Better Contrails Mitigation - BeCoM

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D5.2

Report on the assessment of the new policy driven flight planning approach with regard to effectiveness and feasibility

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Executive Summary

Historically, CO_2 emissions accounts for only one-third of the current climate effect of air traffic, with the majority arising from non- CO_2 effects like contrail-induced cloudiness and nitrogen oxides. In response, the EU revised its Emissions Trading System, requiring Member States to ensure that aircraft operators monitor and report total climate effects and provide CO_2 equivalent (CO_2e) emissions per flight since January 2025. By December 2027, the EU might propose further legislation introducing non- CO_2 pricing to incentivize mitigation. Following the 'Polluter-Pays Principle', CO_2e pricing will affect operators, influencing ticket prices and encouraging climate-optimized routings.

This deliverable and the associated work package (WP) contribute to objective (5) targeting the integration of non-CO_2 effects (e.g. contrails) into current policy schemes, such as the revised EU Emission Trading System, ICAO CORSIA and EU Green Deal.

Effective non-CO_2 policies must be simple, transparent, economically viable, and compatible with current operational frameworks. To support this, an automated CO_2e calculation method using algorithmic Climate Change Costs (aCCC) was developed, enabling airlines to estimate the climate cost of emissions per kilogram of fuel based on location and meteorological conditions. Incorporating CO_2e costs into total operating costs aligns operator incentives with climate goals, transforming the traditional trade-off between operational efficiency and climate impact into a “win-win” scenario. Without non-CO_2 accounting, climate-optimized flight planning must balance two conflicting objectives: minimizing monetary costs (fuel, time, operating costs) and reducing climate impact (emissions, ERF, ΔT) by selecting a Pareto-optimal trajectory. Internalizing climate effects simplifies this decision-making and ensures that climate-optimized routes are also cost-effective, creating a financial incentive for re-routing flights in an environmentally optimal way.

Due to large uncertainties in non-CO_2 modelling, which can affect MRV accuracy and risk harmful rerouting under CO_2e pricing, risk-mitigation strategies are needed. These include using ensemble weather forecasts to reduce formation risks or risks of unnecessary detours, and implementing uncertainty-based CO_2e accounting, where emitters hold permits proportional to confidence in climate effect estimates. Ongoing research, validation, and targeted risk assessments are key to improving non-CO_2 modelling and ensuring effective climate policy. Occasional high impacts may be acceptable if most flights reduce annual climate effects, while adaptable policies and ongoing research, such as better prediction of ice-supersaturated regions, are crucial for incorporating the latest scientific understanding and enabling effective climate action in aviation.

This study examines how key policy design choices, like CO_2e accounting methods, carbon price levels, and climate metrics, affect routing, mitigation potential, ticket prices, and demand. Results for selected routes and weather situations show operational mitigation potentials depend strongly on weather, while ticket price increases are mainly driven by the accounted share of CO_2e and carbon price. Gradual CO_2e accounting could moderate passenger costs. Uncertainty-based CO_2e accounting is more effective than gradual accounting, achieving higher mitigation with moderate ticket price increases. Our estimates, based on weather-dependent climate effect modelling, show ticket price increases averaging 1.1% to 5.6% for on intra-European flights, with CO_2e abatement costs between EUR 3-74 per ton (median EUR 14). Estimated costs are lower than in other sectors like wind, solar, or direct air capture, especially on days with effective contrail avoidance. While fare increases are noticeable, they remain relatively small compared to overall fare fluctuations.

A daily analysis of 2018 for the TOP 100 intra-European routes confirms the effectiveness of non-CO_2 pricing across a full year of meteorological conditions. In this course, we identify strong seasonal influence especially when focusing on contrail mitigation potentials and associated fuel and cost penalties. CO_2e accounting is also suitable when limited to CO_2 and contrail-induced cirrus (CiC) effects.

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Implementing CO_2e policies regionally, such as in the EU, requires balancing competitiveness, innovation, and economic efficiency. We analysed non-CO_2 pricing effects on a Hamburg–New York network under three regulatory scopes: full scope, intra-European scope and departure-based allocation. Cost impacts varied by route and fleet, affecting ticket prices, demand, and network structure, including shorter paths and shifts in airport centrality. The study shows that integrating non-CO_2 costs into airline pricing is feasible but must balance environmental goals with economic and market considerations.

Non-CO_2 policies should also incentivize climate-friendly technologies, alternative fuels, and operational measures. We demonstrated that non-CO_2 accounting lowers relative costs and enhances the attractiveness of operational mitigation, such as climate-optimized intermediate-stop operations (ISO), flight profile adjustments or formation flights, even if absolute costs rise due to. Sustainable aviation fuels offer high potential, although their high fuel costs cannot currently be offset through extended accounting alone. Additional mitigation can be achieved through technical efficiency improvements, while policy design options such as reduced accounting shares for non-CO_2 effects can help limit cost and ticket price increases.

Because CO_2e charges are set shortly before departure, airlines must factor expected costs into ticket prices. Even when passed to passengers, competitive pricing is crucial. Rerouting can lower climate costs, allowing operators to reduce fares or retain savings. Including cooling contrails could offset costs further, but raises scientific, ethical, and governance challenges.

To evaluate the feasibility of including mitigation of non-CO_2 effects, in particular from contrails, into future day-to-day operations and policy measures, we organized a series of four stakeholder expert workshops: three virtual workshops with single stakeholder groups (airlines, air traffic/ weather services, and authorities), and a final hybrid workshop in January 2026 at TU Delft. Early virtual workshops focussed on discussions within the same stakeholder groups, while the final hybrid workshop took place in smaller mixed-stakeholder break-out groups about the research focus topics in the BeCoM project (Measurements, Weather models, Contrail observations, Trajectory optimization, Policy instruments). The final plenary session resulted in a series of recommendations for future research and implementation of operational and policy measures for contrail mitigation. Key recommendations from the Stakeholders included: comparing weather models and sharing the weather schemes developed in BeCoM with met services; expanding onboard humidity measurements on selected routes, ideally with low-weight/volume equipment and public funding; and addressing various types of uncertainties (weather-related, climate response, trajectory, emissions) through flight test validation. While uncertainties should not block action, they pose a risk of creating false incentives, so regulatory decisions should focus on relative comparisons and consider trade-offs between uncertain non-CO_2 effects and certain CO_2 impacts. Operationally, contrail effects should be evaluated for entire airspaces rather than individual flights, to account for saturation effects of multiple contrails and ensure fairness amongst airlines, using strategies like targeting high-impact flights or constraining operations in climate-sensitive airspaces. Contrail avoidance may be easier in areas such as the North Atlantic rather than in congested European airspace, but close cooperation between airlines and ANSPs remains essential. Policy measures must carefully manage uncertainties, and balance short-lived non-CO_2 and long-lived CO_2 effects (e.g. by choosing a climate metric). ETS-like mechanisms would need to be complemented by measures like incentivizing contrail avoidance in ANSP performance evaluation. The current non-CO_2 MRV can provide valuable primary data for model validation, but their conservative assumptions need to be considered when interpreting estimates.

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1 Introduction

The content of this deliverable report has been developed in the EU Horizon Europe Project BECOM (Better Contrails Mitigation), in particular in work package (WP) 5 dealing with policy driven flight planning.

1.1 BeCoM project

BeCoM aims to develop and assess measures to largely reduce (>50%) or eliminate the global mean contrail radiative forcing, hence a substantial reduction of aviation's share of global warming to be achievable on a short time horizon. These measures include a reliable forecast of persistent contrails, reduced weather-dependent individual contrail radiative effects, and successful avoidance of strongly warming contrails via trajectory optimization. To this end, BeCoM focuses on:

- obtaining a larger and higher resolution database of relative humidity and ice super saturation at cruise levels for assimilation into Numerical Weather Prediction (NWP) models;
- developing more adequate representation of ice clouds in their supersaturated environment in the NWP models;
- validation of the predictions to determine and reduce the remaining uncertainties of contrail forecasts;
- developing a policy framework for effective contrail avoidance through a trajectory optimization approach.

BeCoM will develop novel Artificial Intelligence (AI) algorithms to complement the assimilation and validation process. BeCoM will predict the exact location and time of persistent contrail formation and formulate recommendations on how to implement strategies to enable Air Traffic Management to reduce aviation's climate impact. The BeCoM consortium, composed of one university, three research institutes, two companies and one international association, builds on its knowledge and expertise covering a wide spectrum from atmospheric science, climate research and AI capabilities to aviation operations research and policy development.

Hence, BeCoM can be divided into five main technical objectives, namely

(1) Enhance the routine measurements of atmospheric humidity at the cruise altitude;
(2) Improve the treatment of ice supersaturated regions in numerical weather prediction models;
(3) Develop appropriate AI algorithms for data assimilation, contrail detection, contrails classification, and uncertainties of contrail prediction;
(4) Minimize cost impact when implementing climate optimized trajectories;
(5) Develop and evaluate non-CO_2-based measures to be applied for ATM strategies for climate impact mitigation.

Furthermore, a sixth objective of dissemination and exploitation of BeCoM results has been defined.

1.2 Policy-driven flight planning in BeCoM project (WP5)

This deliverable and the associated WP contribute to objective (5) targeting the integration of non-CO_2 effects (e.g. contrails) within current policy schemes, such as the EU Emission Trading System, ICAO CORSIA and EU Green Deal. Furthermore, it includes the analysis of existing and discussed operational policy instruments for non-CO_2 effects, such as climate-charged areas, climate restricted areas, restricted flight altitudes, etc. Subsequent to the project definition phase and the project start, a revision of the European CO_2 emissions trading system (EU ETS) was decided at EU level. In this

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context, non-CO_2 effects from aviation shall be covered by a monitoring, reporting and verification (MRV) framework from 2025 on, as a first step towards full integration into the EU ETS.

As illustrated in Figure 1, WP 5 of policy driven flight planning is strongly interconnected within the BeCoM work package structure. It relies on inputs from WP3 regarding the persistent contrail prediction as well as optimized flight trajectories from WP4 focusing on the evaluation of climate optimized trajectories. The defined regulatory measures and the approach of aCCCs is fed back to WP4, so that it can be considered in the trajectory assessment.

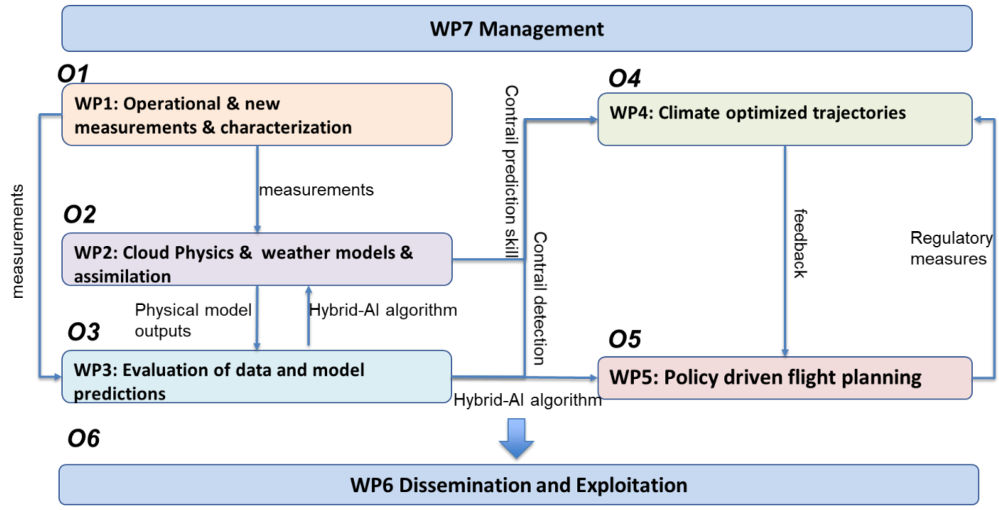

Figure 1. Work package overview of BeCoM project

This deliverable presents the final results achieved in WP5 of the BeCoM project, focusing on the assessment of non-CO_2 policy driven flight planning approach with regard to effectiveness and feasibility. This assessment was carried out collaboratively by the German Aerospace Center (DLR), Delft University of Technology (TU Delft), and Envisa.

The work builds on Task 5.2 (see Figure 2), which addressed the development of a methodology for integrating non-CO_2 policies into flight planning and trajectory optimization. This included the design of an algorithmic framework to characterize weather-dependent climate charges associated with aircraft emissions at specific locations and times through four-dimensional cost functions for climate change (aCCCs). This includes a monetization logic that quantifies the number of emission certificates to be surrendered, or alternatively the level of emission charges to be paid, according to the climate impacts of CO_2, H_2O, NO_x, and contrail cirrus. This monetization framework helps overcome the typical trade-off in non-CO_2 mitigation strategies, where climate-optimized routings often increase operating costs due to detours (more fuel, more time), creating a conflict between economic efficiency and climate impact reduction.

On this basis, it was possible to derive a first approach on how to integrate existing non-CO_2 uncertainties into the calculation of algorithmic cost functions for climate change. Based on aCCCs, the direct operating cost model was expanded with climate charges, which can be fed into the trajectory optimization in close collaboration with WP4. Furthermore, a parametric analysis of the developed algorithmic cost functions is performed to enable robust climate-sensitive flight planning. Finally, the optimization results from WP4 are incorporated to evaluate the developed climate policy concept from both scientific as well as Stakeholders' perspective.

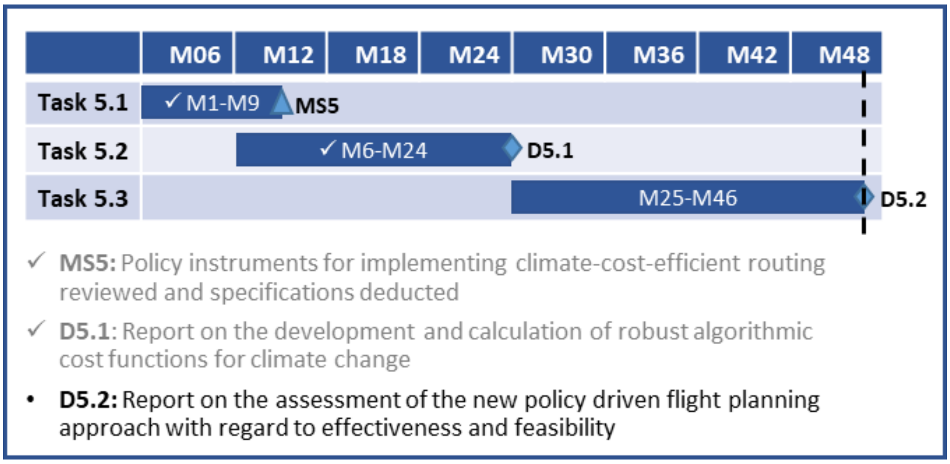

Figure 2: Gant Chart for WP5

To present the concept of aCCCs and demonstrate their applicability to incorporate non-CO_2 policies into climate-optimized flight planning, this deliverable is structured as follows: Subsequent to this introduction describing the project background of the BeCoM project , we present the results from the review of possible policy instruments and resulting requirements integrating non-CO_2 policies into flight planning and trajectory optimization in Chapter 2. Chapter 3 presents the concept of algorithmic cost functions for climate change as the schematic for integrating price-based CO_2 equivalents in operational flight planning. Stakeholder feedback is presented in Chapter 4, before we conclude this document with a final summary and outlook in Chapter 5.

1.3 Motivation for policy-driven flight planning

Non-CO_2 effects from contrail-induced cirrus (CIC), nitrogen oxides (NO_x), water vapor (H_2O), and particulates account for about two-thirds of aviation's effective radiative forcing (ERF) from 1940 to 2018 (Lee et al., 2021). Recent studies highlight the non-CO_2 mitigation potential of operational measures, like climate-optimized re-routings to climate-sensitive regions like persistent contrail formation areas (PCFAs) (Grewe et al., 2014, 2017; Lührs et al., 2016, 2021; Teoh et al., 2020; Matthes et al., 2021; Yin et al., 2023; Simorgh et al., 2023; Martin Frias et al., 2024; Sausen et al., 2024), or targeted use of sustainable aviation fuels (SAF) (Teoh et al., 2022; Märkl et al., 2024; Quante et al., 2025).

However, non-CO_2 mitigation faces economic challenges due to higher fuel use, longer flight times, air traffic complexity, capacity constraints, and higher SAF costs. Climate-optimized rerouting relies on multi-objective (Pareto) optimization, aiming to minimize both monetary parameters (such as flight time, fuel consumption, and/or operating costs) and climatological impacts (e.g., emissions, radiative forcing, or average temperature response). Since these objective functions are typically conflicting, there is no single solution that optimizes all objectives simultaneously. Instead, Pareto-efficient "trade-offs" need to be identified, where none of the objective functions can be improved without degrading the other objective values (see Pareto Frontiers in Figure 2, excluding MBM). Selecting a trajectory therefore requires weighing acceptable cost increases against desired climate savings—for example, +1% costs for -10% climate impact versus +5% costs for -20% impact.

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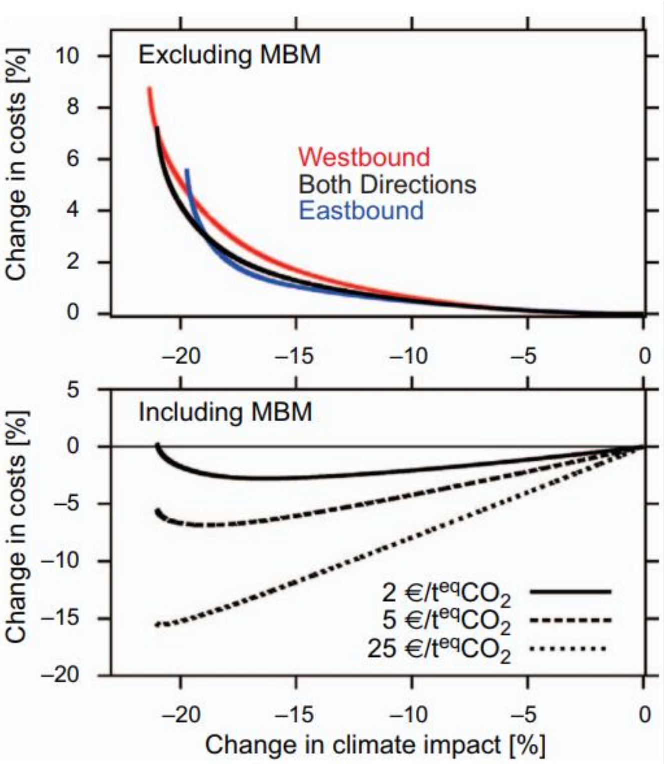

Figure 3: Top: Optimal climate-cost relations of trans-Atlantic air traffic for 5 winter and 3 summer days (averaged over the climatological frequency). West- and eastbound traffic is given relative to the climate impact of aviation flown west- and eastbound at minimum costs, respectively. Bottom: inclusion of costs for non-CO_2 effects through market-based measures, in addition to the operational costs (Grewe et al., 2017, p. 4)

Climate effects also saturate: initial persistent contrails contribute most to warming, while repeated flights through the same region have diminishing effect. As a result, individual operator efforts, though valuable for experience, often fail to reduce the overall impact if other flights continue forming contrails in the same area. Without regulatory support or financial incentives, operational mitigation can put operators at a competitive disadvantage. Effective contrail reduction thus requires coordinated action across multiple operators, underscoring the importance of climate policy.

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2 Consideration of non-CO_2 effects in climate policies

The following sections outline the framework and key considerations for integrating non-CO_2 effects into aviation policy and flight planning. Section 2.1 provides an overview of CO_2 and non-CO_2 policies; primary dependencies, LOSU and key performance indicators of individual non-CO_2 effects are visualized in Figure 3 as well their implications on LAQ, climate and every flight. Section 2.2 presents our framework for calculating weather-dependent CO_2 equivalents (CO_2e) and climate costs for individual flights. Section 2.3 explores strategies to address uncertainties in CO_2e accounting and how they can be managed in pricing and flight planning. Key design parameters for integrating non-CO_2 effects into aviation policy are summarized in Section 2.4.

2.1 Overview of CO_2 and non-CO_2 policies

In aviation, international and domestic CO_2 emissions are addressed through market-based mechanisms such as the EU ETS and ICAO's CORSIA, with ongoing discussions on tighter caps, net-zero alignment, or a global carbon price. National measures, like distance- and fuel-based taxes, or SAF quota, can complement these schemes (Larsson et al., 2019; Scheelhaase et al., 2021). The ReFuelEU Aviation Regulation (European Union, 18 October 2023), for instance, mandates a rising SAF share (6% by 2030 to 70% by 2050) and a sub-quota for synthetic fuels, mainly to reduce CO_2; lower soot emissions from SAF can also shorten contrail lifetime and effective radiative forcing (ERF) (Kärcher, 2018; Burkhardt et al., 2018).

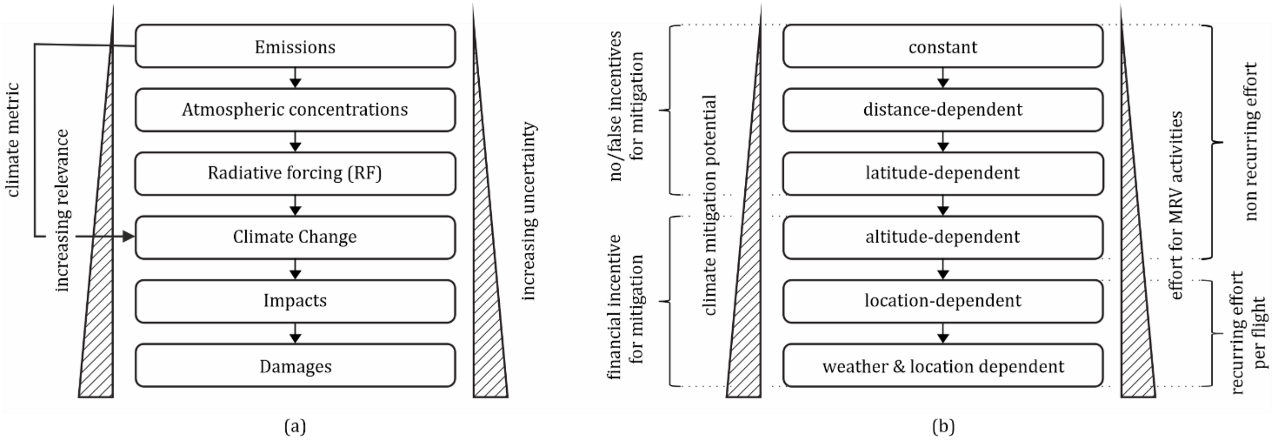

Figure 4a) Cause-effect chain from emissions to climate change and damage (adapted from Fuglestvedt et al., 2003). b) Mitigation benefit and effort for monitoring, reporting and verification (MRV) activities of different CO2e calculation methods (adapted from Niklaß et al., 2020, p. 43)

Non-CO_2 policy options can target (1) reductions of individual emissions (e.g. CO_2, NO_x, nvPM), (2) the resulting climate effects (e.g. changes in temperature, precipitation, or sea level), including indirect chemical (e.g., O_3 formation) and microphysical processes (e.g., contrail formation), or even (3) the downstream damages of climate change, including impacts on the economy and human health (c.f. Figure 4a). This distinction shapes how measures are designed, prioritized, and evaluated, highlighting the potential for both direct emission control (e.g. ICAO's Annex 16, Volume III sets a global CO_2 standard for new and in-production aircraft based on fuel efficiency and range. Engine emissions standards for NO_x and nvPM are in Annex 16, Volume II, tested over the LTO cycle, with nvPM limits adopted in 2020 as a key step in regulating engine particulate emissions) and broader climate-oriented strategies. Price-based policies aim to reflect such damages by translating climate impacts into monetary terms and incorporating simplified estimates of social costs or welfare losses into the cost structure of emitters.

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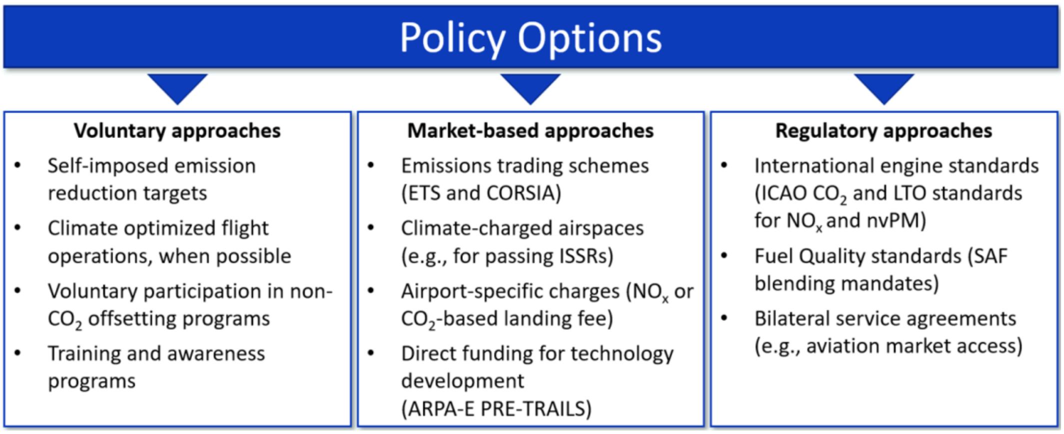

Figure 5. Overview of voluntary, market-based, and regulatory non-CO_2 policy options

Against this background, non-CO_2 mitigation can be pursued voluntarily or through policies such as regulations, taxes, cap-and-trade systems, or subsidies (see Figure 5), but it is more complex than for CO_2 due to weather, engine and fuel dependent implications. Figure 6 illustrates the main dependencies, level of scientific understanding (LOSU), and key performance indicators of individual non-CO_2 effects, along with their implications for local air quality (LAQ) and climate (main focus in the BeCoM project). It also highlights differences in occurrence: contrails appear only on selected flights, while all others are present on every flight. These dependencies and parameterizations provide essential information for integrating non-CO_2 effects into aviation policy.

