of aromatics, sulphur and hydrogen could be considered through the SAF Mandate’s reporting rules, taking a similar approach to ReFuelEU’s Article 10.
- The Jet Zero non CO_2 group suggests prioritising low contrail fuel for flights that would benefit the most. The UK could trial this alongside Operation Blue Skies.

06

Supporting non-CO_2 mitigation with aircraft technology

6.1 Airframe and engine efficiency

Innovative aircraft designs with reduced drag and weight reduce energy consumption, which results in decreased fuel burn. This, in turn, entails a reduction in non-CO_2 emissions such as water vapour, SO_x, soot, and NO_x roughly in proportion to the fuel saved, which can also contribute to reduced contrail warming.

Innovations such as laminar flow, high-aspect-ratio wings, blended-wing-body concepts, and the widespread use of advanced composite structures have the potential to significantly decrease fuel burn compared to incremental improvements of current technologies. As such, their support should be prioritised in the upcoming Aviation Moonshot, which will provide R&D funding for aviation technologies in the next European budget, the MFF.

Engine efficiency improvements can also deliver savings in fuel consumption. However, they may also introduce environmental trade-offs.

Firstly, higher thermal efficiency, achieved through elevated overall pressure ratios and higher combustor temperatures, reduces fuel consumption, but also increases thermal NO_x formation. So far, the focus of engine design has been to reduce fuel consumption as much as possible, while complying with landing and take off (LTO) NO_x emissions standards from ICAO, introduced to limit air pollutant emissions at and around airports. As a result, CO_2 emissions have reduced faster than NO_x in modern engines. Future engine designs should consider not just air quality, but also the climate impact of NO_x emissions, and aim to reduce them during landing and take off, and also in cruise.

When it comes to engine combustor design, lean-burn combustors cut soot particle numbers by approximately three orders of magnitude and reduce landing and take-off (LTO) NO_x. However, in-flight measurements have revealed that contrail ice crystal numbers are not reduced, as volatile particles driven by fuel sulphur replace soot as ice nuclei. Consequently, lean-burn engines may only deliver contrail benefits only when combined with strict fuel-quality regulations.

Moreover, higher propulsive efficiency leaves less heat in the exhaust plume, expanding contrails across deeper altitude bands.

Finally, turboprop aircraft can also reduce non-CO_2 effects. On top of a high propulsive efficiency, these aircraft fly at lower altitudes than jet-powered aircraft, which limits their risk of encountering ISSRs and of forming persistent contrails.

All of this proves that, although engine improvements can reduce non-CO_2 emissions and contrail formation, they can also introduce trade-offs. For this reason, any design improvement must be part of a comprehensive set of mitigation measures that should also include contrail navigational avoidance and improved jet fuel quality.

6.2 Zero-emission and hybrid technologies

Innovative propulsion systems, such as hydrogen and electric, have zero in-flight carbon emissions, but some of them can still generate non-CO_2 emissions.

Battery electric-powered aircraft produce zero in-flight emissions, thus eliminating their non-CO_2 climate effects and air quality impacts. However, many electric aircraft currently under design are hybrid, combining battery power with a turbine for electric power or thrust generation. These hybrid propulsion systems still produce non-CO_2 emissions, although these are expected to be smaller than those of a jet engine of similar power.

Hydrogen fuel cells emit only water vapour, eliminating NO_x, soot and SO_x. That means they may still form contrails, although the absence or particle emissions to facilitate nucleation may reduce their duration and warming effect compared to the ones formed by jet engines.

Hydrogen combustion, on the other hand, emits water vapour and NO_x. As in the case of fuel cells, hydrogen combustion-powered aircraft may still form contrails, although these may also have a smaller warming effect.

6.3 Policy recommendations

01 Incentivise research and development of high risk, high reward technologies, and support new entrants:

Public support for aviation R&D in the next MFF should move from incremental improvements to high risk, high reward technologies that mitigate carbon and non-CO_2 emissions. On top of CO_2 reduction and fuel efficiency improvements, the reduction of non-CO_2 emissions should be a key awarding criterion for this public support, which should prioritise disruptive aircraft architectures, such as blended wing bodies and truss-braced wings, advanced materials, and engine configurations such as open fans. The EU should also ring fence €1 billion for novel propulsion systems, including electric, hybrid and hydrogen, which significantly reduce or even completely eliminate non-CO_2 emissions.