Primary factors		Effects on LAQ[1]	Effects on climate	Effects on every flight	LOSU[2]	Key Performance Indicator	EU MRV[3] reporting
Weather	Contrail		X		Low	km of contrail formed, km of flight that satisfied the SAC	Modeled net climate impact in CO_2 equivalents (CO2e) at a per-flight basis
Engine	NO_x	X	X	X	Med.-Low	Quantity of emission (variable EI)	
Engine / Fuel	nvPM	X	X	X	Low	Quantity of emission (variable EI)	
Fuel	Sulphur	X	X	X	Low	Quantity of emission (constant EI)	
Fuel	Water vapor		X	X	Medium	Quantity of emission (constant EI) Altitude (Troposphere vs. Stratosphere)	

[1]Local Air Quality
[2]Level Of Scientific Understanding
[3]Monitoring, Reporting and Verification system for aviation non-CO_2 effects in the EU

Figure 6. Key Dependencies, Scientific Understanding, and KPIs of Individual Non-CO_2 Effects for Policy Integration

To address climate effects, many approaches integrate non-CO_2 effects into existing CO_2 pricing schemes (e.g., EU ETS) by converting them into CO_2e, a common metric to express the climate impact of different agents. Since CO_2 is long-lived and well understood, non-CO_2 effects are often expressed relative to one kilogram of CO_2. The total CO_2e from all considered non-CO_2 effects thus defines the total climate effect, and can guide the determination of equivalent emission allowances, charges, or offsets under future policy measures. Various CO_2e calculation methods exist, differing in accuracy and data requirements (c.f. Figure 4b)[1]. Simplified methods, such as constant or distance-based factors, are easy to apply for footprinting or voluntary offsetting but are criticized for policy use because they risk misaligned incentives and may overlook key climate dynamics (Forster et al., 2006; Dahlmann et

[1] Note that the choice of CO_2e calculation method defines determines how non-CO_2 effects are simplified and quantified. A climate metric (e.g., Global Warming Potential over 100 years; GWP_{100}) must be selected to compare these effects (e.g. for converting non-CO_2 effects into CO_2 equivalents), and this choice applies consistently across all of the calculation methods discussed here (c.f. Figure 4a)

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al., 2021). More effective, but data-intensive, are flight-specific, weather-dependent CO_2e calculations that better reflect real climate effects but require detailed monitoring (Niklaß et al., 2020). Grewe et al. (2026) stress that integrating CO2e into political frameworks must create real incentives for climate mitigation, account for uncertainties in atmospheric processes, and rely on pilot projects, risk assessment, consistent monitoring, and economic evaluation.

In December 2022, the EU agreed to align EU ETS with Europe's ambitious climate target of reducing emissions by 55% by 2030 compared to 1990 level (European Union, 10 May 2023). The revision also addresses non-CO_2 aviation effects non-CO_2 effects: since January 1, 2025, aircraft operators must monitor and report weather and location dependent CO2e effects per flight. Implementing an effective non-CO_2 monitoring, reporting, and verification (MRV) system is essential for tracking progress towards climate neutral aviation, incentivizing mitigation measures, and demonstrating compliance with international agreements such as the Paris Agreement. By December 31, 2027, the Commission will submit an assessment report on the application of the MRV framework and, if appropriate, a second legislative extension of the EU ETS to include non-CO_2 pricing, following the Polluter-Pays Principle.

Alternatively, targeted flanking measures are also under discussion to reduce non-CO_2 impacts. Regulatory options include cruise NO_x certification standards (Wit et al., 2004), altitude restrictions (Williams et al., 2003), or dynamic closure of highly climate-sensitive airspace (e.g., PCFAs) (Niklaß et al., 2019). Price-based measures include en-route NO_x charges (Faber et al., 2008), climate-dependent altitude charges (Scheelhaase et al., 2016), or weather-based climate tolls for flying through PCFAs (Niklaß et al., 2021; Bolic et al., 2024), allowing airlines to fly cost-optimally while internalizing non-CO_2 impacts.

2.2 Schematic for integrating price-based CO_2e in policies and operational flight planning

Our concept for integrating price-based CO_2e in policies and operational flight planning is outlined below, providing a schematic for calculating CO_2e and climate costs of single flights. Our work on policy-driven flight planning began well before the formal adoption of the EU non-CO_2 MRV regulation, agreed by the EU trilogue in December 2022 and adopted in May 2023 under EU Directive 2023/958 revising the EU ETS (Recital 11 & Art. 14(5) define the MRV scope for non-CO_2 aviation effects). Parts of the WP5 team provided scientific support to the European Commission during the design of the non-CO_2 MRV scheme and its Implementing Regulation (de Haes et al., 2024; Linke and Niklaß, 2025; Grewe et al., 2026), approved by Member States in August 2024. This early involvement ensured that the project's concept development and assessment activities are closely aligned with ongoing EU regulatory developments. By December 2027, a second legislative extension of the EU ETS could require financial accounting of CO_2e emissions, influencing ticket prices and incentivizing climate-optimized flight operations. The timeline of BeCoM activities and EU non-CO_2 regulatory milestones is visualized in Figure 7.

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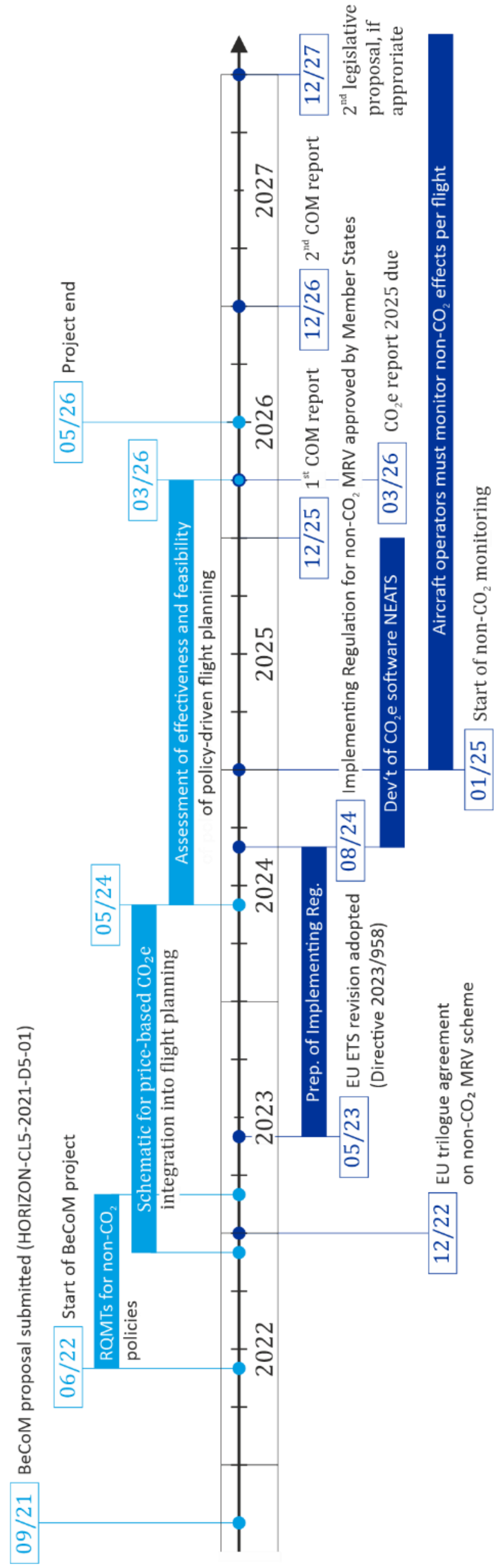

Figure 7. Timeline of WP 5 activities in BeCoM (light blue) and EU non-CO_2 regulation (dark blue)

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For integrating CO_2e into operational flight planning, it is essential to specify, (1) what emissions aircraft release into the atmosphere, (2) where these emissions occur, and (3) how the atmosphere responds to these emissions. To address the first question, operators need to consider combustion processes of the fuel as well as the performance of the aircraft and the engine. As non-CO_2 effects are sensitive to the location of the emissions, fuel and emission calculations must be performed along the actual flight path (latitude, longitude, altitude, and time), to address the second point. The third point concerns the response of the climate system to the various non-CO_2 effects, which differ greatly in their atmospheric lifetimes (hours for persistent contrails, months for ozone changes and years for methane and methane-induced changes). This requires the application of rapid climate response models for CO_2e calculations, as well as data input. In order to reduce the effort to a minimum, all necessary CO_2e calculation steps should automatically be performed by a standardized CO_2e software.

Required data include flight details, aircraft and engine types, trajectories, emissions, fuel, and meteorology. Data collection should be limited to what is necessary to achieve environmental benefits while minimizing effort. Requirements depend on the modelling approach, mitigation measures, and purpose. CO_2e calculations must also be available for operators during pre-flight planning and post-flight monitoring, reporting, and verification (MRV) (de Haes et al., 2024; Grewe et al., 2026):

In pre-flight planning, aircraft operators use weather forecast data to optimize fuel consumption, operating costs, and safety. For mitigation measures that rely on weather-dependent decisions, such as climate-optimized routing for contrail avoidance or targeted SAF use, emission and CO_2e calculations, along with CO_2e pricing, must be integrated directly into the flight planning process.

In post-flight mode, CO_2e calculations must support long-term climate mitigation measures, including technical options (e.g., new fuels, innovative propulsion, or aircraft designs) and general operational measures that are applied regardless of daily weather variations, such as intermediate-stop operations or general flight profile adjustments. Post-flight reporting is possible via primary data, monitored directly by the operator and accessible to verifiers; and secondary data, used for conservative pre-filled CO_2e calculations to reduce MRV effort to a minimum and allow cross-checks by authorities.

For the EU non-CO_2 regulation, the standardized CO_2e software NEATS (Non-CO_2 aviation effects tracking system) is therefore being provided by EUROCONTROL (c.f. Figure 7) that includes:

(1) **A fuel burn module** that estimates fuel flow along the flight path for conservative, pre-filled CO_2e calculations based on secondary data.
(2) **an emissions module** that provides emission inventories along the flight path for CO_2, H_2O and NO_x,
(3) **a climate (response model)** for the CO_2e estimations of the flight for H_2O, NO_x, CiC under consideration of uncertainties (e.g. 5% percentile, 50% percentile, 95% percentile) for different climate indicators (e.g. ATR, GWP) and time horizons (e.g. 20, 50, 100 years), and

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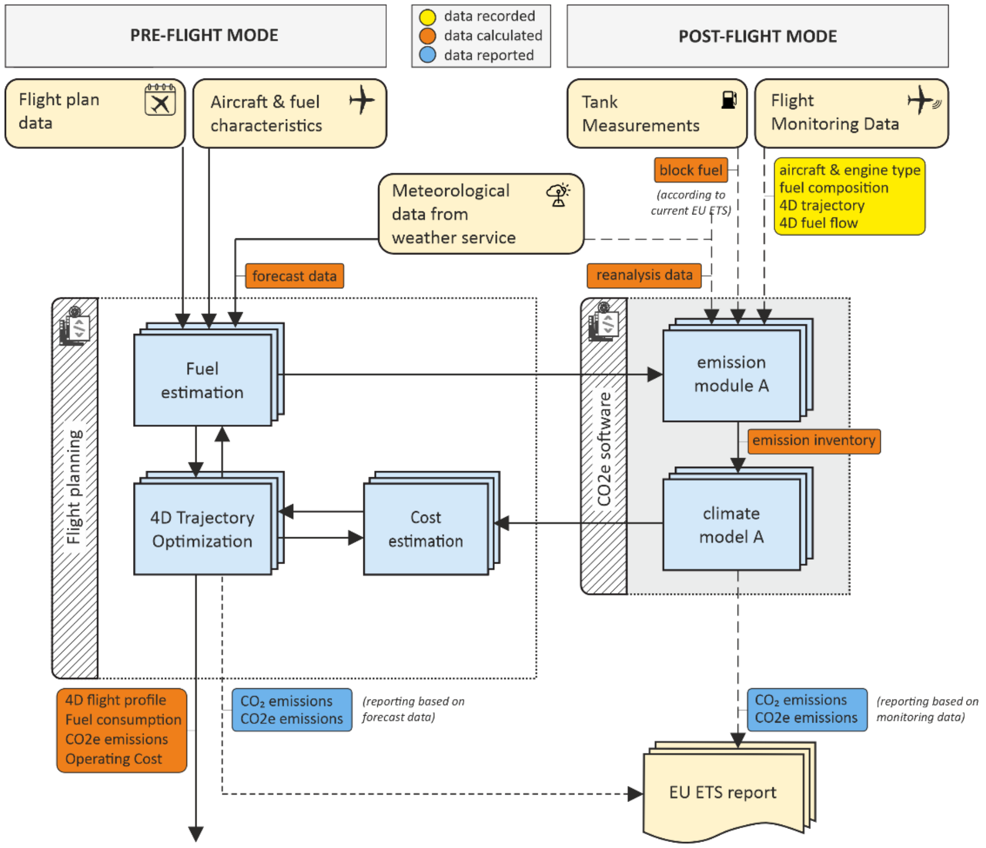

Figure 8. Flowchart for integrating non-CO2 aviation effects into flight planning procedures (pre-flight mode) and monitoring and reporting processes (post-flight mode) of aircraft operators. In order to reduce the operational MRV effort to a minimum, all necessary CO2e calculation steps need to be performed by a standardized CO2e software, possibly provided by a higher-level authority (Niklaß et al., 2025 pre-print).

The integration of the CO_2e software into flight planning is illustrated in Figure 8. For CO_2e-optimized flight planning, operators' fuel and cost estimates must be linked to both the emission and climate response module. By implementing a policy that prices non-CO_2 effects, the total operating cost (TOC) accounts for both direct costs borne by operators and indirect costs of climate change imposed on society. Climate costs are calculated by scaling CO_2e emissions with the carbon price and incorporating the resulting value into the direct operating costs (DOC), creating a financial incentive for operators to reduce their environmental impact. The actual obligation to surrender allowances, to pay a climate levy or to purchase offsets is subject to political decisions that determine, among other things, the climate metric to be used (e.g. ATR_{50}, GWP_{100}) and the share of calculated CO_2e that is monetized (e.g. based on uncertainty intervals).

To model the TOC of a flight mission j, DOCs are extended with a climate cost term, calculated by multiplying the weather- and location dependent $\mathrm{CO_2e}(x,t)$ of the flight[2] with a carbon price, specifically the cost of European Union Aviation Allowances (EUAA):

[2]Under the EU non-CO_2 monitoring framework for aviation, two CO_2e calculation methods are defined. The default Method C uses detailed flight, aircraft, engine, fuel, and meteorological data to calculate climate impacts at the actual time and location of each flight (Figure 8). It provides the highest accuracy, particularly for contrails, and allows mitigation incentives under non-CO_2 pricing. Method D is a simplified climatological approach for small emitters under Article 55(1) of the Regulation (i.e. AOs with less than 243 flights per period for three consecutive four-month periods and AOs with less than 25,000 tonne CO_2/year), relying on flight location,

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$$\mathrm{TOC}_j = \mathrm{DOC}_j + \mathrm{CO_2e}(x,t) \cdot \mathrm{EUAA}$$

Weather- and location dependent CO_2e costs can only be estimated shortly before departure, while ticket prices are set well in advance and respond to demand fluctuations. One approach is to incorporate estimated CO_2e costs into fares at booking, using historical CO_2e data as a reference. Airlines could hedge against CO_2e price volatility by pre-purchasing emission allowances, similar to fuel hedging. Since a small fraction of flights contributes to the majority of contrail radiative forcing (e.g., Teoh et al., 2020), these flights would face high CO_2e charges per passenger without re-routing. Spreading the costs across all flights makes ticket price increases smaller and more predictable. Airlines aim to offer competitive fares, especially in price-sensitive markets, even if additional CO_2e costs are fully passed on to passengers. If re-routing reduces additional costs, they can gain a competitive advantage by offering lower prices or increase profit margins by retaining the difference between actual and expected CO_2e costs.

Beyond individual airlines, CO_2e pricing influences market behaviour, encouraging innovation and supporting sustainable practices that help achieve policy goals. Effective implementation, however, requires careful handling of uncertainties to ensure pricing reflects environmental impacts accurately without causing unintended side effects (c.f. Sections 3.4 and 3.5)

2.3 Options for addressing uncertainties in policy measures

In contrast to CO_2 climate effects which can be assumed to be proportional to fuel burn, non-CO_2 effects do not only depend on emission quantities but also on further parameters such as emission location, altitude, time and meteorological boundary conditions. According to Lee et al. (2021), quantifying (effective) radiative forcing from non-CO_2 effects is associated with eight times higher uncertainties than from CO_2 effects. Therefore, the aspect of uncertainties in the assessment process needs special attention also affecting the incorporation of non-CO_2 effects into the EU ETS. In the following, we will differentiate the following three types of uncertainties:

(1) Uncertainties in weather models and weather forecast
(2) Uncertainties in climate impact modelling
(3) Uncertainties in trajectory and emissions modelling

Weather-related uncertainties can be addressed by incorporating ensembles of meteorological data sets, such as those provide by the European Centre of Medium Range Weather Forecast (ECMWF), or by combining data from multiple weather services. One approach is to focus on areas where all ensemble members predict conditions conducive to contrail formation, minimizing unnecessary detours. Alternatively, planners could consider any area flagged by at least one ensemble member, reducing the risk of forming contrails but potentially creating excessive rerouting. A practical compromise is to apply a threshold—for example, targeting areas where 80% of ensemble members indicate persistent contrail formation areas (PCFAs). Figure 9 illustrates the mean and standard deviation of PCFAs for 16 June 2018 based on ECMWF ERA5 ensemble data, highlighting regions of consistent contrail formation (mean = 1; standard deviation = 0) as well as areas with greater variability. Higher standard deviations along the boundaries indicate discrepancies in temperature and humidity forecasts. Using ensemble-based PCFAs reduces the risk of misidentifying contrail-formation areas and improves the reliability of mitigation strategies.

trajectory, aircraft data, and basic weather inputs. By using climatological assumptions instead of flight-specific weather, it reduces reporting effort but also lowers precision and mitigation incentives compared with Method C (de Haes et al., 2024).

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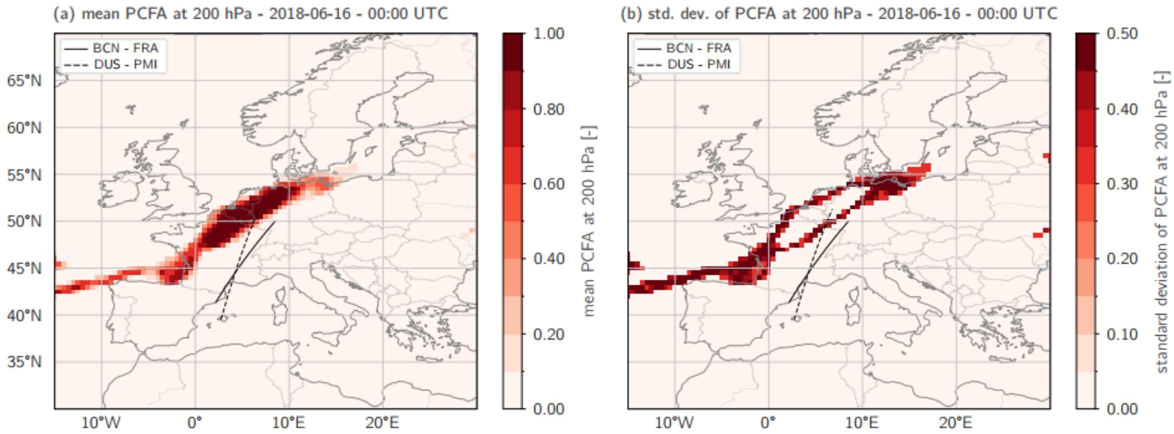

Figure 9: Mean (left) and standard deviation (right) for areas of persistent contrail formation (PCFA) calculated with Clim-aCCF library for June 16th, 2018, based on ERA5 re-analysis ensemble members (Niklaß et al., 2025 pre-print).

Uncertainties in climate effect modelling of non-CO_2 effects arise from the complexity of atmospheric processes with many variable and interacting components. The chemical reactions and physical interactions between different emissions and atmospheric processes are extremely difficult to model accurately. Aerosols and contrails, for example, can have both cooling and warming effects, depending on their properties, atmospheric conditions and time of the day. Changes in cloud cover due to aerosols and contrails can have lasting climate effects, which are often inadequately accounted for in models. Scientists are continuously working to reduce these uncertainties by improving data collection, enhancing the understanding of physical and chemical processes, and refining models. Nevertheless, the current level of scientific understanding for climate impact modelling is summarized, i. a., by Lee et al. (2021), who report best estimates of the effective radiative forcing (ERF) for all relevant climate effects and the 5-95% confidence intervals, respectively.

For policy application, these uncertainties can be reflected by incorporating confidence intervals of individual climate agents into CO_2e calculations. One option is to require emitters to account only allowances for all non-CO_2 effects with a confidence level. For example, applying an 80% confidence threshold means that only the lower 20th percentile of the estimated climate impact of a given species is included in the CO_2e accounting. To implement this approach, we estimated probability density functions for cirrus contrails and nitrogen oxides (see Figure 10) assuming a Gaussian distribution for contrails and a Pearson distribution for NO_x. According to the assumed distributions, we obtain an ERF of 37.0 mW/m^2 for CiC (64.5% of the median value of 57.4 mW/m^2) and an ERF value of 8.8 mW/m^2 for NOx (56% of the median value of 17.5 mW/m^2) at a 20% percentile. Table 1 summarizes the resulting share of CO_2e considered for the 10th–50th percentiles of both climate agents under uncertainty-based accounting, as applied in the sensitivity analysis of key policy design parameters in Section 3.3.

Table 1: Considered share of climate impact with uncertainty-based accounting

Climate Agents	**Percentiles** 10th	20th	30th	40th	50th
CiC, H_2O	45.3%	64.5%	78.4%	90.6%	100.0%
NO_x	26.3%	56.0%	77.1%	94.3%	100.0%

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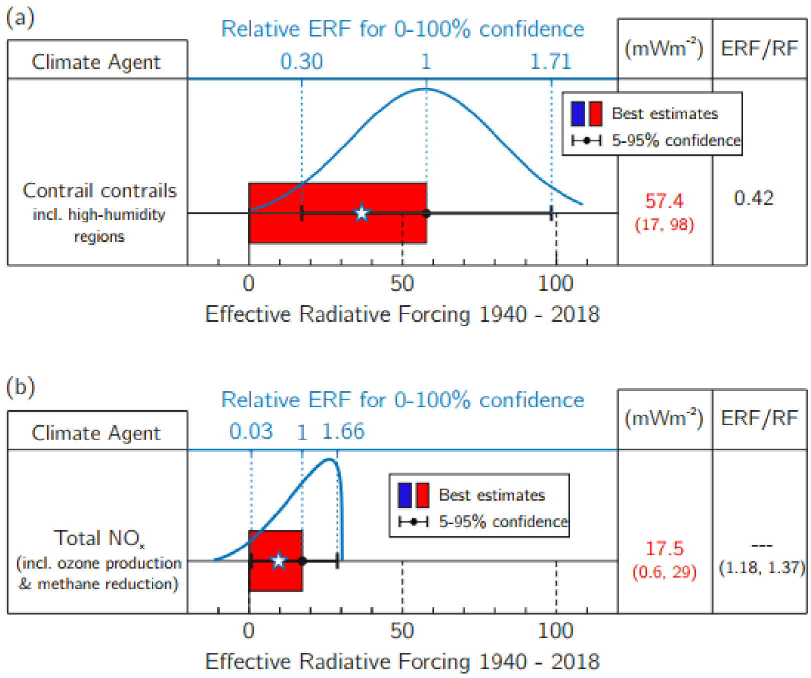

Figure 10 : Estimated probability density functions for (a) cirrus contrails assuming a Gaussian normal distribution and (b) NOx assuming a Pearson distribution (derived from Lee et al., 2021). The 20% percentiles for both functions are exemplarily visualized as stars.

Uncertainties in trajectory and emissions modelling are estimated to be significantly smaller compared to the two above mentioned uncertainties in weather models and forecasts. Nevertheless, it makes sense to qualitatively estimate their impact on the results: Trajectory modelling results in four-dimensional information of fuel burn along flight trajectories, which is significantly influenced by the considered flight performance models. In NEATS, Base of aircraft data (BADA) version 3 or 4 flight performance data provided by EUROCONTROL is applied in a majority of trajectory modelling cases. According to Nuic et al. (2010), BADA4 data is associated with a mean error of fuel consumption of less than 5%. Studies in the course of other projects, such as the German LuFo project DKULT (Kirschler et al., 2026 pre-print), show inaccuracies in the same order of magnitude when validating trajectory simulations with airline fuel consumption data.

A further inaccuracy results from the calculation of emissions from the fuel flow. Unlike the direct combustion products CO_2 and H_2O, emissions of nitrous oxides (NO_x) are a by-product caused by oxidation of nitrogen contained in the air, under high combustion temperatures. Hence, NO_x production rate is strongly dependent on the temperature and the residence time of the fuel-air mixture in the combustion chamber. Different calculation methods based on flight condition, fuel flow and NO_x flow have been established in literature, i.e. Boeing (2) Fuel Flow Method, DLR Fuel Flow Method or p3T3 methods, which differ in complexity, accuracy and data requirements (DuBois, 2006; Döpelheuer and Lecht, 1999, Madden & Park, 2003). While p3T3 method provides highest accuracy but requires detailed engine information which is typically confidential, BFFM2 and DLR method can directly be applied considering flight conditions, fuel flow and sea level engine emission indices from ICAO's data base (ICAO 2023). These fuel flow correlation methods are associated with uncertainties of approximately up to +/- 10% for NO_x emissions during cruise (Schaefer & Bartosch 2013), but have limitations for rich-burn, quick-mix, lean-burn (RQL) combustors. To better characterize cruise emissions of lean-burn engines using BFFM2, the ICAO CAEP/13 meeting in February 2025 recommended the development of a new cruise NOx metric system (EASA, 2025).

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En-route non-volatile particulate matter (nvPM) emissions[3] can be calculated using the latest implementation of the black carbon emissions methodology (Stettler et al, 2016), as detailed in the nvPM Mission Emissions Estimation Methodology 2 (MEEM2, Ahrens et al., 2025). To improve cruise nvPM modelling, CAEP/13 proposed a fifth LTO reporting point at cruise thrust (57.5% of maximum sea-level static thrust) for inclusion in ICAO Annex 16 Volume II certification requirements (EASA, 2025). This aims to enhance the understanding of engine nvPM emissions. However, generating and integrating measurement data for all engine types into the database will require additional time.

We have excluded these uncertainties from assessing policy-driven flight planning, since they are significantly smaller than uncertainties of meteorological and climate effect modelling. However, further research and more validation data is required to reduce uncertainties from trajectory and emission modelling. It is expected, that the introduced non-CO_2 MRV will extend the data basis in this context, thus models can be improved and uncertainties will be reduced.

2.4 Key parameters for internalization of climate effects

Key design parameters for integrating non-CO_2 effects into aviation policy strongly influence allowances, climate charges, or offsets:

- **Selection of climate agents:** Despite substantial improvements in the level of scientific understanding of non-CO_2 effects, it is their nature, i.e., the dependence on meteorology, that largely impedes a fast reduction of uncertainties in the current scientific understanding. Therefore, risk assessments are essential to better understand how these uncertainties affect the calculation of non-CO_2 effects and the potential for setting inappropriate incentives. The choice of considered climate agents strongly affects the level of CO_2 equivalents (climate impact assessment) and the data and models applicable for operationalization. While stepwise integration of non-CO_2 effects is possible, this may influence the selection of mitigation measures and may lead to unintended trade-offs. Thus, the decision to include a climate agent in a policy measure depends not only on its uncertainty but also on its contribution to total climate impact (relevance) and on how well the underlying processes are understood, to avoid misinterpretation of effects (e.g., considering warming effects as cooling or vice versa).
- **Climate metrics** combine a climate indicator (e.g. RF or Temperature), emission scenario (emission course, background emissions, etc.) and time horizon (often 20, 50, 100 or 500 years, see e.g. Fuglestvedt et al., 2010). The appropriate choice depends on the policy objective (Grewe et al., 2015): short horizons are more suitable for near-term mitigation, while longer horizons better reflect long-term sustainability. Pulse emissions are appropriate for single flights, whereas constant emissions are better for assessing long-term technology improvements. The choice of metric strongly influences the trade-off between uncertain but mitigation-relevant short-lived agents (e.g., contrail cirrus) and well-understood long-lived species (in particular CO_2): pulse emissions with a long horizon emphasize long-lived species, while constant emissions with shorter horizons highlight short-lived species.
- Several **CO_2e accounting options** are possible, which highly influence the number of allowances/offsets to be purchased in a policy scheme. As with EU ETS (no surrender obligation in 2010 and 2011, CAP decrease over time) and CORSIA (baseline period, voluntary and mandatory phases), a stepwise introduction seems to be most feasible. To incorporate uncertainties in modelling climate impacts into policy measures, also the confidence interval of each climate agent could be included in the CO2e accounting. If non-CO_2 effects are integrated

[3] nvPM emissions climate impact is primarily indirect through their influence on contrail and cloud properties. Sensitivities of the climate impact towards nvPM emission quantities are excluded from the following analysis but need to be considered in future research.

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into the EU ETS, they can either be included under the existing emissions cap and counted against CO_2 limits, or managed separately. In either case, it must be decided whether and by how much the overall emissions limit should be adjusted; a policy choice that could significantly affect allowance prices. If only a single cap is used, there is a risk that highly promising but uncertain non-CO_2 mitigation options may be favoured, potentially delaying proven and effective CO_2 reduction strategies.

- The **CO_2e price** may be linked to the price of prices of EU emissions allowances and directly influences total costs. In the EU ETS, emission allowance prices have fluctuated strongly since 2012, rising from below EUR 20 for many years to around EUR 80 in 2022 before declining to EUR 65–70 per ton CO_2. Future prices remain uncertain, as they depend on supply and demand, but are expected to increase as the cap is reduced. Higher CO_2e prices can strengthen mitigation incentives and lead to greater trajectory adaptations, potentially at the expense of higher fuel burn.
- The **geographical scope of the policy** is determined by political, legal and environmental considerations. Options range from full inclusion of all flights to and from the EU to a more limited intra-European scope. A narrower scope may be much easier to implement, as it involves less coordination with third countries, but it can reduce environmental effectiveness, increase the risk of CO_2 and non-CO_2 leakage. Potential competitive disadvantages for European airlines compared to non-EU carriers should be considered when defining the policy scope.

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3 Effectiveness of policy driven flight planning

To demonstrate the suitability of the proposed policy-driven flight planning approach, Section 3.1 first presents the modelling approach. Section 3.2 then illustrates the general incentive effects of non-CO_2 pricing, followed by a sensitivity analysis of key policy design parameters in Section 3.3. To further evaluate the effectiveness of non-CO_2 accounting in mitigating climate impacts and to assess its feasibility (T5.3), Sections 3.4-3.7 address the following key questions:

- **Tickets & Demand implications per flight:** What impact might non-CO_2 pricing have on ticket prices and air travel demand? (Sec. 3.4)
- **Network implication:** How route-specific non-CO_2 pricing might affect ticket prices, demand shifts, and network dynamics across different geographical scopes? (Sec. 3.5)
- **Effectiveness of non-CO_2 policies**: Can non-CO_2 policies promote both Climate-Optimized Flying as well as technological mitigation measures? (Sec. 3.6)
- **Mitigation Potential:** What Is the Impact of Non-CO_2 Pricing Across 100 Routes in Daily Simulations of 2018? (Sec. 3.7)

3.1 Modelling Approach

The modelling framework used to assess the effectiveness of policy-driven flight planning is adapted to the requirements of each use case and varies across several dimensions, as summarized in Table 2. These include, among others, the number of simulated missions, geographic scope, applied trajectory and climate response models, meteorological conditions, mitigation options, CO_2e price assumptions, and accounting methods. The mitigation options considered include 2D and 3D climate-optimized trajectories (COTs, 3D as standard application), climate-optimized intermediate-stop operations (ISO), flight profile adjustments (FPAs), formation flights (FF), the use of sustainable aviation fuels (SAF), and technical improvements (TECH).

The route selection for demonstrating the suitability of the proposed policy-driven flight planning approach and for sensitivity studies (Sections 3.2- 3.4), along with the most commonly used modelling approaches for trajectory and climate response simulation, are outlined below, while use-case-specific variations are detailed in the corresponding subsections.

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Table 2: Overview of the modelling applied in individual case studies

<table>
<tr><th></th><th colspan="6">Sections</th></tr>
<tr><th></th><th>Sec. 3.2
Operating principle</th><th>Sec. 3.3
Sensitivities of key params</th><th>Sec. 3.4
Rel. Impact on Demand</th><th>Sec. 3.5
Network Demand Imp.</th><th>Sec. 3.6
Tech & Ops. Incentives</th><th>Sec. 3.7
Daily simulations</th></tr>
<tr><td>Missions</td><td>1</td><td>2</td><td>2</td><td>9</td><td>50</td><td>100</td></tr>
<tr><td>Geographic Scope of non-CO_2 Policy</td><td colspan="3">Reduced Scope (Intra-EU)</td><td>Red. scope;
Full scope;
Dep.-based</td><td>Full scope</td><td>Reduced Scope (Intra-EU)</td></tr>
<tr><td>Met. Situations</td><td>1</td><td>2</td><td>12</td><td colspan="2">Climatological mean</td><td>365</td></tr>
<tr><td>Traj. Model</td><td colspan="3">pyTOM[1]</td><td colspan="2">iTCM[2]</td><td>AirTaf[3]</td></tr>
<tr><td>Clim. Res. Model</td><td colspan="3">aCCF[4]</td><td colspan="2">AirClim[5]</td><td>aCCF[4]</td></tr>
<tr><td>Cooling Contrails</td><td colspan="2">no</td><td>yes</td><td colspan="3">no</td></tr>
<tr><td>Acc. Share</td><td>100 %</td><td colspan="2">20-100 %</td><td>50 %</td><td>20-100 %</td><td>100%</td></tr>
<tr><td>Unc. Based Acc.</td><td>no</td><td>yes</td><td colspan="4">no</td></tr>
<tr><td>CO_2e price</td><td>EUR 80</td><td>EUR 50;
EUR 80;
EUR 115</td><td colspan="4">EUR 80</td></tr>
<tr><td>Mitigation</td><td colspan="4">3D COT</td><td>2D COT, ISO, FPAs, FF, SAF, TECH</td><td>3D COT</td></tr>
<tr><td>Considered species</td><td colspan="5">CO_2, H_2O, NO_x, CiC</td><td>CO_2, CiC</td></tr>
<tr><td>Climate metric</td><td>p-ATR</td><td>p-ATR;
p-EGWP</td><td colspan="2">p-ATR</td><td>F-ATR;
p-ATR</td><td>p-ATR</td></tr>
<tr><td>Time horizon</td><td>100a</td><td>50a, 100a</td><td colspan="4">100a</td></tr>
</table>

[1] Lührs et al. (2016); Lau et al. (2022)
[2] Linke et al. (2017); Zengerling et al. (2023)
[3] Yamashita et al. (2020); Castino et al. (2024)
[4] Dietmüller et al. (2023); Matthes et al. (2023, pre-print)
[5] Grewe and Stenke (2008); Dahlmann et al. (2016)

Route and meteorological data selection for demonstration and sensitivity studies

Due to the regional scope of the EU non-CO_2 MRV scheme, we analysed the intra-European flight schedule using the Sabre Market Intelligence (Sabre MI) database. Flights were filtered by aircraft type (Airbus A320 or A320neo) and a minimum distance of 750 km. Routes were pre-selected based on traffic volume, measured in available seat kilometres (ASK) from Sabre MI. Finally, we identify two especially interesting routes, which lead to the formation of contrail cirrus at one time of day and do not lead to contrail cirrus at another time of the same day (see Figure 11) over a sample of possible analysis days considering the respective weather situation.

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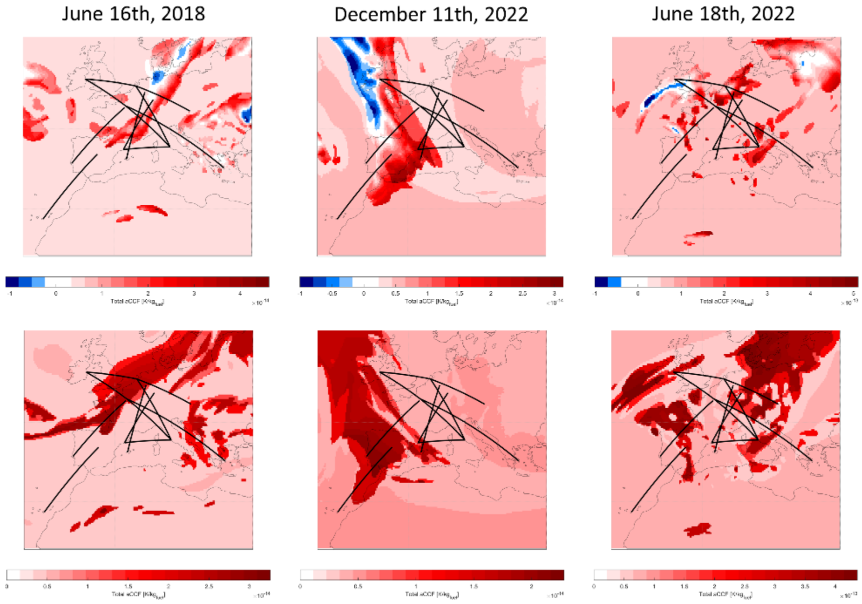

Figure 11: Top-10 routes for selected days and times (day-time and night-time).

Based on this analysis, we select June 16th, 2018 as the day for representing the meteorological situation and the mission from Barcelona (BCN), Spain, to Frankfurt (FRA), Germany, as well as a mission from Düsseldorf (DUS), Germany, to Palma de Mallorca (PMI), Spain, with an A320neo for the following analysis. Figure 11Figure 11 shows a large area of contrail formation along the route during daytime (12 UTC) and no contrail formation during night time (00UTC).

Algorithmic cost functions for climate change & meteorological data

For climate response modelling, a number of different climate models are available for CO_2e calculation, e.g. AirClim (Grewe and Stenke, 2008; Dahlmann et al., 2016), CoCiP (Contrail Cirrus Prediction Tool; Schumann, 2012), LinClim (Lim et al., 2007), FaIR (Finite-amplitude Impulse-Response; Millar et al., 2017; Smith et al., 2018), OSCAR (Gasser et al., 2017; Terrenoire et al., 2019), LEEA (Low Emissions Effect Aircraft project; Köhler et al., 2008; Rädel and Shine, 2008) and aCCFs (algorithmic Climate Change Functions; Dietmüller et al., 2023; Yin et al., 2021, 2023; Matthes et al., 2023 pre-print).

For contrail avoidance, weather-depended modules are required, as implemented in tools like CoCiP or aCCFs. These modules estimate the likelihood and intensity of contrail formation and other climate-relevant effects along flight paths, enabling rapid and consistent four-dimensional CO_2e calculations that account for meteorological conditions, emission location, and time. The NEATS IT tool uses a combination of both models, but for our non-CO_2 pricing demonstration we employ only aCCFs, as it includes climate response calculations for CO_2, H_2O, NO_x, and cirrus contrails (CiC).

Algorithmic climate change functions (aCCFs) are simple linear equations that estimate the climate impact from aircraft emissions as a function of meteorological conditions at time and location of emissions (van Manen and Grewe, 2019; Yamashita et al., 2020; Dietmüller et al., 2023). Since extensive climate simulations are not feasible for application in flight planning and trajectory optimisation, climate change functions (CCFs) have been derived from extensive climate simulations with climate model EMAC to derive response surfaces in terms of average temperature response for eight representative weather patterns in summer and winter (Frömming et al. 2021). Based on these results, aCCFs have been derived by statistically relating meteorological parameters with the climate impact, so that a set of linear functions was derived describing average temperature response over 20 years resulting from a pulse emission (p-ATR20). These functions for the climate forcers CO_2, H_2O, NOx-

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induced Ozone (O_3) and methane (CH_4) changes as well as contrail-induced cloudiness can easily be evaluated with the forecasted or reanalysed weather situation along the flight trajectory. The detailed definition of those functions can be found in Dietmüller et al. (2023) and Matthes et al. (2023 pre-print).

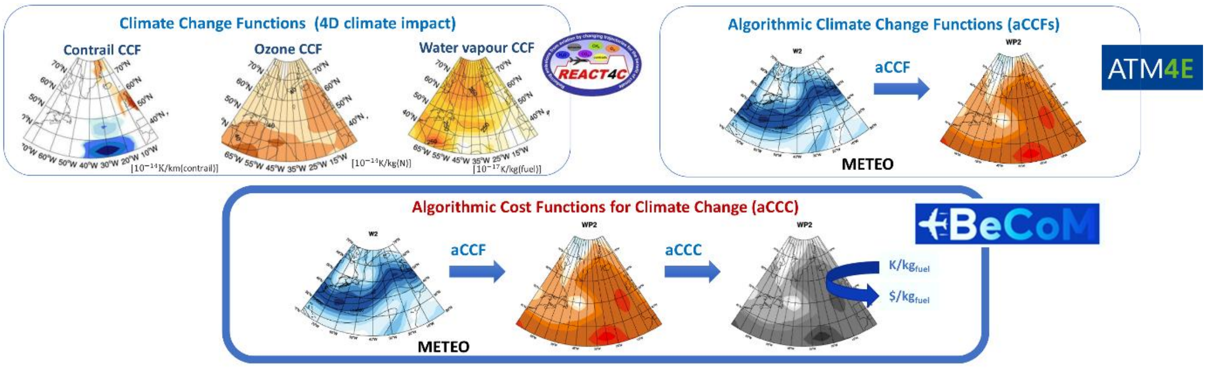

Figure 12: Concept of deriving aCCC from aCCF

Four-dimensional CO_2e functions in dependence of emission location(x) and time (t) are obtained as the temporal integral of $aCCF_i(x,t)$ multiplied with the fuel flow for CO_2, H_2O, emission flow for NO_x or the true airspeed v_{TAS} in the case of CiC:

$$\mathrm{CO_2e}(x,t)=\left(\sum_i \int_{t_0}^{t_f} \frac{aCCF_i(x,t)\cdot \dot{m}_i(t)dt}{aCCF_{CO_2}} + \int_{t_0}^{t_f} \frac{aCCF_{CiC}(x,t)\cdot v_{TAS}(t)dt}{aCCF_{CO_2}}\right)\cdot EI_{CO_2}$$

With a simplification of the aCCFs with average values for emission quantities per burnt fuel as well as flight distance per burnt fuel in dependence of aircraft type and flight altitude, the formula can be simplified to:

$$\mathrm{CO_2e} = \int_{t_0}^{t_f} \frac{aCCF_{merged}(x,t)\cdot \dot{m}_{fuel}(t)dt}{aCCF_{CO_2}}\cdot EI_{CO_2}$$

Here we introduce the concept of algorithmic cost functions for climate change (aCCCs), that are derived by multiplying CO_2e functions with carbon costs, specifically the price of European Union Aviation Allowances (EUAA):

$$aCCC(x,t) = \mathrm{CO_2e}(x,t)\cdot \mathrm{EUAA}$$

Figure 13 illustrates the aCCCs over the European airspace on June 16, 2018 at 00:00 and 12:00 UTC at 250hPa describing trajectory-dependent climate costs based on meteorological parameters. The colour coding represents climate charges in EUR per kilogram of burnt fuel. Higher charges are indicated red and negative charges in dark blue.

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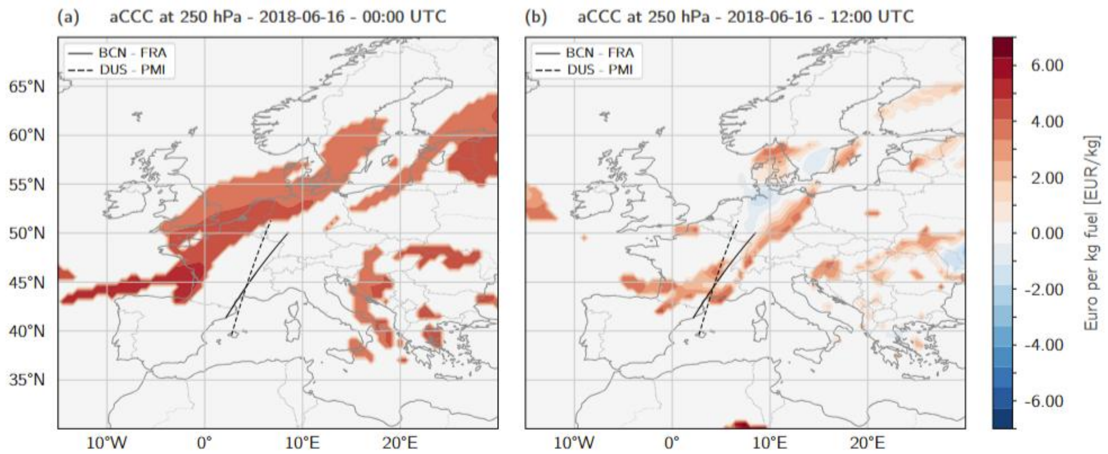

Figure 13. Climate costs in EUR per kg fuel over Europe at 250 hPa on 16 June 2018 at 00:00 UTC (left) and 12:00 UTC (right), calculated using algorithmic cost functions for climate change (aCCC), assuming a carbon price of EUR 80 (Niklaß et al., 2025 pre-print).

These functions represent climate cost in dependence of emission location and time to be applied in policy-driven trajectory optimisation. aCCCs can be calculated for various climate metrics, with conversion factors and efficacy parameters provided by Dietmüller et al. (2023) and Bruder et al. (2026), which are summarized in Table 3.

Table 3: The following conversion factors, provided by Dietmüller et al. (2023) and Bruder et al. (2026), were used to convert P-ATR$_{20}$ to other metrics.

Conversion	**CO_2**	**H_2O**	**O_3**	**CH_4**	**CiC**	**PMO**
p-ATR$_{20}$ → P-ATR$_{100}$	1.801	0.446	0.446	0.758	0.446	0.758
p-ATR$_{20}$ → P-ATR$_{50}$	1.588	0.709	0.709	1.061	0.709	1.061
p-ATR$_{20}$ → P-EAGWP$_{50}$	216.970	66.220	66.220	114.644	66.171	114.644
P-ATR$_{20}$ → P-EAGWP$_{100}$	343.028	66.220	66.220	116.381	66.171	116.381

If non-CO_2 climate effects are considered in flight planning based on CO_2e cost, the total operating cost (TOC) of a flight mission j are extended as follows, while we consider the direct operating cost as a simplified function of mission distance d_j, fuel burn $m_{fuel,j}$ and flight time t_j derived from the ClimOP project (Zengerling et al., 2023) as well as a cost term accounting for the climate impact of this flight.

$$\mathrm{TOC}_j = f_{DOC}\left(m_{fuel,j}, t_j, d_j\right) + aCCC(x,t)$$

To relate cost changes to ticket prices, we use the 2023 average ticket price for each analysed route from the Sabre Market Intelligence (MI) database (Sabre, 2024) as the reference ($\mathrm{TP}_{\mathrm{Sabre2023},j}$). To assess the effect of surrendering CO_2e certificates on airfares, we assume all additional costs ($\Delta\mathrm{TOC}_j$) are passed on to passengers ($n_{\mathrm{PAX},j}$).

$$\mathrm{TP}_j = \mathrm{TP}_{\mathrm{Sabre2023},j} + \Delta\mathrm{TOC}_j \cdot n_{\mathrm{PAX},j}{}^{-1}$$

Sections 3.2 and 3.3 calculate the impact of CO_2e pricing on ticket prices ($\Delta\mathrm{TP}_j$), while Section 3.4 applies price elasticities (η) to estimate the resulting effect on passenger demand.

$$\Delta n_{\mathrm{PAX},j} = \eta \cdot \Delta\mathrm{TP}_j \cdot \mathrm{TP}_{\mathrm{Sabre2023},j}{}^{-1}$$

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Trajectory optimisation and emissions calculation

In Sections 3.2-3.4, we apply DLR's Trajectory Optimization Module in python (pyTOM), which detects eco-efficient trajectories based on optimal control techniques (Lührs et al., 2016; Lau et al., 2022). In the latest version, pyTOM is combining the Theta* path planning algorithm with optimal control techniques. After computing a good initial solution with Theta*, an optimal control algorithm is applied to generate a feasible and dynamically optimal trajectory, taking into account a detailed flight performance model. Aircraft motion is described as the temporal evolution of state variables (e.g., position, mass, emissions), which can be modified using control variables (e.g., aircraft heading, thrust). Thrust, fuel flow and aerodynamic drag are obtained from Eurocontrol's BADA4 aircraft performance models (Nuic and Mouillet, 2012).

Emission flows along the flight trajectory are calculated by the emission module (see Figure 8) by multiplying the fuel flow, assuming a stoichiometric combustion for CO_2 and H_2O with emission indices. For the emission index of NOx, we apply the BFFM2 (DuBois and Paynter, 2006; Jelinik et al., 2004). BFFM2 comprises a standardized step-by-step application procedure and is therefore well suited for automated application, e.g. as part of a software tool. The methodology makes use of measured and certified sea level static engine emissions and fuel flow data as published in ICAO's Engine Exhaust Emissions Data Base (EDB) for each engine type in service (ICAO, 2023). The required input data are engine UID of the engine attached to aircraft, engine fuel flow, ambient pressure and temperature and flight Mach number.

Optimized aircraft trajectories are determined by identifying a control input which minimizes a multi objective (MO) cost functional J_{MO} while satisfying dynamic constraints as well as control, state and path limitations. Here, we define J as weighted sum of direct operating cost (square brackets) and climate impact (curly brackets), which is obtained as the temporal integral of aCCFs multiplied with the associated emission flow $\dot{m}_i$ for CO_2, H_2O, and NO_x or the true airspeed v_{TAS} in the case of contrail-induced cirrus cloudiness (CIC):

$$J_{\mathrm{MO}} = \omega_{\mathrm{DOC}} \cdot [f_{\mathrm{DOC}}(m_{\mathrm{fuel}}, t, d)] \cdot \mathrm{DOC_{ref}}^{-1}$$
$$+\omega_{\mathrm{clim}} \cdot \left\{ \sum_i \int_{t_o}^{t_f} aCCF_i(x,t) \cdot \dot{m}_i(t) dt + \int_{t_o}^{t_f} aCCF_{CiC}(x,t) \cdot v_{TAS}(t) dt \right\} \cdot ATR_{ref}{}^{-1}$$

Where t is the time, d the distance, and m_{fuel} the burnt fuel of the aircraft. The Pareto optimal set is found by varying the weights $(\omega_{\mathrm{DOC}}, \omega_{\mathrm{clim}}) \in [0; 1]$ with $\omega_{\mathrm{DOC}} + \omega_{\mathrm{clim}} = 1$.

For the accounting of non-CO_2 allowances, the multi-objective (monetary costs vs climate costs) optimal control problem was transformed into a purely economic cost minimization:

$$J_{\mathrm{cost}} = \min\{f_{\mathrm{DOC}}(m_{\mathrm{fuel}}, t, d) + \mathrm{CO_2e}_j(x,t) \cdot \mathrm{EUAA}\}$$

The continuous optimal control problem is transformed into a nonlinear programming problem (NLP) and solved using standard NLP solvers within pyTOM applying Dymos, an open-source Python library that extends OpenMDAO to solve optimal control and trajectory optimization problems in dynamic systems.

3.2 Incentive effects of non-CO_2 pricing: conceptual demonstration of the policy mechanism

The impact of non-CO_2 pricing on flight routing, climate impact, and ticket prices is investigated across various weather conditions, CO_2e accounting options, climate metrics, and carbon prices.

Figure 14 (left) shows the cost-optimized reference trajectory (BAU, without CO_2e accounting) for the flight from Barcelona to Frankfurt on 16 June 2018 at 12:00 UTC under conditions of high contrail

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climate impact. When CO_2e accounting is applied (right), the trajectory changes significantly, particularly in the vertical dimension, to avoid regions of high climate cost associated with contrail formation, as indicated by the contour lines in Figure 4. Thereby, CO_2e can be reduced by 55% compared with the reference case, demonstrating the effectiveness of CO_2e accounting in lowering climate impact along the trajectory.

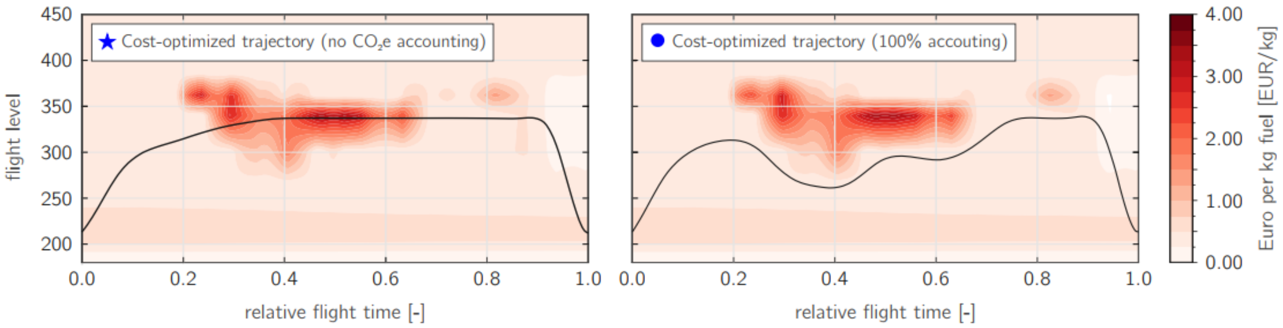

Figure 14: Cost-optimized trajectories in vertical plot considering DOC optimization without CO_2e accounting (left) and with CO_2e accounting (bottom) assuming a full accounting, exemplary for reference mission from BCN to FRA on June 16, 2018 at 12:00 UTC (Niklaß et al., 2025 pre-print)

Figure 15 illustrates the resulting cost-benefit trade-off between CO_2e reduction and operating costs. Without CO_2e pricing, climate-optimized routes (black dots) must balance the trade-off between two conflicting objectives: minimizing costs (fuel, time, or operating expenses) on the one hand and reducing climate impact (given in CO_2e in this example) on the other hand. Higher climate mitigation potentials usually require larger deviations from cost-optimized trajectories, leading to increased operating costs and creating a typical "win-lose" trade-off.