02 Leverage existing aviation legislation to create the right market conditions for disruptive aircraft technologies:

Current aviation regulations were built around kerosene-powered aircraft. Fossil jet fuel remains too cheap compared with its climate impact. Weight-based charges penalise cleaner aircraft with heavier propulsion systems. Slot rules protect incumbent operations. Clean fuel mandates do not yet fully recognise renewable electricity. The result is a framework that still reflects the needs of conventional aircraft, even as new aircraft technologies move closer to market.

The EU should strengthen the polluter pays principle to send a price signal in favour of cleaner aircraft technologies that reduce carbon and non-CO_2 emissions, and reinvest part of the revenues to support their developmentment. The introduction of financial mechanisms in ReFuelEU or EU ETS could help cover the early cost gaps of disruptive ZEHA technologies.

Furthermore, the widespread use of environmental modulation of airport or air navigation charges, and giving priority airport slot access for cleaner planes, can strengthen the business case for new, cleaner aircraft. Public service obligations (PSO) routes can also be used as an early market for cleaner aircraft, particularly ZEHA. The reduction of non-CO_2 emissions should be central to any policy design that rewards cleaner aircraft technologies.

03 Strengthen NO_x, vPM and nvPM engine emission standards, and introduce a cruise standard

Existing engine emission standards were created to limit pollutant emissions at and around airports. They measure engine performance at take off, climb out, approach, and taxi regimes. Emission standards should be strengthened to drive an improvement in the performance of future engines, and should also include the cruise phase, to ensure non-CO_2 emissions are minimised during the cruise phase, where their climate impact is higher.

Infobox: UK perspective and recommendations

The UK Government recently announced £975m of additional funding for the ATI programme out to 2030 which should be used to further develop airport technology that reduces non CO_2. Similar to the EU, the UK should ring fence some of this funding for novel propulsion systems, including electric, hybrid and hydrogen, which significantly reduce or even completely eliminate non-CO_2 emissions.

The UK Government should lead the way at ICAO CAEP, asking for stronger NOx, vPM and nvPM standards, including a cruise-phase standard.

07

Conclusion

Aviation's environmental footprint cannot be mitigated solely by addressing the sector's CO_2 emissions.While achieving carbon net zero goals remains crucial for long term decarbonisation, there is scientific consensus that non-CO_2 emissions account for an equally significant environmental impact. Furthermore, addressing them is a necessity to stay on track with international long-term temperature goals set out in the Paris Agreement. Beyond climate, non-CO_2 emissions adversely affect air quality and pose a health risk, especially for people living near major airports.

As this roadmap demonstrates, there is no single bullet solution, but meaningful mitigation can be achieved by combining different policies.

Defining the overarching climate law vision

Including non-CO_2 emissions into the EU climate architecture and gradually into climate targets give the necessary long-term vision needed to guide sectoral legislation for mitigation. This would also provide the basis to track progress.

Incentivising airline action via the EU ETS

Mitigating non-CO_2 emissions is currently neither regulated, nor incentivised in the EU. In order to take key stakeholders - such as airlines - onboard, the EU must fine-tune its non-CO_2 monitoring system by extending it to all flights departing and arriving Europe and launch a fit-for-purpose incentive scheme, that helps airlines to onboard the tools and rewards actual contrail avoidance at scale.

Modernizing and adjusting ATM

Existing mitigation solutions, such as navigational contrail avoidance can only scale up if the regulatory framework is favourable. Two key elements of such a framework would be a new environmental and climate KPI for ANSPs with flexibility for contrail avoidance and the extension of the Network Manager's mandate to centrally coordinate re-routing. Besides that, prioritising large-scale trials and the development and deployment of the necessary tools and processes are also vital to complement research with a view to the gradual rollout of mitigation measures.