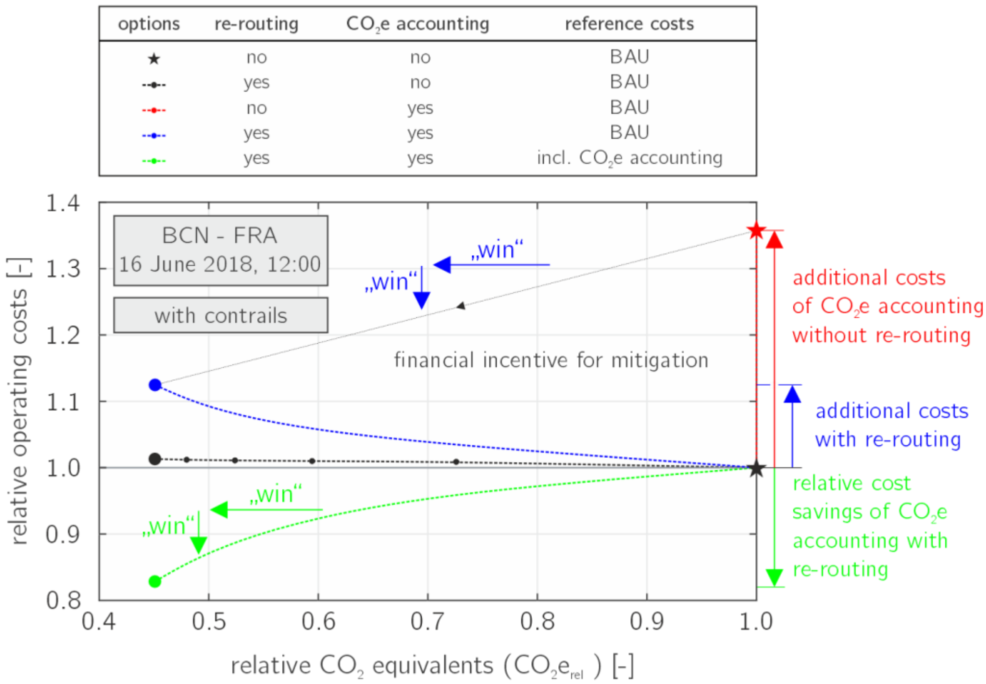

Figure 15: Schematic of CO2e accounting in pareto-front opposing climate impact mitigation and cost increase (Niklaß et al., 2025 pre-print)

In contrast, implementing CO_2e accounting incorporates the broader societal costs of the resulting climate impact into the balance sheet of the aircraft operators, increasing absolute costs (red dot), but enabling savings through more sustainable operations. As the policy defines the CO_2e calculation

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method and, for the EU ETS, the carbon price is determined by the market (in this example full CO_2e accounting measured in p-ATR_{100} at EUR 80 per ton of CO_2, c.f.

Table 4), it results in a single cost-optimal solution (blue dot), replacing multiple equivalent Pareto-optimal solutions (black dots).

In this CiC-intensive mission, a 55% mitigation potential can be achieved either voluntarily, with a 1.3% increase in operating cost, or via CO_2e accounting (blue dot). The CO_2e scenario raises costs by 12.5% compared to today's BAU trajectory (black star, no accounting, no re-routing) but is 18.6% cheaper than BAU with CO_2e applied (red dot). As CO_2e accounting raises costs across all trajectories, the extended balance can be regarded as the new reference (green line), making the re-routed trajectory the most cost-efficient and yielding a 17.2% financial benefit alongside reduced climate impact. By narrowing options to a single optimal route, the policy simplifies and promotes socially responsible decision-making.

3.3 Sensitivity analysis of key policy design parameters

Assuming aircraft operators pass all additional climate-related costs directly to passengers, ticket prices may rise, potentially affecting affordability and demand. Figure 16 a–h show these effects across the examined routes, with varying contrail intensity (horizontal dimension) and in dependence of differences in key design parameter (vertical dimension). While non-CO_2 accounting works independently of the chosen allocation method, carbon price, or climate metric, these parameters can strongly influence mitigation options and ticket price changes. Their sensitivities are assessed based on the variations defined in Table 4.

Table 4: Study set-up for sensitivity analysis with reference values in bold

	Considered variations
Missions	**BCN-FRA** and DUS-PMI
Temporal scope	16th of every month of 2018 (**June**)
Accounting share	20%, 40%, 60%, 80%, **100%**
CO_2e price	EUR 50, **EUR 80**, EUR 110
Climate metric	**p-ATR_{100}**, p-ATR_{50}, p-$EGWP_{100}$, p-$EGWP_{50}$
Uncertainties	10%, 20%, 30%, 40%, **50% (median)**
Contrail effects	Warming and cooling vs. **warming only**

As shown in Figure 16, operational mitigation potentials are primarily driven by contrail avoidance, while ticket price increases are influenced by the accounted share of CO_2e and carbon price. Gradual implementation could help moderate passenger costs at first. Resulting ticket price increases vary between 1.0% and 4.8%. CO_2e abatement costs range from 3 to 74 Euro per ton CO_2e, with a median of 14 Euro and lower costs on days with effective contrail avoidance. These cost estimates are below expected abatement cost in other sectors such as wind or solar energy and direct air capture. Incorporating cooling contrails into pricing could neutralize or reduce costs through compensation but is controversially discussed due to higher risks. Given large uncertainties in non-CO_2 modelling, which affect data accuracy in a monitoring, reporting and verification (MRV) framework but could incentivize harmful re-routing under CO_2e pricing, strategies to mitigate risks in climate policies are proposed. These include using ensemble weather forecasts to reduce formation risks or risks of unnecessary detours, and implementing uncertainty-based CO_2e accounting, which relies on confidence levels in

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climate-impact modelling. Ongoing research and adaptable policies are crucial to incorporate the latest scientific understanding and drive meaningful climate action in aviation.

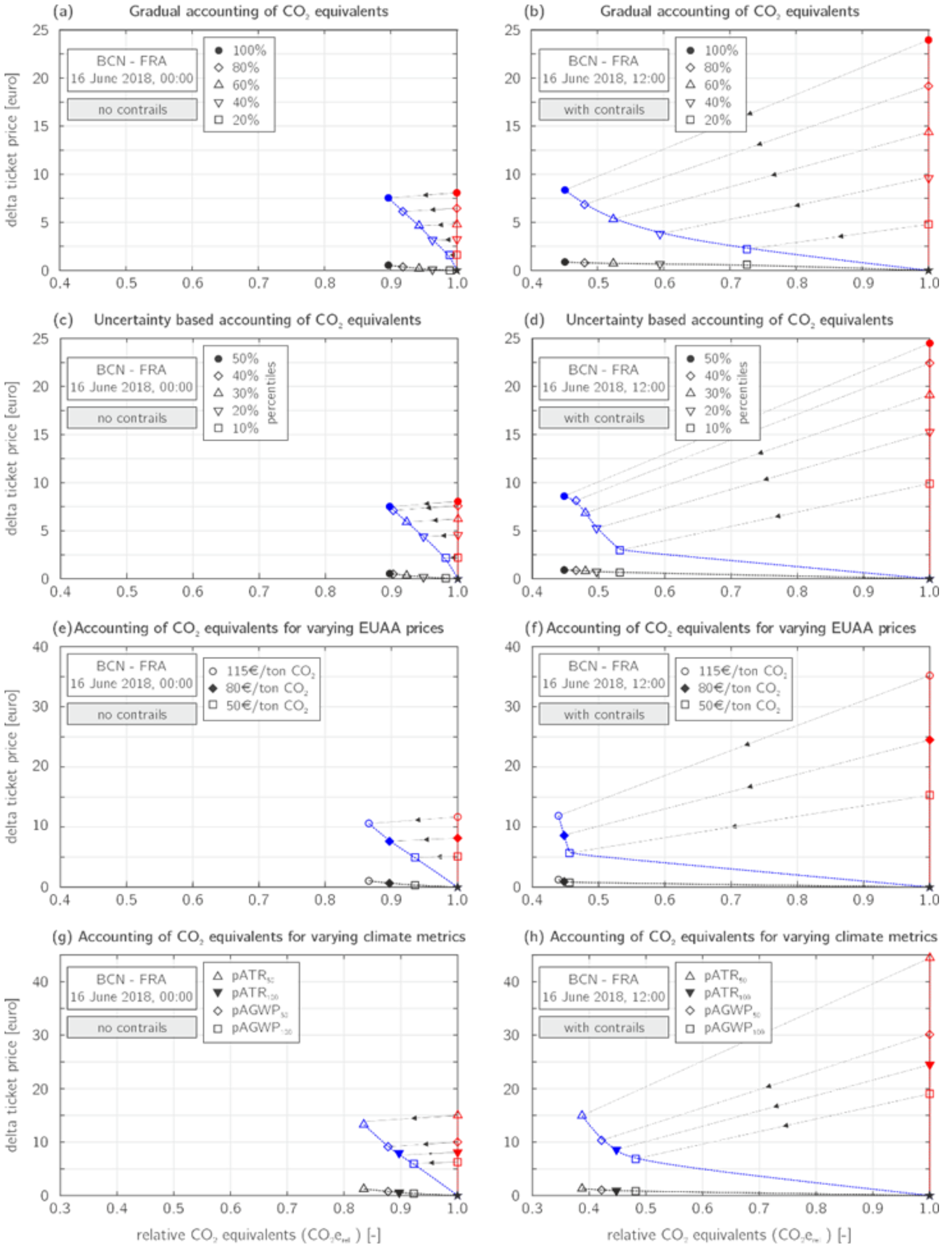

Figure 16: Changes in ticket price and climate impact (CO_2e) in dependence of policy design parameters, namely accounting share (a-b), consideration of uncertainties (c-d), CO_2e prices (e-f), and climate metric (g-h). Results are displayed for exemplary missions from BCN to FRA on June 16th, 2018, low contrail intensity (left) and with high contrail intensity (right) along the mission (Niklaß et al., 2025 pre-print).

3.4 Route-level impacts of non-CO_2 accounting: demand and cost implications under different weather situations

Non-CO_2 accounting increases operating costs, which are typically passed on to passengers, resulting in higher ticket prices. The magnitude of the increase depends on the chosen mitigation measures. Niklaß et al. (2025) analysed its impact on selected intra-European flights. Weather conditions, particularly the presence or absence of PCFAs, strongly affect the climate mitigation potential of operational measures but have limited influence on ticket prices (see Figure 17).

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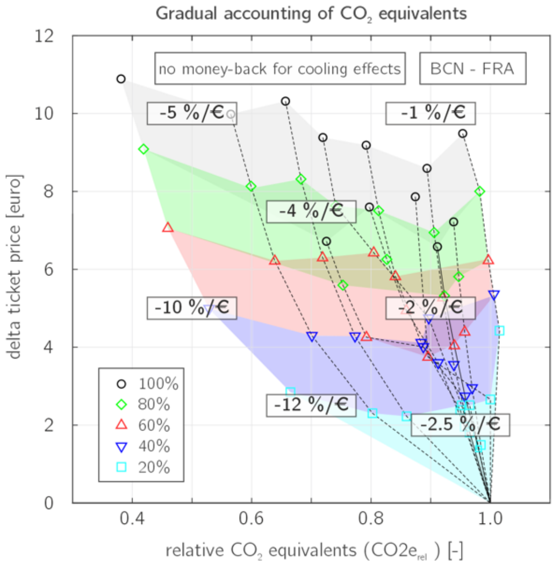
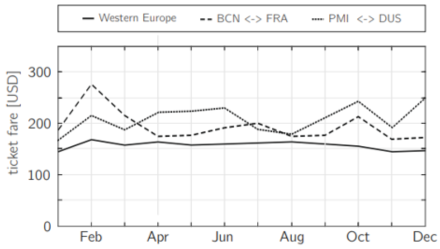
Ticket price sensitivity is higher with respect to the share of non-CO_2 effects included in the accounting (c.f. color variations). In most cases, the increases remain small relative to natural fare fluctuations driven by seasonality, route, and demand (see Figure 34b). For example, CO_2e charges on Western European flights in 2023 raised average ticket prices by 1–6 %, while fares varied seasonally by over EUR 100 on some routes.





Ticket fare		Additional CO2e charge per ticket				
		2.00 €	4.00 €	6.00 €	8.00 €	10.00 €
25th Percentile	137.91 €	1.5%	2.9%	4.4%	5.8%	7.3%
Mean	179.85 €	1.1%	2.2%	3.3%	4.4%	5.6%
75th Percentile	252.23€	0.8%	1.6%	2.4%	3.2%	4.0%

Impact of CO2e pricing on passenger demand		Additional CO2e charge per ticket				
		2.00 €	4.00 €	6.00 €	8.00 €	10.00 €
Mean	179.85 €	-1.0%	-1.9%	-2.9%	-3.9%	-4.8%

Assuming an aggregated elasticity value of -0.87 (Oesingmann and Kölker, 2025)

Figure 17: (left) Variation of ticket price increases and associated CO_2e mitigation potentials in dependence of different weather situations (16th day of each month in 2018) and accounting shares (20-100%) for a mission from BCN to FRA. (right) Sabre ticket fare statistics of the year 2023 for selected Western European flights and relative impact of additional CO2e charges on ticket fares and passenger demand (adapted from Niklaß et al., 2025 pre-print)

To assess the impact of CO_2e accounting on fares, we compare it to overall ticket price variations over time. In 2023, ticket prices for Western European flights showed considerable variation (see Figure 17 right) with BCN-FRA average fares from EUR 138 (November) to EUR 252 (February) and strong seasonal effects. This fluctuation is caused by dynamic pricing. While fares must cover operating costs (e.g., fuel, staff, maintenance, airport charges) in the long term, short-term prices are primarily demand-driven – rising with high demand and dropping through discounts when demand is low. For the route BCN-FRA, an additional CO_2e charge per ticket results in an average fare increase of 1.1%-5.6% (e.g., EUR 2 increases fares by 0.8–1.5%, EUR 10 by 4.0–7.3%). These increases are small relative to overall fare fluctuations and affect low and high fares less, as demand-driven dynamic pricing dominates.

Price elasticity measures how demand responds to ticket changes, varying by route, distance, passenger type, and market. Aggregated elasticities, which include substitution effects, are crucial for policy evaluation Assuming an elasticity of -0.87 (Oesingmann and Kölker, 2025), CO_2e accounting reduces demand by 1.0–4.8 %.

Abatement costs of CO_2e avoidance

The cost of CO_2e avoidance is calculated as the change in total operating cost (ΔTOC) per tonne of CO_2e reduced, primarily driven by operational expenses such as fuel burn and flight time, though capital investments in infrastructure (e.g., satellites, sensors) could also contribute. Focusing on operational costs, abatement for full mitigation on the BCN–FRA route ranges from EUR 2.8 to EUR 74.4/tCO_2e (median EUR 14.1, mean EUR 19.0), with the lowest costs when contrail avoidance is effective and the highest on days without PCFAs. The mitigation potential per euro of ticket price increase ($\Delta CO_2e/\Delta TP$) ranges from 1–12%/EUR, depending on weather and contrail avoidance effectiveness (see Fig. 8a).

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Other studies focusing on contrail mitigation estimate abatement costs between EUR 1–25/tCO_2e by 2040 (Cathcart et al., 2024; Martin Frias et al., 2024). Compared to other sectors, operational CO_2e avoidance in aviation is cost-effective, with abatement costs lower than wind (EUR 82–276 / tCO_2), solar (EUR 411–1,944 / tCO_2), or direct air capture (USD 341–374/t CO_2; Sievert et al., 2024).

Pricing of cooling contrails

Contrails can also produce a cooling effect, which could in principle be incorporated into pricing schemes, potentially providing economic compensation to operators. For example, a DUS–PMI flight on 16 July 2018 (c.f. Figure 18) passes through a warming contrail area while avoiding a cooling region under the BAU trajectory. By adjusting the flight path into the cooling contrail area, additional CO_2e costs could be neutralized or ticket prices reduced by EUR 1.5–3.6, depending on the accounting level, while reducing climate impact by 83–94%.

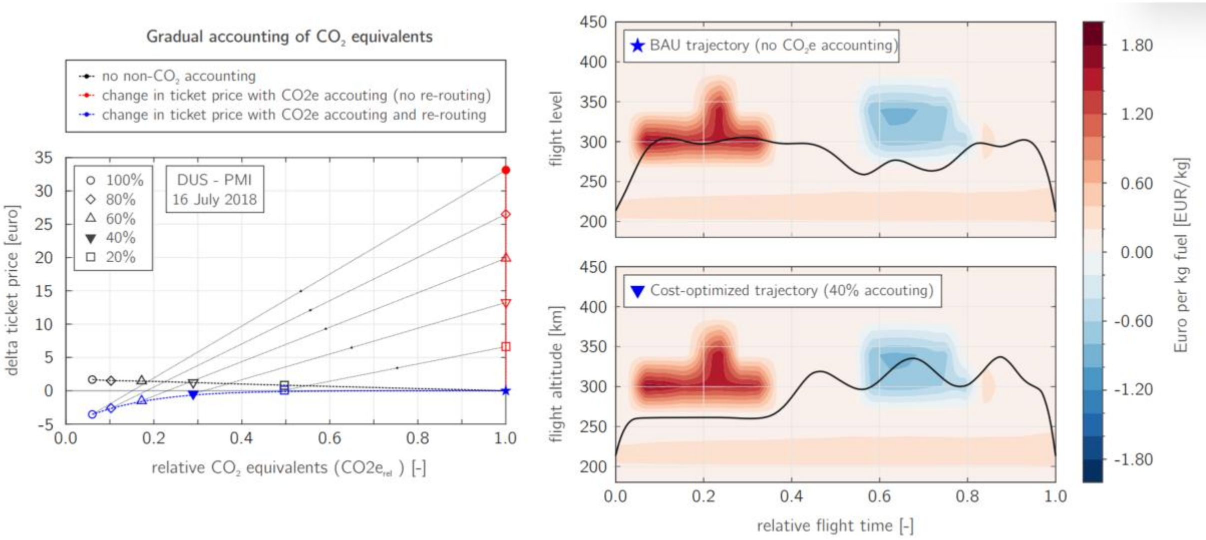

Figure 18: Changes in ticket price and CO_2e mitigation from cooling contrail effects for a mission from DUS to PMI on July 16, 2018 at 12:00 UTC (left), based on cost-based re-routing of flight trajectories (right): vertical plots of the BAU trajectory (top) and the 40% CO_2e accounting scenario (bottom) (Niklaß et al., 2025 pre-print)

However, actively generating cooling contrails remains far more controversial than avoiding warming contrails. It is often viewed as a geo-engineering measure with uncertain atmospheric risks and potential moral hazard, as it could weaken incentives for structural emission reductions. Therefore, all other analyses focus exclusively on persistent warming contrails. In the case of cooling PCFAs, CO_2e values account solely for other trace substances.

3.5 Network-level impacts of non-CO_2 accounting: demand and ticket price dynamics across geographic scopes

Network effects can be assessed at increasing levels of complexity.

- **Route-Dependent Elasticity** considers a static network and measures demand sensitivity to ticket prices on the same route, ignoring competitors. Typical values range from –0.6 to –1.1; in BeCoM we use -0.89 (Oesingmann & Kölker, 2025).
- **Market-Dependent Demand Effects** account for competitors' prices and market characteristics, such as average fare and fare dispersion.
- **Airline Network Effects** treat the network as dynamic, with carriers adapting routes, schedules, and capacity in response to price and demand changes. Over the long term, this leads to a system-wide equilibrium.

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To evaluate how route-specific non-CO_2 accounting affects ticket prices, demand shifts, and network dynamics across different geographical scopes, Kölker et al. (2026) applied the three approaches and analysed the origin-destination demand between Hamburg (HAM) and New York (JFK) and potential passenger routes including a direct connection, and eight transfer connections via major hubs. The selected passenger routes are subject to different CO_2 pricing schemes (EU ETS, UK ETS; CORSIA) and visualized in Figure 19. Three regulatory scenarios were evaluated:

(1) full scope, including all flights;
(2) regional scope, including intra-European flights only; and
(3) departure-based, attributing emissions and non-CO_2 charges to the (European) country of departure.

Market-dependent effects are calculated using Kölker et al. (2023). The model applies route- and market-level elasticities and cross-elasticities to estimate spilled demand when ticket prices rise. Demand can be recaptured on other routes facing similar price changes. Final market share is the sum of spilled and recaptured passengers, reflecting all alternatives available to travellers.

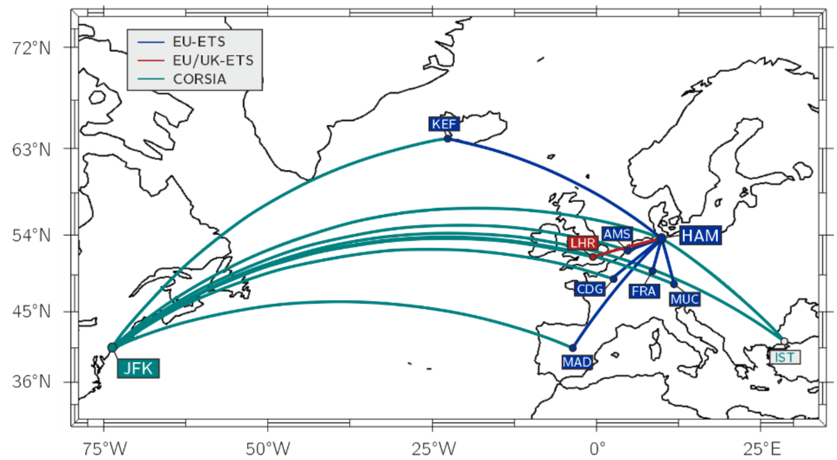

Figure 19: Network scenario of our study showing: different routing options between HAM and JFK with varying intermediate stops, subject to different CO_2 pricing schemes (EU ETS, UK ETS, CORSIA)) (Kölker et al., 2026)

Airline network effects are analysed using four structural indices: average path length, Herfindahl–Hirschman Index (HHI), closeness centrality, and clustering coefficient (Kölker et al., 2025). Because ticket prices may not fully reflect network structure, demand-based indices are used. Monthly passenger demand (2022–2024) is regressed against each index, showing significant correlations and demonstrating how network structure drives observed demand variations.

Flight trajectories and emissions were simulated using iTCM (Linke et al., 2017; Zengerling et al., 2023), BADA4 data (Nuic et al., 2010), and BFFM2 (DuBois & Paynter, 2006), then processed in AirClim (Grewe and Stenke, 2008; Dahlmann et al., 2016) to estimate CO_2e using the ATR 100-year metric. Climate mitigation potentials of alternative routings were derived from Castino et al. (2024, Tables 3–4). EU ETS and CORSIA charges were calculated per flight from CO_2 emissions or fuel burn, including additional fuel costs from climate-optimized rerouting at EUR 800/ton fuel. Non-CO_2 charges were applied based on route scope (50% inclusion) and assumed fully passed to ticket prices.

Initial results show that ticket-price and demand changes vary across the full-scope, reduced-scope, and departure-based scenarios, reflecting their sensitivity to climate-mitigation measures. Short-haul intra-European routes with lower market concentration and lower average fares are most sensitive, where even moderate cost increases can significantly reduce demand. Overall effects depend on route-specific factors, including base fares and geographic characteristics.

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Table 5: Resulting differences in ticket price and induced difference in demand for outward and return flights on selected routes, including the impact of different geographical scopes for non-CO_2 pricing (Kölker et al., 2026).

Route	Geographical Scope	Δ ticket price				Δ demand (route level)	Δ demand (market level)
		Δfuel cost	ΔETS cost	ΔCORSIA cost	non-CO_2 charge		
HAM-FRA-JFK	Full Scope	+12.74 €	+30.96 €	-1.67 €	+50.48 €	-10.2 %	-9.7 %
	Reduced Scope	+0.74 €	+0.07 €	-	+0.67 €	-0.2 %	0.0 %
	Departure Allocation	+6.73 €	+15.47 €	- 0.83 €	+25.29 €	-5.1 %	-4.8 %
HAM-IST-JFK	Full Scope	+3.36 €	+8.65 €	-0.47 €	+16.14 €	-2.8 %	0.3 %
	Reduced Scope	-	-	-	-	0.0 %	0.2 %
	Departure Allocation	+1.68 €	+4.33 €	- 0.23 €	+8.05 €	-1.4 %	0.2 %
HAM-JFK	Full Scope	+10.94 €	+28.18 €	-1.52 €	+61.13 €	-9.2 %	-9.7 %
	Reduced Scope	-	-	-	-	0.0 %	0.2 %
	Departure Allocation	+5.47 €	+14.09 €	- 0.76 €	+30.78 €	-4.6 %	-4.8 %

Table 5 shows the differences in ticket prices for three routes, including the resulting change in demand at the route level and when all routes on the market are considered simultaneously (market level). In general, the highest non-CO_2 costs are applied in the full-scope scenario, as all flights are charged in this scenario, whereas in the departure allocation calculation, only outbound flights are considered. The direct route HAM-JFK has higher costs due to its different trajectory and different operated aircraft types with a smaller number of seats. However, because of higher ticket prices in general for the direct flight, the relative difference in demand is smaller compared to most connecting routes and even smaller at market level. This effect is evident for all routes.

These findings highlight the variability of demand changes from non-CO_2 charges due to market structure, route characteristics, and network competitiveness. Structural network effects (Figure 20) include reduced weighted path length as direct flights gain share, increased closeness centrality at major hubs like London and New York, decreasing HHI for most airports due to balanced market effects, and increased clustering coefficient at hubs, while non-hub airports often show opposite trends.

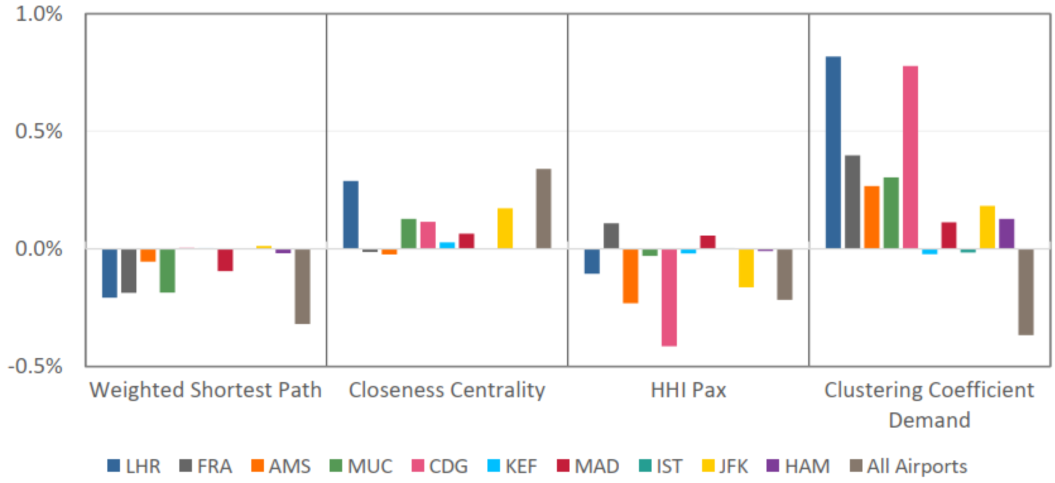

Figure 20: Network effects as changes for network indices for all routes (Kölker et al., 2026)

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3.6 Effectiveness in incentivizing additional operational and technological mitigation measures

To assess the effectiveness of non-CO_2 accounting in promoting further operational and technological mitigation, we focused on the following approaches in Zengerling et al. (2026a):

- **Flight profile adjustments:** Flying lower and slower to reduce climate-sensitive non-CO_2 effects while compensating for higher fuel burn through reduced speeds (Zengerling et al., 2023).
- **Lateral rerouting:** Avoiding climate-sensitive areas laterally.
- **Climate-optimized intermediate stops (ISO):** Selecting stopover airports and altitudes to maximize fuel efficiency and minimize climate impact (Zengerling et al., 2022).
- **Formation flight:** Considering aerodynamic benefits and reduced climate impact from saturation effects (Marks et al., 2021).
- **Use of sustainable aviation fuels**: Reducing CO_2 over the fuel lifecycle and non-CO_2 effects (Teoh et al., 2022)
- **Technical improvements** enhancing fuel efficiency and reducing NO_x emissions (parametric study).

The assessment focuses on long-haul flights due to their high traffic volume (ASK) and climate impact. The analysis covers 50 representative flights to and from the ECAC area, capturing key routes, distances, regions, and aircraft types. Climate impact and operating costs for the ATR100 are assessed using the integrated Trajectory Calculation Module (iTCM) (Zengerling et al., 2024). Trajectories are generated for specific routes and aircraft, providing fuel consumption and performance parameters. CO_2 and H_2O emissions are proportional to fuel burn, while NO_x is calculated via DLR's fuel flow correlation method. Emissions are then evaluated for climate impact using aCCFs or AirClim (Grewe and Stenke, 2008; Dahlmann et al., 2016). Mission-specific direct operating costs (DOC) are calculated based on distance, fuel burn, and flight time (ClimOP, Zengerling et al., 2023). Based on the calculated CO_2e, a pricing scheme can be applied, which adjusts the DOC of a flight mission according to fuel burn (m_{fuel}), flight time (t), and distance (d) to an adjusted DOC (aDOC) that includes the total CO_2e cost at the EUAA price:

$$\text{aDOC} = f\left(m_{fuel}, t, d\right) + \text{CO}_2\text{e}(x, t) \cdot \text{EUAA}$$

The change in operating cost (ΔaDOC) can also be expressed per passenger (n_{Pax}), providing an estimate of potential ticket price increases under the assumption of zero price elasticity.

Figure 21 illustrates the impact of operational mitigation measures on a reference mission from Paris (CDG) to Boston (BOS) with a Boeing 777 under realistic meteorological conditions (Dec 11, 2018). Without CO_2e accounting, selecting the optimal cruise altitude and speed typically involves a trade-off between operating costs and climate impact. Implementing a CO_2e-based pricing scheme simplifies this decision. For example, reducing cruise altitude by 4,000 ft (yellow square in the centre) results in the largest cost reduction (–2.3 %) while achieving a 10.5 % reduction in climate impact. More aggressive measures, such as a 6,000 ft altitude reduction combined with a 10 % speed decrease (blue circle on the left), achieve the highest climate mitigation potential, yet do not significantly affect adjusted direct operating costs (aDOC) compared to the reference. Climate-optimized intermediate stop operations (ISO; red triangle) show no aDOC improvement, indicating limited suitability in this scenario. The choice of mitigation measure also impacts passenger costs. Assuming full cost transfer, ticket prices increase between EUR 61 and EUR 84 depending on the measure applied. For comparison, the reference case without operational measures but including non-CO_2 pricing results in a price increase of approximately EUR 74.1. The most cost-effective option, corresponding to the 4,000 ft altitude reduction, results in a EUR 61.4 increase for this long-haul mission.

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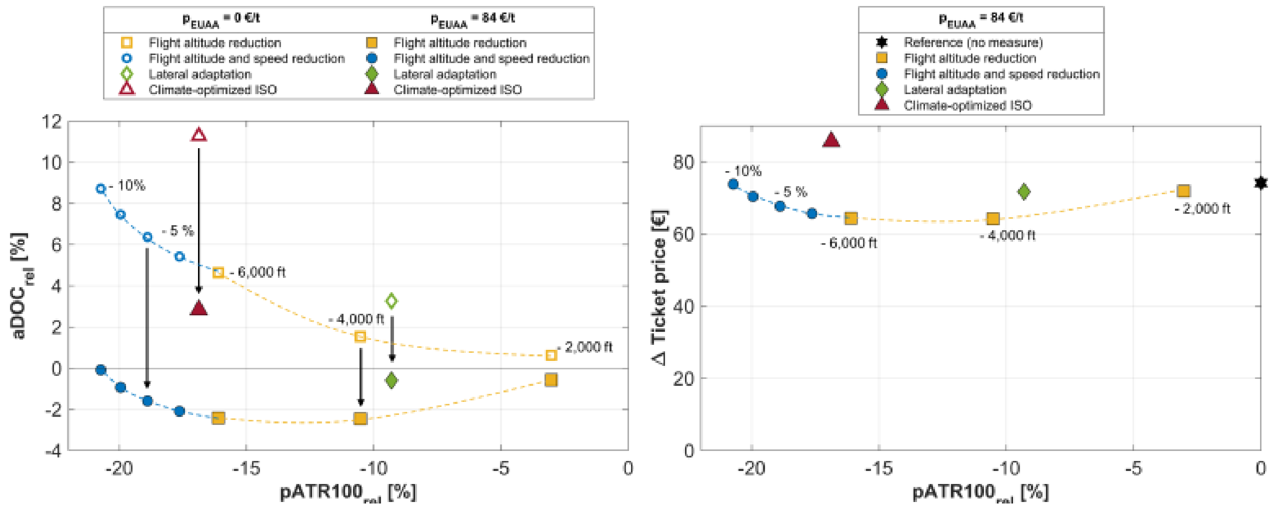

Figure 21: Climate mitigation potential in relation to cost changes (left) and ticket price increases (right) for different climate mitigation measures assuming CO_2e accounting for an exemplary long-range mission. Changes on the left are relative to a reference case without measure implementation assuming different accounting approaches, changes on the right are relative to a reference without measure implementation and without any CO_2e accounting (Zengerling et al., 2026a)

Figure 22 shows the effect of CO_2e accounting on operating costs and ticket prices across all analysed routes. Implementing CO_2e accounting increases costs compared to a business-as-usual scenario without non-CO_2 accounting, with ticket price increases ranging from EUR 197 to EUR 440 depending on the selected mitigation measure. For the reference case without operational measures, the average long-haul ticket price rises by about EUR 273. Technical improvements enhancing fuel efficiency and reducing NO_x slightly lower costs while mainly increasing climate mitigation potential. Adjustments to the accounting scheme can further limit ticket price impacts. For example, considering only 20 % of non-CO_2 effects reduces the ticket price increase for a cruise altitude reduction to EUR 50.7, below the EUR 54.6 increase for the reference scenario. Gradually increasing the accounting share over time can also reduce short-term impacts on operators.

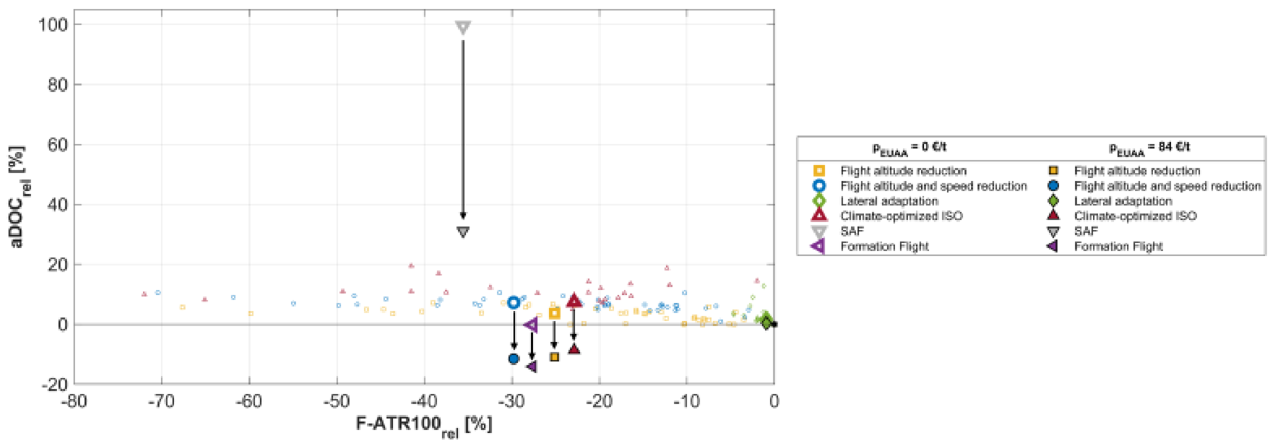

Figure 22: Climate mitigation potential and cost changes for different climate mitigation measures representative long-distance flight scenario. Small symbols represent individual results for considered representative flight missions, large symbols illustrate average values over considered mission sample. Changes are relative to a reference case without measure implementation assuming different accounting approaches (Zengerling et al., 2026a)

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3.7 Mitigation potential of non-CO_2 accounting across 100 routes: daily analysis for 2018

To assess the mitigation potential of non-CO_2 accounting across Europe, we extended the simulations from section 3.2 to more flights and weather scenarios (Zengerling, Castino et al., 2026b, in preparation). For this purpose, the EMAC (ECHAM/MESSy Atmospheric Chemistry) model (Jöckel et al., 2010) is applied, which includes sub-models for troposphere and middle-atmosphere processes and their interactions with oceans, land, and human activities. EMAC employs MESSy2 to integrate multi-institutional codes, with ECHAM5 (Roeckner et al., 2006) as the core model. Key submodules are CONTRAIL (Frömming et al., 2014), ACCF (Yin et al., 2023), and AirTraf (Yamashita et al., 2020). EMAC provides atmospheric conditions, CONTRAIL calculates potential contrail coverage, which is used as input for the ACCF submodule, applying aCCFs to deliver spatially and temporally resolved climate effects of aviation emissions to AirTraf. AirTraf then optimizes aircraft trajectories using a genetic algorithm (ARMOGA, Sasaki and Obayashi, 2005), solving single-objective problems (only operating costs in case of CO_2e accounting) or multi-objective problems (operating costs and climate effects without CO_2e accounting). Simulations use a T42L31 ECMWF setup (2.8° × 2.8°, 31 vertical levels) and 12-minute time steps. The optimization in this study is based on a full year of operations by including weather information over the year 2018. The flight sample includes 100 European routes from the FlyATM4E project (c.f. Figure 23), assuming midnight departures to capture only warming contrail conditions, and using the A320neo as a reference aircraft.

In contrast to previous investigations, we focus the analysis on contrail mitigation by restricting the additional non-CO_2 accounting to CiC effects. Hence, CO_2e are calculated based on contrail and CO_2 climate effects only. Changes to other emission species and their climate effects can be investigated but are not included in the optimization. By doing so, we additionally investigate the impact from changing the selection of considered climate forcers, as discussed in section 2.4 and possible implications on the concept's robustness. Direct operating cost are considered based on a simplified operating cost (SOC) model considering fuel and time cost terms (Castino et al., 2024).

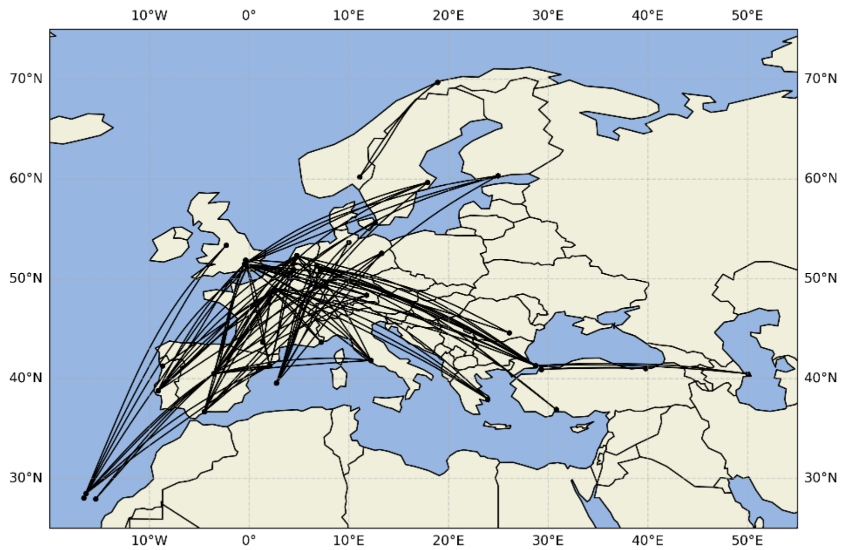

Figure 23: 100 representative European routes from the FlyATM4E dataset (Zengerling, Castino et al., 2026b, in preparation)

The clarge-scale analysis using AirTraf trajectory optimization confirms the results obtained from the conceptual demonstration in section 3.2: Figure 24 illustrates the climate impact in p-ATR_{100} from emission species CO_2, H_2O, NO_x and CiC for the considered 100 European routes for each day between October and December 2018. For each day, bars represent flights without non-CO_2 pricing (blue; reference flights, no contrail avoidance) and with non-CO_2 pricing (orange; targeted contrail avoidance

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based on CO_2e accounting). In all cases, the blue bars exceed the orange ones, indicating that non-CO_2 pricing effectively reduces the climate impact by avoiding persistent contrails. The magnitude of climate effects and mitigation is largest on days with a high climate impact, which is primarily driven by the varying contrail climate impact.

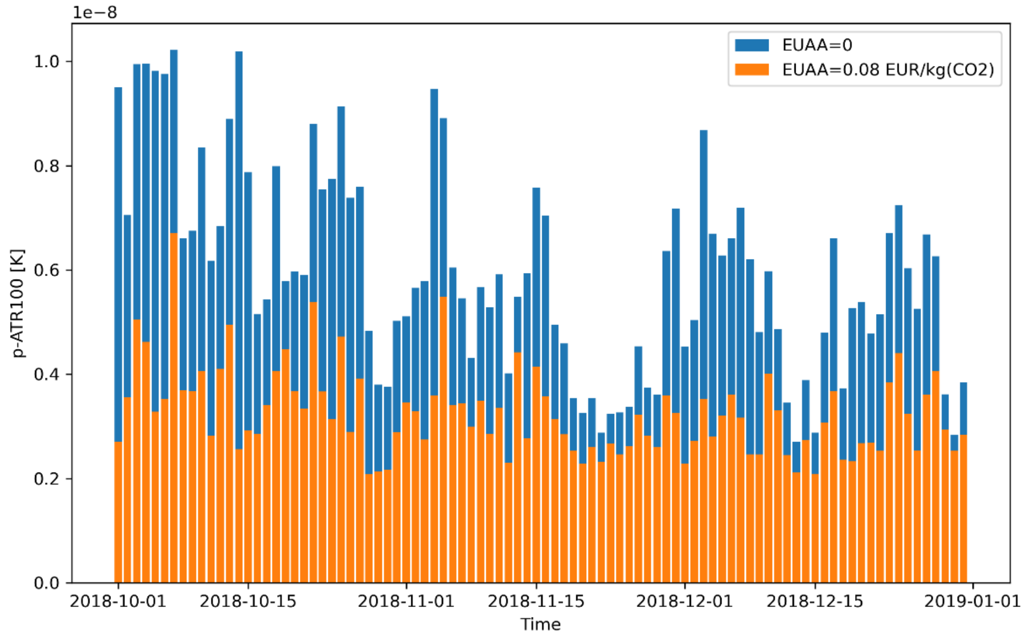

Figure 24: Daily data for Q4 2018: Climate mitigation potential for the Top 100 intra-European routes (Zengerling, Castino et al., 2026b, in preparation).

Figure 25 presents the same results aggregated as monthly averages over the full year 2018. The highest contrail formation and associated CO_2e mitigations occur between June and September, while the lowest values are observed from January to May. Large reductions in climate impact are typically associated with larger fuel burn penalties compared to the cost-optimal reference without accounting (cf. Figure 25, left). The obtained mitigation potentials as well as the cost increase from non-CO_2 accounting varies with the reference case (e.g. the contrail distance of the reference mission scenario) as well as the season. As we expect larger contrail forming regions in winter compared to summer, contrail distance can more effectively be reduced with CO_2e accounting in summer compared to winter (cf. Figure 25, right). This affects the mitigation potentials for contrails in particular and the aggregated climate impact from all climate forcers in general (cf. Figure 25).

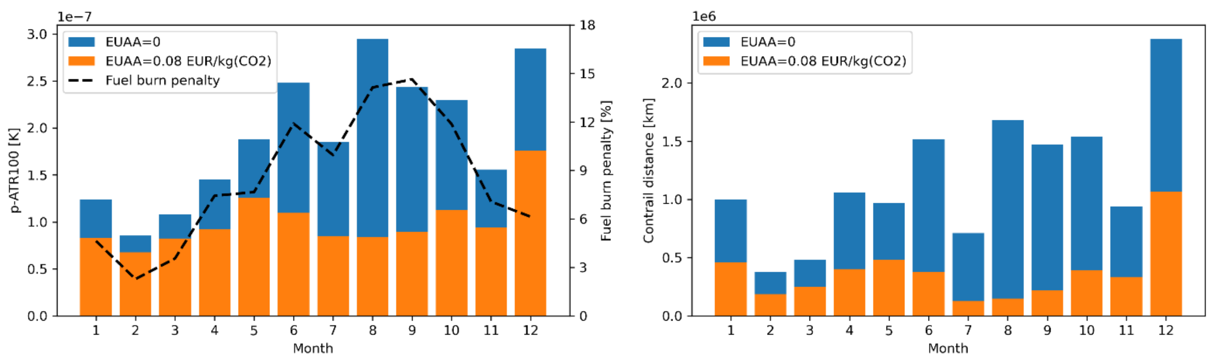

Figure 25: Monthly averages of 2018 for the Top 100 intra-European routes. Left: Changes in climate impact in dependence of the accounting scheme and associated fuel burn penalty. Right: Contrail distance in dependence of the accounting scheme (Zengerling, Castino et al., 2026b, in preparation).

Furthermore, this can be confirmed when focusing on the reduction of contrail climate effects as displayed in Figure 26 (left). The meteorological situation in summer allows for a full avoidance of

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contrail climate effects on some days (reduction of p-$ATR_{100,CiC}$ of up to 100% between July and September). However, mitigation potentials and associated fuel penalties from deviating from the reference routes vary considerable for the different weather situations of the investigated days. In general, mitigation potentials and fuel penalties appear to be lower during winter (October to March) compared to summer (April to September). Furthermore, higher mitigation potentials during summer also lead to higher cost benefits from implementing optimized routings considering the non-CO_2 accounting approach (cf. Figure 26, right). In this context, high mitigation potentials in simplified TOC (s-TOC) are observed which is caused by the simplification of focusing on time and fuel dependent cost and neglecting further cost terms (i.e., fix operating cost, cycle and flight distance dependent variable cost). Future research should investigate the impact on ticket price increase per passenger for the large-scale study as demonstrated in section 3.4. Nevertheless, high fuel penalties of up to 20% are observed for July – September (8% for Jan – March, Figure 26, left).

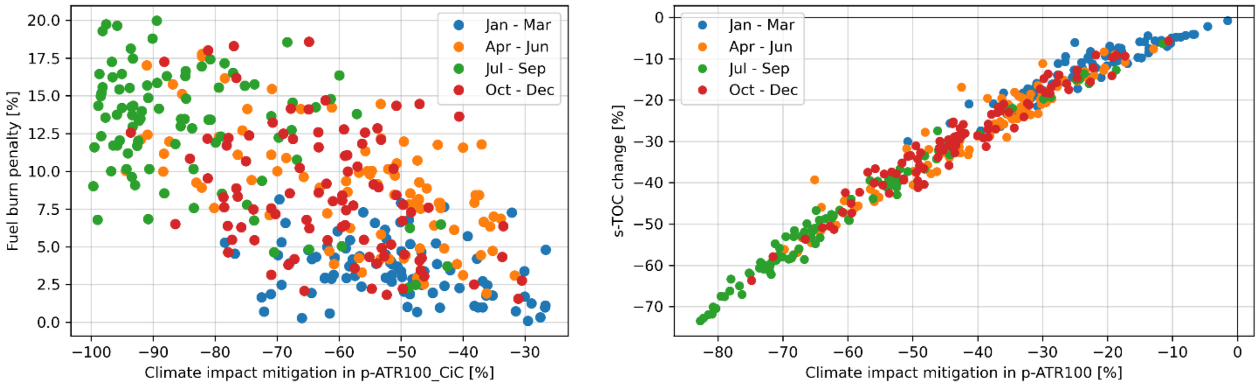

Figure 26: Seasonal cost-benefit potentials for the Top 100 intra-European routes, showing relative climate impact mitigation in p-ATR_{100} versus relative fuel burn penalty. Left: contrail CiC avoidance only; right: including NO_x and H_2O effects (Zengerling, Castino et al., 2026b, in preparation).

All in all, the effectiveness of a non-CO_2 accounting can be confirmed on a larger scale independent of seasonal patterns considering the combined influence of weather conditions and flight schedules on contrail occurrence. On the one hand, this extends the significance of the results demonstrated in section 3.2. On the other hand, this study demonstrates both suitability and robustness of the accounting concept when focusing on contrail climate effects, which vary substantially with emission location and time. Nevertheless, limitations regarding uncertainties must be considered when interpreting the results, especially when applying contrail aCCFs in other seasons than winter, which is outside of the intended application scope (Yin et al., 2023).

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4 Feasibility Assessment from a Stakeholder Perspective

The transition from theoretical design of climate-optimized trajectories and proposed policy measures supporting their adoption to implementation in the operational reality of commercial aviation requires a strong involvement of the stakeholders who will ultimately be responsible for implementing these policies and applying the related operations.

A core objective of the BeCoM project is to develop operational procedures and related policy measures that are not only effective in mitigating non-CO_2 effects but also compatible with the current operational framework and economically viable for the aviation ecosystem. To bridge the gap between scientific modelling and practical feasibility, the consortium has developed a multi-phase stakeholder engagement strategy designed to gather honest and informed expert feedback on the proposed policy-driven flight planning approaches.

Section 4.1 describes the stakeholder engagement process. Section 4.2 summarizes the main outcomes of the discussions across the four workshops, grouped by themes, and Section 4.3 concludes with a set of recommendations for future work.

4.1 Stakeholder engagement process in BeCoM

The engagement process was centred around four primary events: three online workshops targeted at single stakeholder groups and one larger final workshop with hybrid (both in-person and online) participation. This structure has facilitated both in-depth analysis of specific topics and a broad, cross-sectoral dialogue. The main features of these events were:

- **Group-specific Stakeholder Workshops (Online)**: Three separate two-hour sessions were held to allow for focused discussions within homogenous groups: (1) airlines, (2) air navigation service providers (ANSPs) and weather services, and (3) authorities. This separation was intentional, promoting an environment where stakeholders felt comfortable sharing unfiltered perspectives on competitive or sensitive regulatory concerns. Each meeting followed a rigorous format to ensure consistency and high-value output. Sessions began with a brief overview of the BeCoM project goals provided by the project coordinator, followed by a detailed presentation from DLR on specific non-CO_2 policy options. The core of the workshops consisted of moderated discussions based on a list of targeted questions formulated and circulated to participants in advance.
- **Final Stakeholder Workshop (Delft, The Netherlands)**: To conclude the consultation phase, a full-day hybrid event was hosted at TU Delft, bringing all stakeholder groups together. This session included a plenary project overview followed by two rounds of parallel breakout sessions, where participants were assigned to different groups to debate specific topics (measurements, weather models, contrail observation, trajectory optimization and policy instruments, following the work package structure of BeCoM) and develop targeted recommendations.

To ensure the highest degree of openness, all discussions were conducted under the Chatham House Rule. This convention allows participants to use the information received during the meeting but does not allow revealing the identity or affiliation of the speaker.

Following each workshop, the consortium produced thematic reports summarizing the discussions, included in this document as Appendices 1 – 4. These reports were circulated among all participants for their comments, providing a transparent record of the diverse (and sometimes conflicting) views regarding the multiple aspects of contrail avoidance methods and the challenges of implementing them, in particular the trade-offs between economic and operational efficiency and climate impact reduction.

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4.2 Thematic Synthesis of Stakeholder Workshop Results

To ensure the highest degree of openness, all discussions were conducted under the Chatham House Rule. This convention allows participants to use the information received during the meeting but does not allow revealing the identity or affiliation of the speaker.

Modelling

Weather models

Weather models provide the essential input for climate optimised trajectory planning by enabling the identification of ice supersaturated regions (ISSRs) in four dimensions. ISSRs serve as the primary operational indicators for contrail formation risk and are used by trajectory optimisation tools to assess rerouting options. The quality of humidity representation in numerical weather prediction (NWP) models is therefore critical, and the assimilation of additional upper tropospheric humidity data—particularly from in situ aircraft measurements, thanks to their high resolution —was widely recognised as a key pathway to improving forecast reliability. Note that weather models do not include contrail-induced cirrus clouds as they do not contain flight information.

Stakeholders discussed the necessity of comparing different available weather models to find a most reliable source of weather data for trajectory optimisation and further improvement of the MRV reporting. The DWD two-moment scheme and the DIPS one-moment scheme were compared in BeCoM. A comparison between weather models used in different met centres regarding humidity prediction is planned in the SESAR project CICONIA. DWD's improved ICON two-moment scheme version will become fully operational for MRV use during 2026. Datasets using the current ICON version are available for 2025. The DIPS scheme, developed in BeCoM, is currently not available for MRV, but if weather centres are interested, it could be integrated into a future 4-dimensional weather model.

A key discussion point was whether operational flight planning should rely on a single harmonised weather model or continue to use multiple models to better characterise uncertainty. While a unified model could simplify operational use, many participants emphasised that model diversity helps capture uncertainty, provided that outputs are translated into clear, consistent, and usable products for airlines and ANSPs. Overall, stakeholders agreed that improving forecast skill, transparency, and uncertainty communication is more important than selecting a single "best" model at this stage.

Forecast accuracy and validation

Stakeholders agreed that the accuracy of weather forecasts—particularly for ice-supersaturated regions (ISSRs)—is a critical prerequisite for effective and acceptable contrail mitigation. Forecast uncertainty is still insufficiently quantified, and further validation is required to understand model reliability. Various participants recommended to apply contrail avoidance selectively, focusing on situations where forecasts are sufficiently reliable, rather than systematically. Ensemble forecasting was widely recognised as a useful tool to assess uncertainty and determine whether climate-optimised flight planning is justified within the next 1 – 2 days.

Different contrail avoidance strategies were discussed, ranging from conservative avoidance based on any indication of contrail risk to more selective approaches that avoid only regions with consistently high forecast probability. The development of shared thresholds for forecast confidence should be defined in cooperation with airlines and harmonised at a European level, balancing climate benefits against operational and economic costs.

Improved validation through coordinated flight trials, satellite observations, and systematic comparison of forecasts with real-world outcomes was seen as essential to increase confidence in both pre-flight planning and post-flight assessment.

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Measurements

Airborne measurements

Airborne humidity measurements were identified as an important enabler for better locating contrail formation risk areas and for improving numerical weather prediction (NWP) through data assimilation. While such sensors are not the only means to identify and avoid ice-supersaturated regions, additional in-situ data—especially at cruise altitude—would strengthen both forecasting and model validation. Existing programmes such as IAGOS and AMDAR already provide water vapour observations, but participation is currently limited to relatively few aircraft and routes (10 IAGOS aircraft worldwide, for AMDAR 9 European and 130 US aircraft), allowing constrained coverage only.