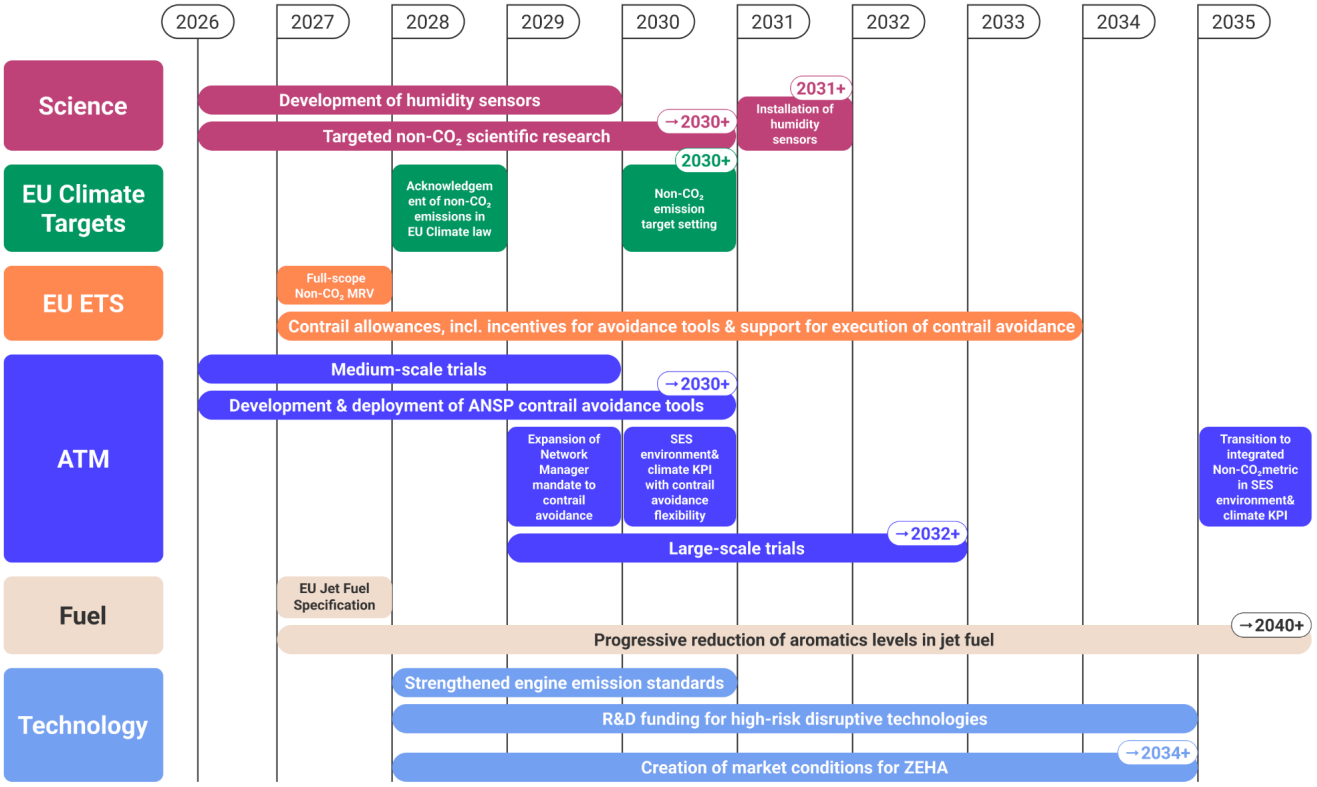
Cleaning up jet fuel

As kerosene remains the main source of fuel for aircraft in the next two decades, the EU must use the lever of changing the composition of jet fuel in a new EU fuel specification to address both climate and health impacts of aviation non-CO_2 emissions.

Steering aircraft and engine innovation

Mitigation strategies must include the support of high risk, high reward aircraft and engine technologies both in terms of advancement of combustion technology and creation of favourable conditions for the development and rollout of hybrid and zero-emission aircraft. Advancing these technologies can address both CO_2 and non-CO_2 emissions.

EU Aviation Non-CO_2 Policy Roadmap (2026–2035+)



Source: Transport & Environment (T&E) Study – A policy roadmap for aviation non-CO_2 emissions in Europe (Nov 2026)