Stakeholders stressed that wider deployment must reflect airline operational constraints: equipment should be lightweight and low-volume, robust in day-to-day operations, and not create disproportionate maintenance burdens. A targeted equipage of selected aircraft was therefore favoured; EUMETNET estimates suggested that on the order of ~50 aircraft could provide substantial coverage over Europe if routes are selected strategically. Incentives—providing public funding as well as potentially bundling humidity sensors with other operational benefits (e.g., turbulence sensing) and supporting coordination across airline alliances—were seen as key to scaling up. In addition, a limited set of ground-based reference stations (e.g., multi-wavelength lidar measuring water vapour and contrail altitude) could provide useful calibration and validation support.

Uncertainties

Uncertainties were consistently identified as a central challenge for contrail mitigation, affecting the full chain from meteorological forecasting through emissions and trajectory modelling to climate impact assessment. Stakeholders distinguished three main categories—weather-related uncertainties, uncertainties in non-CO2 climate response modelling, and uncertainties in trajectory and emissions modelling (these being smaller than the two other categories but still relevant)—and emphasised that decisions should consider their combined effect rather than focusing on individual models.

Stakeholders discussed the complex role of uncertainties in assessing non-CO_2 climate effects. While some argued that uncertainty should not delay action given the clear relevance of contrails, others highlighted that uncertainties can lead to both over and underestimation and even false incentives. As a result, regulatory decisions should focus on relative comparisons and trade-offs, particularly between uncertain non-CO_2 effects and certain CO_2 impacts, rather than absolute values.

A key challenge is translating system level uncertainties to individual flights, especially regarding the reliability of pre-flight predictions and post flight assessments. To address this, participants emphasised the need for systematic model validation through large scale real flight studies. Comparing model predictions with observations, including both avoided and unavoided contrails, would help quantify false and true positives and improve confidence in forecasts.

Improved access to real world data is essential. Integrating observations from satellite and ground-based sensors with onboard aircraft data could significantly enhance validation. Airline flight data recorders and operator-maintained databases were identified as particularly valuable sources for verifying trajectory, emissions, and contrail mitigation models. Participants discussed the possibility of "no-regret" measures that deliver more than marginal benefits with low assessed risk. An example of these would be the reduction of aromatics content (not limited to SAF); also in this case, a prudent approach would need to be adopted.

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Data processing and harmonisation

Stakeholders highlighted that operational use of contrail-relevant forecasts requires better harmonisation of weather data and commonly defined thresholds, e.g. for uncertainty limits, across providers. As airlines typically plan climate-optimised trajectories pre-flight while ANSPs often have access to more up-to-date meteorological information during flight operations, common rules (or a shared data basis) are needed to avoid inconsistencies between airline plans and ATC directives. Participants discussed options such as a central database and ensemble forecasts shared between national weather services. While the parallel use of different models allows a better estimate of uncertainties, airlines would require a clear, operationally usable product, either a European harmonised model or from a selection of national ones.

Improved links between models and observations were also seen as a priority. Remote sensing (notably satellite imagery) can support post-flight validation, as done in the D-KULT flight series. Tools such as MCAST (MIT) and Contrails Explorer (Google) provide similar info. However, attribution of contrails to specific flights remains challenging and thin or short-lived contrails may be missed. Additional onboard sensors—especially humidity sensors transmitting data to forecast providers—could substantially improve ISSR forecasts and validation, as described above in "Airborne measurements".

Flight tests

Flight trial campaigns are planned to test contrail-mitigation concepts under real operational conditions. A key objective is to quantitatively describe predicted "blocked" regions (e.g., their size, duration, and vertical extent) to understand when detours, underlying, or overflying are feasible within airspace constraints.

Experience from D-KULT was cited as a useful blueprint, linking meteorological inputs, new models, and flight-planning tools in a real-life experiment. Participants stressed that analysing unavoided contrails—so-called observer flights where deviation is not possible—is as important as demonstrating successful avoidance, because it helps assess prediction skill across the full chain (meteorology, contrail modelling, and climate response). Overall, trials should support systematic validation against observations, including evaluation of false and true positives/negatives (predicted vs. realised contrails), to improve confidence in both pre-flight planning and post-flight assessment.

Operational aspects

Considering individual contrails vs airspaces

Stakeholders emphasised that contrail mitigation needs to move from optimising individual flights to managing climate-optimised flights at the level of airspaces and the wider air transport network. Current tools typically assess flights in isolation and do not capture interdependencies between aircraft or potential saturation effects when many flights share the same climate-sensitive regions, which can limit both effectiveness and fairness amongst airlines.

In particular, rerouting a single flight may deliver little net benefit if other aircraft still generate contrails in the same region, creating a collective-action problem and competitive concerns. This is particularly acute in congested airspace, where capacity constraints differ by sector and deviations can have significant network impacts. A coordinated framework—with clear responsibilities across airlines, ANSPs and the network manager and supported by timely, sector-level data processing—was therefore seen as necessary to enable practical, system-wide implementation.

Operational strategy

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Stakeholders outlined two complementary operational approaches: targeting a small subset of flights that account for a very large part of contrail warming (especially during night time), and embedding contrail avoidance within a broader optimisation that considers capacity and network constraints. Participants also discussed whether mitigation is better implemented by constraining climate-sensitive airspaces or by optimising selected flights, noting that the feasibility of either approach depends strongly on available airspace capacity and on understanding potential saturation effects.

Some participants noted the interest to assess net climate benefit rather than contrails alone by jointly accounting for CO_2 (including life-cycle emissions), NOx and particulate matter, since additional fuel burn for avoidance can increase other impacts. Given remaining uncertainties and model dependence, participants emphasised the need for thorough evaluation and validation using real-flight performance and observational data before scaling operational measures, and for decision frameworks that explicitly balance more certain long-term CO_2 effects against still uncertain non-CO_2 impacts.

Geographical and temporal scope

Stakeholders highlighted that the practicality of climate-optimised routing strongly varied between airspace areas and operational periods. In highly congested airspace such as Europe and in peak traffic periods, even small route changes can trigger knock-on effects across the network, so stronger and operationally verified scientific evidence is needed to justify policy choices and to clarify where avoidance is feasible for different flight types.

Participants therefore favoured a flexible, stepwise approach that starts in geographical areas and periods with low traffic and can expand in scope as models, validation, and operational experience improve, with estimates suggesting that meaningful regulatory conditions may not be met until around 2030. An open question is whether initial implementation should be EU-focused or start in less complex but highly relevant regions such as the North Atlantic, for example by adapting track systems to preferentially open routes with lower ISSR probability, potentially without the need of additional policy measures, before tackling the most capacity-constrained European sectors.

Technology

Some participants highlighted emissions reductions at the source—through engine and fuel improvements—being the most robust long-term pathway to mitigate non-CO_2 effects, because it delivers more certain benefits than operational rerouting under forecast and impact uncertainties. Reducing non-volatile particulate matter (nvPM) was highlighted as a particularly relevant lever, but technologies such as SAF and improved fuel and lubricant formulations will phase in gradually, so operational measures may still be needed in parallel in the near term.

Cooperation

Stakeholders stressed that effective contrail mitigation depends on close collaboration between airlines, ANSPs, and meteorological services, because planning, tactical flight execution, and the underlying weather information are tightly interdependent. Isolated or purely voluntary initiatives by individual actors were seen as insufficient, reinforcing the value of joint forums to align assumptions, share operational constraints, and co-develop workable procedures.

Participants supported a phased engagement approach—initially separating stakeholder groups to enable frank discussion, then moving to mixed workshops (e.g., airlines–ANSPs–weather services) to develop joint solutions and exchange results from R&T projects such as D-KULT (German LuFo) and CICONIA (SESAR). Clear roles were emphasised: airlines are best positioned to plan climate-optimised trajectories, while ANSPs and the network manager facilitate these plans within safety and capacity constraints. At a European level, close coordination between national ANSPs and Eurocontrol is essential. Continued data sharing for modelling and validation, and the possible involvement of

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international bodies, namely ICAO and WMO, to help collect or standardise climate-impact parameters, were identified as enabling conditions for scaling implementation.

Policy instruments

MRV aspects

Stakeholders viewed the EU non-CO_2 MRV as an important tool for future non-CO_2 mitigation policy, but raised concerns about how MRV data will be accessed and used in practice. In the initial years, MRV is expected to function mainly as a learning and awareness tool for operators, with limited direct operational value for ANSPs and little immediate mitigation activity in the absence of financial incentives. Participants stressed that clarity is needed on who can access primary (most valuable) versus secondary data and how the system will support scientific evaluation.

Concerns were also raised about MRV accuracy as a foundation for future policy instruments, given the reliance on conservative estimates and incomplete input data (notably the lack of widespread humidity measurements that are important for contrail-relevant forecasting). With decisions expected around 2028 on connecting non-CO_2 MRV and ETS, participants underlined the need for a transparent assessment of MRV effectiveness, potentially involving independent scientific bodies such as ANCEN. Overall, MRV was seen as useful to improve awareness and modelling of non-CO_2 emissions and mitigation options; however, stakeholders expressed concerns on the MRV in its current status being used to prematurely set CO_2-equivalent rules without fully understanding how to mitigate non-CO_2 emissions.

Policy options

Stakeholders emphasised that the appropriateness of policy instruments depends strongly on uncertainty and on how incentives translate into operational behaviour. While uncertainty is less problematic for monitoring, it becomes critical when moving toward pricing or regulation, because incorrect signals can incentivise rerouting that fails to deliver net climate benefits. “Risk assessment” was therefore discussed as a way to quantify how often models may over or underestimate impacts and how frequently a chosen strategy would succeed.

Voluntary actions by individual airlines and also market-based approaches were seen as challenging because contrail impacts require collective action and because coverage gaps (e.g., flights crossing Europe at night) can undermine effectiveness and raise fairness concerns. ETS type mechanisms were valued for flexibility—allowing operators to choose flight specific responses—but were also viewed as difficult to apply “like for like” to short lived, heterogeneous non-CO_2 effects and as insufficient on their own if not globally applied. Many participants therefore favoured incentivising (not penalising) and solution-oriented policy options in the near term, coupled with transparent communication of assumptions.

Significant discussion took place around the challenge of balancing contrail reductions with potential increases in fuel burn and CO_2 emissions. The priority given to CO_2 or non-CO_2 mitigation depends on the time horizon considered; continued work to reduce uncertainty in non-CO_2 impact quantification is needed so that CO_2 and non-CO_2 trade-offs can be managed within a clear decision framework.

Policy needs

Stakeholders noted that achieving operational contrail mitigation will require policy support beyond MRV, including incentives that engage both operators and ANSPs. One proposal was to include environmental efficiency, and more specifically non-CO_2 impact, in ANSP performance frameworks. Participants also stressed that policy design must explicitly reflect the different time horizons of CO_2 and contrail effects when setting objectives and metrics.

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While ETS-type approaches were viewed as promising in principle, participants emphasised that a broader set of instruments should be explored alongside mandatory MRV, given remaining uncertainties and implementation challenges.

International policy work led by ICAO is progressing (e.g., standards, scientific white papers, and exploration of non-CO_2 concepts), but no plans for a global MRV exists yet; European initiatives such as EASA-sponsored ANCEN and national studies were cited as important enablers for evidence-building and coordination.

Policy design and cost-based incentives

Pricing mechanisms should consider not only fuel penalties but also delays and airspace congestion. The effectiveness of pricing depends on many factors beyond the fuel consumption alone. The choice of metric used, e.g., the amount of CO_2e attributed to contrails, will be critical as it will impact directly the costs or the incentive offered.

The inclusion of cooling contrails in pricing schemes is controversial. Whether to include cooling contrails in pricing schemes remains an open question, with different opinions. Some argue for postponing the inclusion of cooling contrails due to too high uncertainties, while others believe excluding them and delaying the potential payback option would compromise the validity of the system.

Trade-offs

Stakeholders agreed that non-CO_2 mitigation inevitably involves balancing more certain long-term CO_2 impacts against more uncertain, shorter-lived non-CO_2 effects, which in turn requires choosing a metric and time horizon (e.g., GWP100 with efficacy)—a choice regarded as ultimately political rather than technical. While emissions trading is seen as efficient in principle, uncertainty in non-CO_2 attribution and the risk of unintended consequences, such as deliberately flying into ISSRs wrongly located due to prediction uncertainties, it will need to be complemented by other measures, and cumulative impacts of multiple climate policies on airlines should be assessed jointly. Participants also noted that contrail-avoidance fuel penalties increase life-cycle CO_2 as well as NOx and particulate matter emissions, reinforcing the need to pursue CO_2 and non-CO_2 reductions in parallel. The need to continue data sharing between airlines and researchers to improve modelling was highlighted.

4.3 Recommendations for Future Work

- **Weather models**
  - Intercomparison of weather models between weather centres
  - Offer the scheme developed at DLR in BeCoM to weather services beyond DWD, including ECMWF
- **Measurements**
  - Improve weather prediction through enhanced humidity measurements onboard aircraft
    - Carry out a cost-benefit analysis for additional onboard measurements
    - Identify optimal flight route coverage, encourage worldwide airline participation
    - Provide optimised (low-weight, low-volume) measurement equipment, ideally in combination with other weather info (e.g. turbulences) relevant for airlines
    - Identify public funding sources, e.g. through Innovation Fund
- **Contrail observation and modelling**
  - Further work on strengthening the link between models and observations
    - Fight trial campaigns under day-to-day operational conditions
    - Improve scalability of models
- **Trajectory optimisation**

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  - Develop and promote use of automatised flight planning tools that integrate non-CO_2 mitigation
  - Check feasibility of optimised trajectories (e.g. from DLR study)
  - Enhance validation and verification of simulations vs observations,
    - Do not only check if contrails were successfully avoided, but also if predicted contrails were actually created (false & true positive / negative)
  - Include effect of other emission species (NOx, PM) in tools to determine climate-optimised flights
  - Use of non-CO_2 MRV data available from 2026
- **Policy instruments**
  - Collaborate with airlines
    - Share airline data to enhance modelling
  - Extend analysis of effects of specific policy instruments from single flights to full airspace
  - Include more policy options in addition to those studied (“climate charges” and closure of airspace portions)
  - Identify and involve international organisations in charge of collecting climate impact parameters (essentially ICAO and WMO)

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5 Conclusion and outlook

This work contributes to objective (5) targeting the integration of non-CO_2 effects (e.g. contrails) within current policy schemes. For effective implementation, non-CO_2 measures need to remain simple and transparent, support sustainable operations and technologies, and align with existing frameworks such as the EU ETS, CORSIA and EU Green Deal. We analysed current and proposed non-CO_2 policies to derive practical requirements. For both pre-flight planning and post-flight monitoring, reporting, and verification (MRV), all stakeholders need a straightforward, transparent process to calculate CO_2e and associated obligations.

An automated process has been proposed to calculate CO_2-equivalent costs using algorithmic cost functions for climate change (aCCC), which can be readily implemented in existing flight planning software. These simple linear equations estimate the climate cost of aircraft emissions in euros per kilogram of fuel, accounting for meteorological conditions at the time and location of the emissions. Non-CO_2 pricing adds societal climate costs to the TOC, increasing absolute costs for operators. Much of this increase can be avoided through sustainable measures like climate-optimized routing or targeted-use of SAF. Without CO_2e accounting, operators face a trade-off between minimizing operational costs (fuel, time, etc.) and reducing climate impact, creating a “win-lose” situation. By incorporating CO_2e into the cost structure, societal climate costs are internalized, allowing trajectory optimization to consider a single combined objective (operational + climate costs). This aligns operator incentives with climate goals, turning the trade-off into a win-win scenario. This concept can also be integrated into the EU non-CO_2 MRV regulation, for which the NEATS IT tool is currently under development and whose design has been scientifically supported and advised by parts of the WP5 team.

Given large uncertainties in non-CO_2 modelling, which affect data accuracy in an MRV framework but could incentivize harmful re-routing under CO_2e pricing, strategies to mitigate risks in climate policies are proposed. These include using ensemble weather forecasts to reduce formation risks or risks of unnecessary detours, and implementing an uncertainty-based CO_2e accounting, where emitters must hold permits for CO_2e values of a climate agent based on confidence levels in climate-impact modelling. Our results show that uncertainty-based accounting is more progressive than gradual accounting, achieving higher mitigation potential while moderately increasing ticket prices. Continued research, validation, and targeted risk assessments are essential to improve non-CO_2 effect modelling and ensure that policy effectively drives meaningful climate action. Occasional high impacts from individual flights may be acceptable if most flights reduce the overall annual climate impact with minimal risk. Adaptable policies and ongoing research, such as improving the prediction of ice-supersaturated regions (c.f. WP1 and WP2 of the BeCoM Project), are crucial for incorporating the latest scientific understanding and enabling effective climate action in aviation.

To evaluate the effectiveness of non-CO_2 accounting in mitigating climate impacts, performed trajectory simulations along with emission and climate response calculations. Our studies investigate how non-CO_2 pricing affects flight routing, climate impact, ticket prices and demand under different weather conditions, CO_2e accounting options, climate metrics, and carbon prices. The results show that climate mitigation potential is driven primarily by route and weather characteristics, while policy design parameters, such as accounting shares or the choice of climate metric, play a secondary role. Because CO_2e-optimised flights largely avoid persistent contrail formation areas (PCFAs), the remaining CO_2e costs are mainly associated with NO_x and H_2O emissions, which are less weather-sensitive than contrail cirrus (CiC). In contrast, ticket price increases depend strongly on the monetized share of CO_2e and the applied carbon price, suggesting that a gradual implementation, for example starting with 20% of the calculated median CO_2e values, could moderate impacts on aircraft operators and passengers.

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Due to strong seasonal and market-driven ticket price fluctuations, the additional fare impact of CO_2e pricing remains moderate. According to Niklaß et al. (2025), a ticket price increase of about EUR 6, typical for 60% CO_2e accounting on intra-European flights, corresponds to an average fare increase of 2.9%, indicating that the effect is small relative to normal market variability. Although non-CO_2 pricing raises ticket prices on average, very low and very high fares are expected to be less affected because they are primarily demand-driven rather than cost-based. Applying an aggregated price elasticity of −0.78 together with a projected European passenger growth rate of 3.7% suggests that CO_2e pricing could reduce demand growth to 1.1%. In our analysis, abatement costs for CO_2e mitigation range from EUR 3 to EUR 74 per ton CO_2, with the lowest values occurring under effective contrail avoidance. These costs are relatively low compared with mitigation options in other sectors, such as wind or solar energy deployment or direct air capture.

Based on a large-scale simulation study in collaboration with BECOM's WP4 (Zengerling, Castino et al., 2026b), we confirm the suitability for a European flight scenario considering a year of meteorological data. In this course, we identify strong seasonal influence especially when focusing on contrail mitigation potentials and associated fuel and cost penalties. Furthermore, the study confirms the suitability of the approach when restricting the accounting to climate impact from CO_2 and CiC.

Because CO_2e charges are determined shortly before departure while fares are set earlier, airlines need to incorporate expected CO_2e costs into ticket prices at the time of booking. Even when these costs are passed on to passengers, competitive pricing remains essential. If rerouting lowers climate costs, aircraft operators can either offer lower fares or increase profit margins by retaining the difference between expected and actual CO_2e costs. Including cooling contrails in a pricing mechanism could further offset or even reduce costs through compensation, but this raises scientific, ethical, and governance concerns.

Implementing CO_2e policies regionally, such as in the EU, requires balancing global competitiveness by avoiding disadvantages for local operators while fostering innovation and preserving economic efficiency. Kölker et al. (2026) analysed airline network effects of possible non-CO_2 pricing on a Hamburg-New York origin-destination network under three regulatory scopes: full coverage of all flights including those in and out of the EEA (European Economic Area), a reduced scope limited to intra-European routes and a departure-allocation scope covering outbound flights only. Based on the resulting cost increases, demand changes were assessed using passenger preference models that capture intra-market dynamics and behavioural responses across market segments. Their results show that cost impacts vary strongly by route and fleet, leading to differentiated ticket price and demand effects as well as changes in network structure, including shorter paths and shifts in airport centrality. The study demonstrates that integrating non-CO_2 costs into airline pricing is feasible, while highlighting the need to balance environmental effectiveness with economic competitiveness and market impacts.

Non-CO_2 policies must also create incentives for implementing climate-friendly technologies, alternative fuels, and operational measures. Zengerling et al. (2026a) investigated the climate mitigation potential and cost increase from different climate mitigation measures under non-CO_2 pricing. The results show that selected operational measures offer substantial climate mitigation potential, but often at significantly higher operating costs. Extending existing accounting schemes to include non-CO_2 effects can reduce these implementation barriers, as CO_2e pricing lowers costs relative to a reference case without mitigation measures; even though absolute operating costs still increase, as a new cost term is added to the balance sheet of operators. In particular, operational measures appear highly promising when non-CO_2 effects are accounted for, even if they may increase CO_2 emissions. The use of sustainable aviation fuels offers even greater mitigation potential, although their high fuel costs cannot currently be offset through extended accounting alone. Additional mitigation can be achieved through technical efficiency improvements, while policy design options such as reduced accounting shares for non-CO_2 effects can help limit cost and ticket price increases. Overall, the findings support extending existing accounting frameworks to non-CO_2 effects, as this

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improves the economic attractiveness of mitigation measures and strengthens incentives for sustainable innovation.

To evaluate the feasibility of non-CO_2 accounting we organized a series of four workshops with all relevant stakeholder groups, namely airlines, air traffic management (ANSPs and EUROCONTROL), weather services as well as European and national authorities. Lively and open discussions took place, first in virtual workshops within individual stakeholder groups, followed by a final hybrid workshop in Delft with participation of experts from all stakeholder groups. Participants provided valuable feedback about applicability of operational and policy measures in day-to-day flight operations. Recommendations were given for future research and for preparing implementation of contrail mitigation measures in the area of weather models, onboard humidity measurements, contrail observation and modelling, trajectory optimisation and the design of policy instruments. A final policy brief considering results from the BECOM project and Stakeholder Feedback will be provided at the end of the project.

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Appendix 1

Virtual Stakeholder Workshop with Airlines – Meeting summary

Contents

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Meeting details

Date

Tuesday 11th February, 9:30 - 12:00 CET

Meeting scope

The EU-funded research project BeCoM (Better Contrail Mitigation, https://becom-project.eu/) has the objective of largely reducing or even eliminating the global mean contrail radiative forcing, hence a substantial reduction of aviation's share of global warming to be achievable on a much shorter time horizon. This is facilitated by confidently forecasting persistent contrails, reduction of weather-dependent individual contrail radiative effects, and the successful avoidance of strongly warming contrails via trajectory optimization.

To support the implementation of effective contrail avoidance, BeCoM partner DLR is working on a methodology for integrating non-CO_2 policies into flight planning and trajectory optimization, and an assessment of the effectiveness of the policy driven flight planning approach. The BeCoM WP5 team, under the lead of ENVISA, is inviting stakeholders (airlines, air navigation service providers ANSPs, authorities, etc.) to take part in this assessment and share their views about the proposed policy measures, their feasibility, their effectiveness and cost-benefit ratio, and the efforts required by stakeholders to comply with them. This was the first of a series of stakeholder workshop and was held with airlines only. Other meetings are foreseen also with ANSPs and authorities. A larger event where we will have in-person participation of different stakeholder groups is foreseen. In particular, this joint meeting of different stakeholder groups is considered very important.

Participants

15 people participated in the meeting, consisting of airline stakeholders and the BeCoM research team of WP5 - Policy drive flight planning.

***Table 1**: List of participants (alphabetic order).*

Name	Affiliation	Role
Alexander Lau	DLR	BeCoM
Camille Canivet	Air France-KLM group	Stakeholder
Christian Grob	Swiss International Airlines	Stakeholder
Christoph Todt	Tuifly	Stakeholder
Devaiah Nalianda	Tuifly	Stakeholder
Ekkehard Gutt	DHL	Stakeholder
Federica Crova	ENVISA	BeCoM
Feijia Yin	TU Delft	BeCoM
Gerd Saueressig	DLH	Stakeholder
Irène Boyer-Souchet	Air France-KLM group	Stakeholder
Julian Jene	DLH	Stakeholder
Malte Niklaß	DLR	BeCoM
Thomas Rötger	ENVISA	BeCoM
Yves Berweger	Swiss International Airlines	Stakeholder
Zarah Zengerling	DLR	BeCoM

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Agenda Items

#1. Welcome and Introduction (ENVISA).
#2. Brief overview of the BeCoM project (TU Delft).
#3. Presentation on non-CO_2 policy options (DLR).
#4. Discussion about impact on stakeholders (all).
#5. Next steps in the BeCoM project and way forward.

Presentations and Discussion Questions

Presentations

The presentations for Agenda Items #2 (Overview of the BeCoM project) and #3 (Non-CO_2 policy options) were sent to Stakeholders by the BeCoM research team after the meeting.

Major focus of the presentations:

- **Overview of the BeCoM project, by TU Delft**
  - Overview on the contrail climate impact, state-of-the-art estimate of the contribution and uncertainty of contrail on aviation's radiative forcing.
  - Overview on the contrail properties, especially on formation process, persistency, areas where persistent contrail can form depending on weather parameters (Ice Supersaturation Regions - ISSRs), and positive/negative contrail radiative forcing.
  - The major challenge to be urgently faced is that current forecasts of persistent contrail formation are unreliable and need enhancement.
  - BeCoM goals are to better predict persistent contrails by different perspectives (improvement of humidity measurements at cruise level, representation of ice supersaturation in NWP models, data and model predictions, including machine-learning based ones). BeCoM aims to estimate the reduction potential of global mean contrail radiative forcing by flight trajectory optimization and considering non-CO_2-based policy measures. This aspect is connected to the focus of this workshop.
- **Non-CO_2 policy options, by DLR**
  - The focus of these slides is to understand the motivation behind climate-optimised flight planning to avoid climate-sensitive areas and in how far this can be incentivised by policy measures.
  - Non-CO_2 assessment requires a system-wide approach, which needs to include what is emitted in the atmosphere, where these emissions are released, and how the atmosphere reacts to the emissions. Different non-CO_2 emission species have different effects on local air quality and climate, and different levels of scientific understanding as well. The different climate effects are considered and modelled in the EU Monitoring, Reporting and Verification System (MRV) for aviation non-CO_2 effects in terms of CO_2 equivalents on a per-flight basis.
  - Approaches to possible policy options can be categorized into three categories:
    1. Voluntary approaches (e.g., self-imposed emission reduction targets, non-CO_2 offset programs, etc.).
    2. Market-based approaches (emission trading schemes, climate-charged airspaces, etc.).
    3. Regulatory approaches (e.g., international engine and fuel standards, etc).
  - Overview of recent EU ETS Directive policy changes: There were amendments of non-CO_2 aviation effects in the Fit for 55 package and in May 2023, the European Union

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decided on a revision of the EU ETS stating that non-CO_2 aviation effects can no longer be ignored and describing a timeline and scope for establishing a non-CO_2 MRV. In August 2024, the Commission Implementing Regulation was approved by the member states, laying down the detailed rules of monitoring non-CO_2 effects of aviation, and annual reporting on the results from the application of the MRV framework from January 2025 on. If appropriate, the European Commission will also submit a legislative proposal to mitigate non-CO_2 effects in aviation by expanding the scope of the EU ETS to CO_2 equivalents.

  - An overview of the MRV system scheme was given. The motivation for MRV is to establish a system that can incentivise and accelerate aviation climate mitigation actions (aircraft technology, fuel design, and routing). It is a system with primary and secondary data which does not have data requirements for aircraft operators through automation.
  - Finally, it was emphasized that climate-optimized flight planning can mitigate the total climate impact significantly, but it is usually not compatible with cost-minimisation. Market-based/policy measures are seen as an option to incentivise climate mitigation.

- **Uncertainty overview, by DLR**
  - In the context of the discussion on uncertainties (see below) DLR presented a slide (n° 10 in the DLR slide deck) showing the different kinds of uncertainties relevant for contrail formation and impact. There are uncertainties in weather, climate impact modelling of non-CO_2 effects, and trajectory and emissions modelling. Further details are given in the discussion part below.

Discussion Questions

A list of questions to be discussed in Agenda Item #4 was distributed before the meeting and is reported hereafter.

List of discussion questions grouped by topic:

Policy options – selection process

1. Which policy option is best suited to allow airlines/ANSPs to effectively reduce non-CO_2 effects?
2. What time frame and geographical scope is desirable and feasible for the implementation of non-CO_2 measures?
3. Should all non-CO_2 effects be taken into account at a time, or should one effect be prioritized, e.g. contrails?

Data collection and evaluation

4. What level of data input is needed to quantify non-CO_2 impacts and how easy or difficult is it for operators to provide these data with sufficient precision?
5. Impact of different types of uncertainties

Improvement of climate impact

6. Once an MRV requirement for non-CO_2 impacts is in place, how can airlines/ANSPs benefit from the collected data to introduce or improve climate-friendly operations?
7. Are there any no-regret policy options that should be considered?
8. Which requirements must be taken into account when integrating price-based non-CO_2 strategies into flight planning and trajectory optimization?

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Impact on stakeholders

9. How might the proposed policies impact the economic viability of EU airlines and how would they impact customers?

Discussion outcomes

Cooperation among airlines, ANSPs and weather services to find solutions

- **Collaboration among different stakeholders is mandatory**. Stakeholders highly stressed the necessity of collaboration between airlines, ANSPs, and weather services, which are highly interrelated, to effectively mitigate contrail impact. There was strong agreement that isolated efforts by individual airlines but also between individual stakeholder groups like airlines and ANSPs would not be enough. Joint stakeholder workshops are necessary to facilitate open discussions and joint problem-solving.
- **Joint stakeholder groups in the next BeCoM workshops**. The idea of BeCoM partners was to investigate each stakeholder group separately to make it easier for participants to speak more freely amongst people who are all in a similar situation, and then in a further step to bring all the stakeholder groups together, whenever possible in a face-to-face meeting. A possible idea could be to organise intermediate workshops with two or three stakeholder groups before the meeting with all the groups together. In particular, a workshop bringing together airlines, ANSPs and weather services to discuss joint solutions was seen as promising.
- **Continue R&T projects and exchange outcomes.** Participants mentioned their involvement in publicly funded projects, such as D-KULT (national German programme) and CICONIA (SESAR).

Think in "spaces" for wider air transport system

- **Focus must shift from single flights to comprehensive air transport system**. Stakeholders often emphasized the urgent need to move beyond analysing single flights and instead optimise the entire air transport system by considering network-wide impacts. This aspect is closely connected with the previous point of discussion about joint stakeholder collaboration.
- **Think in "spaces"**. Thinking in "spaces" and considering the interdependencies between different flights was mentioned as a crucial aspect of trajectory optimization. Currently, most models evaluate single flights in isolation, without considering how contrails created by multiple aircraft interacting in the same airspace might influence each other's impact and contrail formation and persistence. Saturation effects are currently not considered in models such as CoCiP or aCCFs.
- **Clear definition of responsibilities**. There is the need for clearly defining roles and responsibilities among stakeholders to ensure effective implementation of mitigation strategies.

Select the right metric(s) for trajectory optimisation

- **Appropriate metric selection**. A key point mentioned many times in the discussion was about the importance of choosing appropriate climate metrics for the evaluation of contrail mitigation efforts. Relevance was especially given on radiative forcing versus other climate metrics such as Global Warming Potential (GWP) and Average Temperature Response (ATR). It was noted that while policy often relies on GWP, the benefit of ATR is directly linked to the global surface temperature change, making it a relevant consideration for future evaluations. It was also recalled that the different time horizons can lead to significantly different interpretations of non-CO_2 effects.

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- **Adoption of an international metric**. There was consensus that a globally agreed climate impact metric, ideally set at ICAO or international level, is essential to ensure an effective inclusion of non-CO_2 emissions in the climate trajectory of aviation and comparable reduction objectives. The current absence of a universally agreed metric may lead to uncoordinated mitigation approaches adopted by individual airlines, reducing the overall effectiveness of non-CO_2 mitigation strategies.
- **Political versus scientific issue**. The participants debated whether selecting a climate metric is more a political or a scientific question. Some argued that the choice of metric depends on the political objectives, such as short-term mitigation versus long-term sustainability, making it inherently a political issue. Others contended that the decision should be based on scientific reasoning, particularly in minimizing the peak of global warming. Different metrics can yield varying results depending on the time horizon considered, and while scientific studies have explored this, no consensus has been reached. The discussion also referenced key publications, e.g., the paper by Lee et al., 2021 (https://doi.org/10.1016/j.atmosenv.2020.117834), which is widely regarded as a benchmark for evaluating climate impact in aviation, and Megill et al. (2024) Alternative climate metrics to the Global Warming Potential are more suitable for assessing aviation non-CO2 effects | Communications Earth & Environment .
- **Suitable metric for aviation**. The participants discussed the role of aviation in climate change, recalling that the primary driver is the energy sector. They debated whether the best approach is to choose a metric that reduces global warming as quickly as possible or one that targets a specific point in the future, highlighting the political dimension of this decision.

Critical aspects on weather forecast models

- **Weather model accuracy and validation**. Stakeholders highlighted that there is a substantial lack in understanding of the accuracy of weather prognosis in contrail formation prediction. Currently, insufficient work has been done to validate model predictions and understand model reliability. There is hope that there will be future projects involving observation of numerous flights, will perform model calculations across multiple models, acknowledging the challenges posed by missing or outdated weather data. This approach would help to answer the key questions: Has there been a contrail? How long did it persist? And what are the geometrical extensions of it? Such efforts could provide deeper insight into the reliability of calculations both for pre-flight and for post-flight analysis. Validation of real-flight observations could be performed with satellite images (as in DKULT observation flights).
- **“Superior” model versus several models**. There was some debate over whether it would be more effective to work towards a “superior” weather model rather than integrate different existing weather, climate response and contrail prediction models (CoCiP, ACCF, AirClim etc.) to reduce uncertainty. Stakeholders use different weather models, but comparisons on the same flights prepared with different weather models were still not performed because it is impossible for an operational flight planning system to use different weather models just for the sake of simulation. But it would be interesting to develop a superior weather model, which would help to improve predictions, instead of working with five different ones, not knowing which one is coming closer to reality. This might take time, but it would be extremely helpful to lower the uncertainty.
- **Pre-tactical versus tactical steering**. A key issue is whether pre-tactical or tactical steering should be prioritized. Long-haul flights are planned well in advance (typically about 12 hours before the flight where the routing is already almost fixed). There is the need to answer the question if the goal is to forecast contrail avoidance already about 12 hours in advance or rather in-flight. In this context, it is also important to consider that if the avoidance is planned at the beginning or towards the end of the flight, pilots will react differently, e.g., they could fear to get stuck at a non-optimal flight level if the avoidance is planned at the beginning of the flight.

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Understanding and tackling uncertainties

- **Uncertainty overview**. Different uncertainties influence the quantification of non-CO_2 climate effects. Uncertainties are a major challenge in contrail mitigation and should be addressed at different levels. Three main categories of uncertainties were identified in the BeCoM project and were presented by DLR as a complementary slide to Agenda Item #3:
    1. Weather-related uncertainties, deriving from weather models.
    2. Uncertainties in climate impact modelling for non-CO_2 effects, deriving from complex interactions of different emission species in atmospheric processes.
    3. Uncertainties in trajectory and emissions modelling. These are generally smaller than the ones in the other two categories, but still relevant.

    The participants highlighted the need to consider the entire chain of uncertainties rather than focusing only on individual models.
- **Ambiguousness on the role of uncertainties in non-CO_2 effects**. The participants discussed the delicate role of uncertainties in the repartition of non-CO_2 effects as the one presented in Agenda Item #2. Some participants stated that uncertainties of these estimates should not play a big role in terms of taking actions, as the impact is undeniable and it is only a question of uncertainty width. Nevertheless, it was also pointed out that uncertainties go in both directions, i.e., real contrail effects could be significantly higher or lower than model estimates. The key takeaway was that comparisons with other impacts matter more than the absolute certainty when taking regulatory decisions. Furthermore, the trade-off between uncertain non-CO2 effects and certain CO2 effects has to be balanced in the context of climate-optimized flight planning.
- **How do uncertainties translate to a single flight?** There is the need to differentiate between overall system uncertainties and flight-specific uncertainties. It remains unclear how these uncertainties apply to individual flights. Questions were raised about the reliability of predicting critical regions in pre-flight planning and the accuracy of post-flight analyses.
- **Model improvement and comparison with observations.** A systematic evaluation of model accuracy through flight trials and ensemble analyses is necessary to improve confidence in predictions. Real-flight studies including hundreds of flights are highly needed to improve model accuracy, especially by incorporating observation data and evaluating the warming or cooling effects of contrails. Certain flights could also use model data available before/during the flight for trajectory selection. Such studies would allow to assess how often models under- or overestimate the real likelihood of contrail creation and their climate impact. Using airline flight data recorders could be an option to better understand trajectory uncertainties and emissions. Flights in the IAGOS programme (aircraft equipped with humidity sensors) could be used for an ex-post and ex-ante comparison between models and observations.
- **Military aviation data on contrail mitigation**. Questions were raised about whether military research on contrails aligns with the scientific community work, particularly regarding the U.S. military. Military aviation has historically made research in contrail reduction to reduce aircraft visibility, but with advancements in data and military flights occurring at higher or lower altitudes compared to the ones where contrail typically form, contrails are less of a concern. Moreover, current data on their mitigation strategies is limited. The difficulty in obtaining military flight data for post-operational analysis remains a barrier to fully understanding contrail formation in military operations. However, there is potential for collaboration with government agencies to integrate military research findings into civilian contrail mitigation efforts.
- **Accurate data is essential for understanding the entire chain from the fuel to contrail formation and effects**. Participants highlighted the availability of various data sources, such as flight data, fuel chemistry, and emission data, but they have not yet been fully integrated. There are also challenges in measuring non-CO_2 emissions (such as non-volatile particulate matter nvPM and nitrogen oxides NO_X, which also have a key role in contrail formation) due to factors

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like engine aging, fuel variations, fuel blending, and limited regulated data points which engine manufacturers are obliged to publish (currently, as regulated by ICAO, four measurement points at four different thrust settings in the Landing and Take-Off LTO phase). Beyond these, engine-specific emission data remains difficult to access due to confidentiality concerns from manufacturers, making comprehensive research more challenging. Efforts are ongoing, including updates from ICAO, to improve emission models, particularly for lean burn engines, which could lead to more precise assessments in the future. Both satellite and ground-based observations play a crucial role in capturing contrail formation, but current datasets lack sufficient precision. Flight data recorders and airline-maintained databases could provide valuable real-world validation for contrail mitigation models.

Non-CO_2 policy options

- **Need of a proactive spirit development**. The different potential approaches presented in the Agenda Item #3 were discussed. While some stakeholders suggested a structured, phased approach, others highlighted the need of a more proactive spirit of development. It was remarked that the "American way" was not included in the possible approaches, referring to the approach which emphasizes quick actions with an available budget for incentivising demonstration projects. In contrast, the European approach is slower and based on waiting for impact assessments before taking actions.
- **EU or other areas (e.g., North Atlantic)?** There is an open question on whether the policy options need to be EU-specific or if they can start with less complex regions, like the North Atlantic, which is a particularly relevant test case due to its high regulation, and flexibility in approach may be beneficial. It was also discussed whether a policy measure would be needed at all, or rather a kind of new system for the North Atlantic tracks could be implemented, which would e.g. open only those tracks with the lowest probability of crossing ISSRs; in a less congested airspace compared to e.g. Western Europe, such a measure would be more easily implementable.
- **Effectiveness of rerouting a single flight**. The difficulty in mitigating contrail effects is also connected to the fact that if the rerouting is performed on a first single flight, this might not ultimately reduce overall climate impact if other aircraft generate contrails flying through the same region. The discussion also touched on the fairness of rerouting, as it could not deliver the expected environmental benefits if not all flights adjust to it.
- **Risk assessment**. There was a question about the meaning of "risk assessment" calculation mentioned in the Agenda Item #3 presentation. There is the necessity to understand the implication of uncertainties in climate impact predictions. The implications are lower as long as only a single monitoring is performed. If a step further is made, e.g., towards pricing or a regulatory issue, then the risk of making wrong incentives is much higher, because it creates incentives for rerouting. This is highly important for the impact assessment analysis. The risk assessment is then a calculation of how often models overestimate/underestimate these impacts, based on the current knowledge and modelling tools. The most crucial aspect is not whether there will be control or not, but rather if the climate will be warming or cooling and how often the adopted strategy will be successful.
- **Critical aspects of voluntary and market-based approaches**. Voluntary actions as rerouting are a possibility, but there was debate over whether this would be enough, especially when the climate impact depends on collective actions from all airlines, and not just a few. For instance, if an aircraft of one airline avoids the critical regions for contrail formation and the subsequent aircraft of another airline crosses it and a contrail forms anyway, the evaluation of the effectiveness of voluntary actions would be challenging. This issue applies also for market-based approaches. If an airline does not care for the costs or the price is just too low for that airline, we could still have flights in ice-supersaturated regions, hence it is not clear if mitigation goals

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could still be reached or not. A question also raised on the effectiveness of regulating specific flights or areas. E.g., for Europe, the most climate-harmful flights in terms of contrail formation are those crossing Europe at night, which are not regulated as they depart or land somewhere outside Europe.

- **Balance between reduction of CO_2 and non-CO_2 emission mitigation**. A significant part of the discussion revolved around the challenge of balancing reductions in non-CO_2 effects, such as contrails, with potential increases in fuel consumption and CO_2 emissions. Depending on the time horizon considered, the relative priority given to CO_2 vs non-CO_2 mitigation varies. In any case, uncertainties in the non-CO_2 impact quantification need to be reduced for an effective mitigation. These considerations lead to the need for a well-defined trade-off framework that integrates both CO_2 and non-CO_2 effects into decision-making.
- **Concerns on the MRV system**. The EU non-CO_2 MRV system is thought as a key tool to establish a comprehensive inventory of non-CO_2 effects, but concerns were raised about its accuracy and practical implementation, questioning its capability to provide accurate data for science, as it relies on conservative estimates and incomplete data. Stakeholders expressed concerns about the risk of the MRV being used to prematurely set rules on CO_2 equivalents without fully understanding how to mitigate non-CO_2 emissions. The discussion highlighted the need for clearer, more practical systems that airlines can trust and that can contribute to understanding and mitigating non-CO_2 effects on the climate.
- **Geographical scope of policy options**. There was discussion on the geographical scope and timeframe for implementing climate-optimized flight procedures. The complexity of managing airspace, particularly in congested European regions, where any flight path change can have a knock-on effect on other flights, was highlighted. Stakeholders emphasized the need for a flexible approach, considering both medium-haul and long-haul flights, and the potential for avoidance based on feasibility and relevance. There is uncertainty about conditions for introducing meaningful regulations might be met, with estimates suggesting it could take until 2030 (8-10 years from the 2020 EASA report). Key concerns include understanding how well current models predict flight outcomes, and the challenge of evaluating the success and failure of avoidance strategies in practice. The need for iterative, step-by-step analysis is emphasized, with a focus on improving the precision of climate-optimized operations.

Conclusion and next steps

The workshop provided valuable insights and feedback from participants. Key points included:

- The need for better meteorological data to support trajectory selection
- Airlines, ANSPs and weather services need to work cooperatively to find solutions. Joint BeCoM stakeholder workshops are foreseen.
- Think in “spaces”: focus on wider air transport system rather than single flights.
- Select the right metric(s) for the optimisation of trajectories.
- Real data and observations for many flights are needed to quantify success/failure rate of operational measures.
- Fuel and engine characteristics should also be considered.
- Proactive spirit of development is needed.

The discussion was productive and valuable, with plans to share quantitative results from the BeCoM project with stakeholders for further feedback. The next steps will involve further collaboration with the airline community, ANSPs, weather services, and authorities, with the hope of eventually reaching consistent recommendations for decision-makers. The participants were highly encouraged to continue the dialogue also by communicating via email to the group.

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Appendix 2

Virtual Stakeholder Workshop with ANSPs – Meeting summary

Contents

This project has received funding from the European Union's Horizon Europe
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Meeting details

Date

Tuesday 27th May 2025, 10:00 - 12:00 CET

Meeting scope

The EU-funded research project BeCoM (Better Contrail Mitigation, https://becom-project.eu/) has the objective of largely reducing or even eliminating the global mean contrail radiative forcing, hence a substantial reduction of aviation's share of global warming to be achievable on a much shorter time horizon. This is facilitated by confidently forecasting persistent contrails, reduction of weather-dependent individual contrail radiative effects, and the successful avoidance of strongly warming contrails via trajectory optimization.

To support the implementation of effective contrail avoidance, BeCoM partner DLR is working on a methodology for integrating non-CO_2-related policy instruments into flight planning and trajectory optimization, and an assessment of the effectiveness of the policy driven flight planning approach. The BeCoM WP5 team, under the lead of ENVISA, is inviting stakeholders (airlines, air navigation service providers (ANSPs), meteorological services, authorities, etc.) to take part in this assessment and share their views about the proposed policy measures, their feasibility, their effectiveness and cost-benefit ratio, and the efforts required by stakeholders to comply with them. This was the second of a series of stakeholder workshops and was held with ANSPs and met services. A larger event with in-person participation of different stakeholder groups is foreseen and considered a key step.

Participants

11 people participated in the meeting, consisting of ANSP and met service stakeholders and the BeCoM research team of WP5 – Policy-driven flight planning.

***Table 1**: List of participants (alphabetic order).*

Name	Affiliation	Role
Alexander Lau	DLR	BeCoM
Björn Beckmann	DWD (German Meteorological Service)	Stakeholder
Denis Bilyarski	ENV-ISA	BeCoM
Federica Crova	ENV-ISA	BeCoM
Feijia Yin	TU Delft	BeCoM
Malte Niklaß	DLR	BeCoM
Philippe Very	EUROCONTROL	Stakeholder
Pierre Crispel	CNRM (National Centre for Meteorological Research, France)	Stakeholder
Roland Eichinger	DLR	BeCoM
Sian Andrews	NATS (National Air Traffic Services, UK)	Stakeholder
Thomas Rötger	ENV-ISA	BeCoM

Agenda Items

#1. Welcome and Introduction (ENV-ISA).
#2. Brief overview of the BeCoM project (TU Delft).
#3. Presentation on non-CO_2 policy options (DLR).
#4. Discussion about impact on stakeholders (all).
#5. Next steps in the BeCoM project and way forward.

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Presentations and Discussion Questions

Presentations

The presentations for Agenda Items #2 (Overview of the BeCoM project) and #3 (Non-CO_2 policy options) were sent to Stakeholders by the BeCoM research team after the meeting.

Major focus of the presentations:

- **Overview of the BeCoM project, by TU Delft**
  - Overview on the contrail climate impact, state-of-the-art estimate of the contribution of contrails to aviation's radiative forcing and the related uncertainty.
  - Overview on the properties of contrails, especially on formation process, persistency, areas where persistent contrails can form depending on weather parameters (Ice Supersaturation Regions - ISSRs), and positive/negative radiative forcing by contrails.
  - The major challenge to be urgently faced is that current forecasts of persistent contrail formation are still not sufficiently reliable and need enhancement.
  - BeCoM goals are to better predict persistent contrails by different perspectives (improvement of humidity measurements at cruise level, representation of ice supersaturation in NWP models, data and model predictions, including machine-learning based ones). BeCoM aims to estimate the reduction potential of global mean contrail radiative forcing by flight trajectory optimization and considering non-CO_2-based policy measures. This aspect is connected to the focus of this workshop.
- **Non-CO_2 policy options, by DLR**
  - The focus of these slides is to understand the motivation behind climate-optimised flight planning to avoid climate-sensitive areas, how far this can be incentivised by policy measures, and assess collateral impact on tariffs, demand, competition, and operations.
  - Non-CO_2 assessment requires a system-wide approach, which needs to include what is emitted in the atmosphere, where these emissions are released, and how the atmosphere reacts to the emissions. Different non-CO_2 emission species have different effects on local air quality and climate, and different levels of scientific understanding as well. The different climate effects are considered and modelled in the EU Monitoring, Reporting and Verification System (MRV) for aviation non-CO_2 effects in terms of CO_2 equivalents (CO_2e) on a per-flight basis.
  - Approaches to possible policy options can be categorized into three categories:
    1. Voluntary approaches (e.g., self-imposed emission reduction targets, non-CO_2 offset programs, etc.).
    2. Market-based approaches (emission trading schemes, climate-charged airspaces, etc.).
    3. Regulatory approaches (e.g., international engine and fuel standards, etc).
  - Overview of recent EU ETS Directive policy changes: There were amendments of non-CO_2 aviation effects in the Fit for 55 package, and in May 2023, the European Union decided on a revision of the EU ETS stating that non-CO_2 aviation effects can no longer be ignored and describing a timeline and scope for establishing a non-CO_2 MRV. In August 2024, the Commission Implementing Regulation was approved by the member states, laying down the detailed rules of monitoring non-CO_2 effects of aviation, and annual reporting on the results from the application of the MRV framework from January 2025 on. If appropriate, the European Commission will also submit a legislative proposal to mitigate non-CO_2 effects in aviation by expanding the scope of the EU ETS to CO_2 equivalents in 2028 or later (see below "MRV system and data access").

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  - An overview of the MRV system scheme was given. The motivation for MRV is to lay the basis for a system that can incentivise and accelerate aviation climate mitigation actions (aircraft technology, fuel design, and routing). It is a system with primary and secondary data which does not have data requirements for aircraft operators as all data are automatically collected via other sources (EUROCONTROL flight trajectories, weather data from met services and BADA aircraft performance data).
  - Climate-optimized flight planning can mitigate the total climate impact significantly, but it is usually not compatible with cost-minimisation. Market-based/policy measures are seen as an option to incentivise climate mitigation.
- **Results of BeCoM simulations related to cost and metric impact on the trajectory optimisation for contrail mitigation, by DLR**
  - In the context of the discussion on policies, DLR presented a set of slides showing the results of their study in the BeCoM framework, where they simulated the impact of costs and metric on rerouting (NB: in the following, the term "rerouting" is used for both vertical flight level change and horizontal route change, i.e. diversion, the latter occurring very rarely in real operations). This study has been published in a pre-print form available at https://zenodo.org/records/15438171.
  - They simulated different types of trajectories for each flight, including fuel- and cost-optimal trajectories, as well as climate-optimised trajectories designed to avoid areas with high probability of contrail formation. Since climate-optimized flying typically incurs higher operational costs—due to longer routes, increased fuel consumption, or altitude adjustments that deviate from the most cost-efficient paths—the researchers introduced a fictitious price of €80 per tonne of CO_2e for non-CO_2 emissions. Flight trajectories were then optimized solely based on total costs, including both operational expenses (fuel and time) and the added cost of climate impact. Here, they assumed that all additional costs were fully passed to passengers They repeated the simulations with different meteorological conditions to reflect weather-related variability. Finally, they also tested different policy design parameters like the accounting percentage of the calculated CO_2e emissions (e.g., 20% versus 100% of CO_2e).

  - Operational non-CO_2 mitigation depends on weather, while ticket price increases are mainly influenced by the accounted CO_2e share and the applied carbon price. A gradual rollout of CO_2e pricing, e.g. starting with 20% of CO_2e emissions in the first year, could help to limit initial cost impacts for passengers. Dependent on the accounted CO_2e share, ticket prices of analyzed inner European flights may rise by 20-25 € per flight without rerouting, and 5-8 € per flight with contrail avoidance. This corresponds to an average ticket fare increase of 1.0%-4.8%. Including cooling effect contrails into non-CO_2 pricing may neutralize or lower costs through compensation, though this remains controversial due to its association with geoengineering

Discussion Questions

A list of questions to be discussed in Agenda Item #4 was distributed before the meeting and is reported hereafter.

List of discussion questions:

Policy options – selection process

1. Which policy options are best suited to allow airlines/ANSPs to effectively reduce non-CO_2 effects?
2. What time frame and geographical scope is desirable and feasible for the implementation of non-CO_2 measures?

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3. Should all non-CO_2 effects be taken into account at a time, or should one effect be prioritized, e.g. contrails?

Data collection and evaluation

4. What level of data input is needed to quantify non-CO_2 impacts and how easy or difficult is it for airlines, ANSPs and weather services to provide these data with sufficient precision?
5. Different types of uncertainties and their impact

Improvement of climate impact

6. Once an MRV requirement for non-CO_2 impacts is in place, how can airlines/ANSPs benefit from the collected data to introduce or improve climate-friendly operations?
7. Are there any no-regret policy options that should be considered?
8. Which requirements must be taken into account when integrating price-based non-CO_2 strategies into flight planning and trajectory optimization?

Impact on stakeholders

9. How might the proposed policies impact the economic viability of EU airlines and how would they impact customers?

Discussion outcomes

Lack of efficiency of voluntary measures and policy need

- **Voluntary contrail avoidance is largely ineffective without broader participation**. There was general agreement that voluntary contrail avoidance by single airlines is insufficient on its own to achieve meaningful contrail mitigation. While it may be feasible under low traffic conditions, it becomes problematic in congested airspace. If only one airline re-routes to avoid contrails, it will have higher operating costs, while another airline flying through the same area may still generate a contrail, resulting in no net climate benefit. Therefore, it is important that a policy framework is established to ensure coordinated action.
- **Roles and responsibilities of airlines and ANSPs**. A key question is whether policy needs to be addressed to airlines or ANSPs. From ANSP perspective, airlines are best positioned to lead on planning climate-optimized trajectories as they have detailed knowledge of their operational needs. The ANSPs' role is generally to support airline customers and facilitate their optimal flight plan. If airlines try to avoid non-CO_2 emissions, then ANSPs are naturally incentivised to support that.
- **ANSPs may be incentivised through performance metrics**. Policies could also target ANSPs directly, e.g., by requiring them to demonstrate how often they are supporting what the airlines are requesting in terms of contrail avoidance. Currently, most ANSPs in Europe are not directly incentivised from an environmental perspective. Some European ANSPs have systems to measure the environmental efficiency of trajectories, but currently they do not take into account non-CO_2 emissions.
- **Coordination with network managers is required**. Network managers add an additional layer of complexity since they are actively involved in pre-tactical trajectory validation. Airlines may be dependent on decisions that not only come from them and ANSPs, but also from the network manager. At a European level, close coordination between national ANSPs and Eurocontrol would be essential to define and implement effective contrail mitigation strategy.

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Forecast accuracy

- **Weather forecast accuracy may indicate if contrail avoidance should be performed**. Stakeholders stressed the importance of weather forecast accuracy in determining when contrail avoidance should be implemented. Optimised flights aimed at contrail avoidance could be performed only on days where the weather forecast (especially of ISSRs) is sufficiently reliable. Uncertainty evaluation of ISSR forecast can be performed through ensemble forecast. Limiting contrail mitigation to days with high forecast confidence could improve operational feasibility and operator acceptance.
- **Avoiding all possible contrail formation or unnecessary rerouting?** A key question is what risk we aim to minimize: the formation of any contrail, or unnecessary rerouting. Two approaches are possible: a conservative strategy would avoid all areas where at least one forecast indicate the possibility of contrail formation. A selective strategy would avoid only areas where all the ensemble forecasts indicate a high probability of contrail formation. A proposed method is to analyse forecast uncertainty at the grid-point level in a specific region, which could provide an indicator for whether climate-optimized flight planning is worthwhile in the next 1-2 days.
- **A joint threshold for forecast accuracy could improve operator acceptance**. The definition of a shared threshold for forecast accuracy above which contrail avoidance planning should be triggered can be achieved only by working together with airlines. A common threshold (e.g., at a European level) for all airlines could be established in policy options. This threshold should take into account also re-routing costs, and policies should reflect what airlines would be willing to support in terms of supplementary costs.

Geographical and temporal scope

- **Starting with less congested areas and periods, where rerouting may be more feasible**. Potential congestion threshold needs to be considered. For example, during nighttime in less-congested airspaces, contrails are generally warming, multiple superposed contrails rarely occur and there is a lot of space to effectively re-route flights. However, during peak traffic periods, applying contrail avoidance on a large scale becomes nearly impossible because of multiple superposed contrail formation and knock-on effects through altitude changes of other flights, unless extensive regulations are implemented.
- **A comprehensive understanding of the trade-offs between climate benefits and operational costs is needed**. We need to consider the whole picture of climate and cost trade-offs regarding the forecast uncertainty, the airspace congestion, and chain effects. For instance, the cost caused by delays due to rerouting could exceed the costs established by policies for crossing contrail formation areas. In such cases, airlines might choose to produce contrails anyway, with a consequent failure of mitigation strategies. Chain effects must be also accounted for. While it may seem less costly to deviate a single flight by a few thousand feet, if that deviation occurs to an altitude intended for other flights, those flights will also need to reroute to less efficient altitudes. This results in increased fuel consumption not only for the initially deviated flight but also for others. A system analysis is then required not only for single flights, but on a broader network scale.
- **Less congested oceanic airspaces could serve as a good starting point for contrail mitigation**. Oceanic airspace offers a good place to start for contrail mitigation since there is more space available compared to continental airspace, and aircraft are mainly in cruise phase flying along mostly unidirectional trajectories. Nevertheless, there are some complexities: oceanic airspace lacks radar coverage, making flight level changes more difficult. Therefore, if a small ISSR needs to be avoided, a suboptimal flight level may need to be maintained for longer than expected and this would reflect in higher costs.

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- **Operational coherence must be maintained**. If policy measures are applied only on intra-European flights, transcontinental flights could cross the same ISSRs and form contrails anyway, and efforts by intra-European operators could be potentially nullified. Ideally, such policies should be applied at an international level. For example, if the North Atlantic flight corridor is the initial focus, an option would be to propose a bilateral governmental agreement between UK, which controls the Shanwick oceanic control area in the North-East Atlantic, and Canada, which controls the Gander oceanic control area in the North-West Atlantic.

Data harmonization and use

- **Need for harmonized weather data and common thresholds across providers**. Airlines and ANSPs rely on different weather data providers. While airlines would plan climate-optimised trajectories before a flight, ANSPs often have access to more updated meteorological data at the time of the flight. This raises the question: which should take the priority, the airline planned route or the ANSP directive based on updated data? Establishing a central database or a set of common rules to handle ISSRs could help avoid operational incoherence. Although past attempts to create harmonised meteorological products were unsuccessful due to difficulties in data harmonisation, advances in IT now make sharing ensemble forecasts among national services more feasible. It would be then necessary to define common thresholds, e.g., on uncertainty limits, establish if deterministic or ensemble models should be used, and create a harmonised methodological approach to ensure greater transparency. It should be noted that the usage of different models offers the advantage of better estimates of uncertainties, but the final users, i.e. airlines, require a clear and useful product. There is still no consensus if the airlines should use a single European harmonised product or have the option to choose among different national products that adhere to common specifications and formats.
- **Remote sensing and onboard sensor data implemented on aircraft could help in modelling validation**. Another valuable source of data could be the direct observation from remote sensors (e.g., satellite imagery) to validate contrail modelling predictions. Validation is still a complex process since linking a contrail to a specific flight is still challenging. Additional onboard sensors, such as relative humidity sensors, could be transformative in the future, since they could transmit real-time data directly to weather forecast providers and drastically improve the ISSR forecast accuracy. Incentives would be necessary to standardise the implementation of such sensors on aircraft., especially involving the manufacturers. However, KLM mentioned a study suggesting that it may not be necessary to install sensors on all aircraft, instead installing them on a selected fleet could optimise benefits.

MRV system and data access

- **Concerns were raised about lack of clarity on access and use of MRV-collected data**. Currently, it is unclear how ANSPs will directly use MRV data. ANSPs need information on how many airlines are trying to avoid non-CO_2 emissions, when these efforts occur, and under which conditions. However, the MRV system will probably not give this information directly. It is expected that, in the initial years, airlines will not engage significant mitigation efforts due to the absence of financial incentives. The airlines will use the MRV system primarily to better understand their own climate impact and test the instrument. From the scientific point of view, access to data is crucial, but it remains unclear who will have access to primary data, which are the most valuable. Secondary data may be made available, though this decision is pending, and a concrete plan for scientific evaluation has not been established yet.
- **ANCEN (Aviation Non-CO_2 Experts Network) or other scientific bodies might contribute to evaluating MRV effectiveness**. By 2028, a decision or recommendation is expected on how to

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connect MRV to the emission trading system (ETS). By that time, a transparent evaluation of MRV data will be essential. Involving experts from the ANCEN network could be a promising approach. The DLR is working on preparatory documents and may propose different approaches to the European Commission.

Policy design and cost-based incentives

- **Pricing mechanisms should consider not only fuel penalties but also delays and airspace congestion**. The effectiveness of pricing depends on many factors beyond the fuel consumption alone. The choice of metric used, e.g., the amount of CO_2e attributed to contrails, will be critical as it will impact directly the costs or the incentive offered.
- **The inclusion of cooling contrails in pricing schemes is controversial**. Whether to include cooling contrails in pricing schemes remains an open question, with different opinions. Some argue for postponing the inclusion of cooling contrails due to too high uncertainties, while others believe excluding them and delaying the potential payback option would compromise the validity of the system.

Conclusion and next steps

The workshop provided valuable insights and feedback from participants. Key points included:

- Voluntary contrail avoidance policies are ineffective without a regulatory framework.
- Improved accuracy and reliability of weather forecast (especially of ISSRs) are required.
- Cooperation among airlines, ANSPs and weather services is essential to implement coordinated non-CO_2 mitigation strategies.
- Air traffic congestion must be taken into account: less congested areas such as oceanic ones are a good starting point for mitigation strategies.
- Sharing of MRV data is crucial for consistent and transparent management of non-CO_2 emissions and route optimisation.
- A systemic vision is needed at European and international level, with coordinated involvement of all actors.
- Pricing and incentive policies need to consider not only fuel consumption but also the economic impacts of delays and congestion.

The discussion was productive and valuable, with plans to share quantitative results from the BeCoM project with stakeholders for further feedback. The next steps will involve a larger stakeholder event foreseen for late 2025 to include authorities, ANSPs, airlines, weather services, and researchers in Brussels, Delft, or at another place convenient to reach for most participants.

The CICONIA project was often mentioned during the workshop as a source of complementary information and results, so it could be useful to organise a joint session/workshop with their team to exchange about the results and present the ideas for a way forward.

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Appendix 3

Virtual Stakeholder Workshop with Authorities – Meeting summary

Contents

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Meeting details

Date

Friday 4th July 2025, 10:30 - 12:30 CET

Meeting scope

The EU-funded research project BeCoM (Better Contrail Mitigation, https://becom-project.eu/) has the objective of largely reducing or even eliminating the global mean contrail radiative forcing, hence a substantial reduction of aviation's share of global warming to be achievable on a much shorter time horizon. This is facilitated by confidently forecasting persistent contrails, reduction of weather-dependent individual contrail radiative effects, and the successful avoidance of strongly warming contrails via trajectory optimization.

To support the implementation of effective contrail avoidance, BeCoM partner DLR is working on a methodology for integrating non-CO_2-related policy instruments into flight planning and trajectory optimization, and an assessment of the effectiveness of the policy driven flight planning approach. The BeCoM WP5 team, under the lead of ENV-ISA, is inviting stakeholders (airlines, air navigation service providers (ANSPs), meteorological services, authorities, etc.) to take part in this assessment and share their views about the proposed policy measures, their feasibility, their effectiveness and cost-benefit ratio, and the efforts required by stakeholders to comply with them. This was the third of a series of stakeholder workshops and was held with authorities. A larger event with in-person participation of different stakeholder groups is foreseen and considered a key step.

Participants

22 people participated in the meeting, consisting of authority stakeholders and the BeCoM research team of WP5 – Policy-driven flight planning.

***Table 1**: List of participants (alphabetic order).*

Name	Affiliation	Role
Alexander Lau	DLR	BeCoM
Babette Reimann	Federal Ministry for Economic Affairs and Energy, Germany	Stakeholder
Celia Bedoya	General Directorate of Civil Aviation, Spain	Stakeholder
Diana Agazki	Spanish Aviation Safety and Security Agency	Stakeholder
Denis Bilyarski	ENV-ISA	BeCoM
Dimitar Nikov	Directorate-General for Climate Action (DG CLIMA)	Stakeholder
Federica Crova	ENV-ISA	BeCoM
Feijia Yin	TU Delft	BeCoM
Ignacio Bañeres	SENASA	Stakeholder
Justo Hernández	Civil Aviation Authority, Spain	Stakeholder
Kay Köhler	German Emissions Trading Authority and German Environment Agency	Stakeholder
Malte Niklaß	DLR	BeCoM
Mario Morales	Civil Aviation Authority, Spain	Stakeholder
Markus Nitsche	Federal Ministry for the Environment, Germany	Stakeholder

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Olaf Hölzer-Schopohl	German Emissions Trading Authority and German Environment Agency (UBA)	Stakeholder
Olivier Meynot	General Directorate of Civil Aviation, France	Stakeholder
Roland Eichinger	DLR	BeCoM
Steffen Herrmann	German Environment Agency	Stakeholder
Theo Rindlisbacher	Swiss Civil Aviation Authority	Stakeholder
Thomas Rötger	ENV-ISA	BeCoM
Ulrika Raab	Swedish Transport Agency	Stakeholder
Zarah Zengerling	DLR	BeCoM

Agenda Items

#1. Welcome and Introduction (ENV-ISA).
#2. Brief overview of the BeCoM project (TU Delft).
#3. Presentation on non-CO_2 policy options (DLR).
#4. Discussion about impact on stakeholders (all).
#5. Next steps in the BeCoM project and way forward.

Presentations and Discussion Questions

Presentations

The presentations for Agenda Items #2 (Overview of the BeCoM project) and #3 (Non-CO_2 policy options) were sent to Stakeholders by the BeCoM research team before the meeting.

Moreover, two additional presentations were given by DLR during Agenda Item #4 in the context of the discussion of uncertainties (Uncertainties in policy-driven flight planning) and market-based measures (Results of BeCoM simulations related to cost and metric impact on the trajectory optimisation for contrail mitigation).

Major focus of the presentations:

- **Overview of the BeCoM project (Agenda Item #2), by TU Delft**
    - Overview on the contrail climate impact, state-of-the-art estimate of the contribution of contrails to aviation's radiative forcing and the related uncertainty.
    - Overview on the properties of contrails, especially on formation process, persistency, areas where persistent contrails can form depending on weather parameters (Ice Supersaturation Regions - ISSRs), and positive/negative radiative forcing by contrails.
    - The major challenge to be urgently faced is that current forecasts of persistent contrail formation are still not sufficiently reliable and need enhancement.
    - BeCoM goals are to better predict persistent contrails by different perspectives (improvement of humidity measurements at cruise level, representation of ice supersaturation in NWP models, data and model predictions, including machine-learning based ones). BeCoM aims to estimate the reduction potential of global mean contrail radiative forcing by flight trajectory optimization and considering non-CO_2-based policy measures. This aspect is connected to the focus of this workshop.

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- **Non-CO_2 policy options (Agenda Item #3), by DLR**
  - The focus of these slides is to understand the motivation behind climate-optimised flight planning to avoid climate-sensitive areas, how far this can be incentivised by policy measures, and assess collateral impact on tariffs, demand, competition, and operations.
  - Non-CO_2 assessment requires a system-wide approach, which needs to include what is emitted in the atmosphere, where these emissions are released, and how the atmosphere reacts to the emissions. Different non-CO_2 emission species have different effects on local air quality and climate, and different levels of scientific understanding as well. The different climate effects are considered and modelled in the EU Monitoring, Reporting and Verification System (MRV) for aviation non-CO_2 effects in terms of CO_2 equivalents (CO_2e) on a per-flight basis.
  - Approaches to possible policy options can be categorized into three categories:
    1. Voluntary approaches (e.g., self-imposed emission reduction targets, non-CO_2 offset programs, etc.).
    2. Market-based approaches (emission trading schemes, climate-charged airspaces, etc.).
    3. Regulatory approaches (e.g., international engine and fuel standards, etc).
  - Overview of recent EU ETS Directive policy changes: There were amendments on non-CO_2 aviation effects in the Fit for 55 package, and in May 2023, the European Union decided on a revision of the EU ETS stating that non-CO_2 aviation effects can no longer be ignored and describing a timeline and scope for establishing a non-CO_2 MRV. In August 2024, the Commission Implementing Regulation was approved by the member states, laying down the detailed rules of monitoring non-CO_2 effects of aviation, and annual reporting on the results from the application of the MRV framework from January 2025 on. If appropriate, the European Commission will also submit a legislative proposal to mitigate non-CO_2 effects in aviation by expanding the scope of the EU ETS to CO_2 equivalents in 2028 or later (see below "MRV system and data access").
  - An overview of the MRV system scheme was given. The motivation for MRV is to lay the basis for a system that can incentivise and accelerate aviation climate mitigation actions (aircraft technology, fuel design, and routing). It is a very flexible system with primary and secondary data which does not have mandatory primary data requirements for aircraft operators as all data can also automatically be collected via other sources (EUROCONTROL flight trajectories, weather data from met services and BADA aircraft performance data).
  - Climate-optimized flight planning can mitigate the total climate impact significantly, but it is usually not compatible with cost-minimisation. Market-based/policy measures are seen as an option to incentivise climate mitigation.
  - Some clarifying questions on this presentation were asked by the participants. It was asked whether the package presented a complete picture of regulatory options, suggesting the inclusion of additional measures beyond pricing, such as no-fly zones or altitude restrictions. The topic of coordination with other similar European or national projects (CICONIA, Green Gear, D-KULT, ANCEN) was raised, and the importance of clarifying the level of uncertainty associated with the model results. Some asked how the results of WP5 relate to the other work packages of the project and what interim conclusions are already available to support the debate on policy options. Technical comments were added on the role of water vapour, ICAO's non-volatile particulate matter (nvPM) standards (mainly covering landing and takeoff emissions for engines >26.7 kN since 2023), and the complexity of the interaction between sustainable aviation fuels (SAF), combustion technologies and contrail formation. All this highlighted the importance of addressing uncertainty in a transparent and structured manner.

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- **Uncertainties in policy-driven flight planning (part of Agenda Item #4), by DLR**
    - In the context of the discussion on uncertainties (see below) DLR presented a slide showing the different kinds of uncertainties relevant for contrail formation and impact.
    - Different uncertainties influence the quantification of non-CO_2 climate effects. Uncertainties are a major challenge in contrail mitigation and should be addressed at different levels. Three main categories of uncertainties were identified in the BeCoM project and were presented by DLR as a complementary slide to Agenda Item #3:
        1. Weather-related uncertainties, deriving from weather models. These make it complex to forecast the location of persistent contrail formation areas. An example was shown regarding where different ensembles of the same model provide different predictions, especially in the borders of contrail formation areas. These results suggest that limiting trajectory changes ("rerouting") only to areas where all models agree to a certain degree on the formation of contrails could be a possible solution.
        2. Uncertainties in climate impact modelling of non-CO_2 effects, deriving from complex interactions of different emission species in atmospheric processes.
        3. Uncertainties in trajectory and emissions modelling. These are generally smaller than the ones in the other two categories, but still relevant.
- **Results of BeCoM simulations related to cost and metric impact on the trajectory optimisation for contrail mitigation (part of Agenda Item #4), by DLR**
    - In the context of the discussion on policies, DLR presented a set of slides showing the results of their study in the BeCoM framework, where they simulated the impact of costs and metric on rerouting (NB: in the following, the term "rerouting" is used for both vertical flight level change and horizontal route change, i.e. diversion, the latter occurring very rarely in real operations). This study has been published in a pre-print form available at https://zenodo.org/records/15438171.
    - They simulated different types of trajectories for each flight, including fuel- and cost-optimal trajectories, as well as climate-optimised trajectories designed to avoid areas with high probability of contrail formation. Since climate-optimized flying typically incurs higher operational costs—due to longer routes, increased fuel consumption, or altitude adjustments that deviate from the most cost-efficient paths—the researchers introduced a fictitious price of €80 per tonne of CO_2e for non-CO_2 emissions. Flight trajectories were then optimized solely based on total costs, including both operational expenses (fuel and time) and the added cost of climate impact. Here, they assumed that all additional costs were fully passed to passengers. They repeated the simulations with different meteorological conditions to reflect weather-related variability. Finally, they also tested different policy design parameters like the accounting percentage of the calculated CO_2e emissions (e.g., 20% versus 100% of CO_2e).
    - Operational non-CO_2 mitigation depends on weather, while ticket price increases are mainly influenced by the accounted CO_2e share and the applied carbon price. A gradual rollout of CO_2e pricing, e.g. starting with 20% of CO_2e emissions in the first year, could help to limit initial cost impacts for passengers. Dependent on the accounted CO_2e share, ticket prices of analysed inner European flights may rise by 20-25 € per flight without rerouting, and 5-8 € per flight with contrail avoidance. This corresponds to an average ticket fare increase of 1.0%-4.8%. Including the effect of cooling contrails into non-CO_2 pricing may neutralize or reduce costs through compensation, though this remains controversial as incentivising generation of cooling contrails may be associated with geoengineering.

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Discussion Questions

A list of questions to be discussed in Agenda Item #4 was distributed before the meeting and is reported hereafter.

List of discussion questions:

Policy options – selection process

1. Which policy options are best suited to allow airlines/ANSPs to effectively reduce non-CO_2 effects?
2. What time frame and geographical scope is desirable and feasible for the implementation of non-CO_2 measures?
3. Should all non-CO_2 effects be taken into account at a time, or should one effect be prioritized, e.g. contrails?

Data collection and evaluation

4. What level of data input is needed to quantify non-CO_2 impacts and how easy or difficult is it for airlines, ANSPs and weather services to provide these data with sufficient precision?
5. Different types of uncertainties and their impact

Improvement of climate impact

6. Once an MRV requirement for non-CO_2 impacts is in place, how can airlines/ANSPs benefit from the collected data to introduce or improve climate-friendly operations?
7. Are there any no-regret policy options that should be considered?
8. Which requirements must be taken into account when integrating price-based non-CO_2 strategies into flight planning and trajectory optimization?

Impact on stakeholders

9. How might the proposed policies impact the economic viability of EU airlines and how would they impact customers?

Discussion outcomes

Policy options and strategic approaches to non-CO_2 effects

- **Rely on flexible and globally extended market-based measures**. The group discussed the best strategies to mitigate aviation's non-CO_2 climate impacts. Some participants argued in favour of market-based measures like the EU Emission Trading System (ETS). This system can handle other greenhouse gases different from CO_2 (e.g., nitrogen oxides NOx and methane), therefore it could be adapted also for non-CO_2 emissions and contrails. This system is appreciated especially for its flexibility, i.e., it would allow aircraft operators to decide for every single flight what would be the best option for this specific flight to achieve contrail avoidance. Such a system would need to be combined with others since it does not have global coverage. Many flights cross European airspace without being captured by the ETS, and this could potentially cause unfair competition.
- **Incentivise positive behaviour rather than penalise**. Other participants agreed that imposing pricing would not be the first choice now, mainly because there are still big uncertainties about non-CO_2 emissions' effects. A "solution-oriented" policy design was supported, arguing that every disincentive should be coupled with a viable alternative. Regulatory and incentive-based approaches could be preferred, especially those that encourage positive behaviour rather than penalise negative ones. If confidence of the impact is low and attribution to individual flights is

challenging, constraining regulations should be considered carefully. It was argued that applying the ETS scheme may be conceptually challenging for non-CO_2, as the ETS is based on “like-for-like” rules, while non-CO_2 effects are not directly comparable and have much shorter lifetimes. The EU could experiment and lead the way, but the goal remains global climate change mitigation, not just fairness between actors.

- **EU MRV as a foundation step**. It was highlighted that the EU Monitoring, Reporting and Verification system (MRV) is already in place and can be seen as a foundation for future mitigation policies and to provide guidance on next steps. The MRV can be a valuable tool to gather useful knowledge and improve modelling and understanding of non-CO_2 effects. Moreover, the MRV would help the companies to increase their awareness of their non-CO_2 climate impact. There would be the need to facilitate the implementation of MRV by operators and connect it to technology investment policies. Once an increased knowledge is available, probably the best solution for policy design will include a combination of multiple approaches. However, some airline companies are already aware about their climate impact and see the MRV as a useful and not overly burdensome tool. However, it is unclear whether the monitored and estimated climate effect is close to reality, and whether the collected data will really serve science and policymakers to improve policies (e.g., the lack of humidity data – essential information for contrail formation forecast – has been mentioned).
- **Incentive effect of market-based measures for climate-optimised flight planning**. As mentioned in the “Presentation” Section, DLR presented some slides to show the results of their work on ticket price impact on the trajectory optimisation for contrail mitigation. The key takeaway is that the integration of non-CO_2 climate costs into route planning is technically feasible, can significantly reduce climate impacts and entails modest additional costs for passengers, paving the way for smart and balanced regulation strategies. Some participants noted that this study is conceptual, i.e. based on many assumptions. Thus, it is essential to clearly communicate the uncertainty and sensitivity of the results to these assumptions, to avoid drawing misleading conclusions.

Handling uncertainty and "no-regret" measures

- **Uncertainty overview**. As mentioned in the “Presentation” Section, DLR presented a slide illustrating the three main types of uncertainties determining non-CO_2 climate effects, i.e., uncertainties in weather, climate impact modelling of non-CO_2 effects, and trajectory and emissions modelling. It was suggested that all these uncertainties should be carefully considered in policy-driven flight planning to avoid decisions based on too weak forecasts.
- **Uncertainties in non-CO_2 emission effects are high**. Some participants emphasised that, given the current level of uncertainty of non- CO_2 effects, implementing a policy that might be regretted in the future should be avoided. Specific concerns were raised about future changes in atmospheric chemistry (e.g. NOx climate effects potentially switching from warming to cooling), reinforcing the need for precautionary principles and iterative policy development.
- **However, uncertainty is not an excuse for non-action**. There was broad agreement that uncertainty must not lead to inaction but should inform the design of cautious and flexible measures, especially those including pricing or any similar action.
- **Uncertainties and no-regret measures**. Uncertainties need to be considered, but they should guide towards “no-regret” measures. The “no-regret” term is to be used in the sense that a more than marginal reduction can be reached with an assessed low risk.
- **Give priority to more established aspects?** Some participants suggested to focus initial efforts on more established aspects on which the current understanding and knowledge is at a higher level, e.g., some fuel characteristics such as aromatics content (not only focusing on SAF) which

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shows an increased scientific consensus on their relationship with non-CO_2 effects. Also, in this case, a prudent approach would need to be adopted.

Geographic scope and regional versus global action

- **Prioritise fast regional measure to account for the largest part of the problem**. There was debate over regional versus global solutions. Some participants argued that regional actions, especially regarding Europe and North Atlantic regions, could be immediately effective, since most warming contrails form over those areas. Therefore, a possible effective solution could be to start implementing as soon as possible (e.g., by 2030) a regional measure in those areas, for example through an EU-Canada partnership, and then working on a global solution which will necessarily (as negotiations will take longer) become effective later.
- **Climate change is a global problem**. Many others stressed the need for global frameworks, e.g., promoted by ICAO. Even if such contrail formations manifest in specific areas such as Europe and North Atlantic, the responsibility is global, and solutions should be thought on a global scale consequently. A global action would be preferable, even though much more complex. In this context, it was recalled from some participants that, although global aviation is managed by ICAO, the ultimate responsibility lies with States as parties to the Paris Agreement covering all anthropogenic emissions, including international aviation emissions.

Operational strategies and technological mitigation

- **Reduce emissions at the source**. Some participants highlighted that the priority to reduce aviation non-CO_2 effects should be the reduction of emissions directly at the source, acting on engines and fuels. This approach was seen as the safest as it offers certain benefits, unlike operational measures, such as rerouting, that might, in a few cases, lead to suboptimal or even misleading outcomes due to uncertainties. For example, reducing non-volatile particulate matter (nvPM) lowers ice nucleation, causing larger crystals that fall faster and shorten contrail lifetime. However, new technologies phase in slowly and deliver mitigation only over time, whereas operational measures can be implemented directly. If sufficient emissions reductions are achieved in the future through advances in engine technologies and fuel composition, e.g., SAF, improved lubricant and fuel formulation, emission location might become less important.
- **Dealing with congested airspaces like the European one**. Participants discussed routing strategies to avoid contrail formation areas but also highlighting the added complexity in highly congested airspace such as the European one. Some argued that the problem of European airspace congestion is well known, but more published and verified scientific evidence is needed to justify policy choices related to this issue.
- **Impact could be limited on few flights**. Participants recalled that only a small fraction of flights (e.g., around 2%) may account for a large portion of contrail-related warming, especially those occurring during night time. Therefore, targeted re-routing solutions on those flights could be an efficient strategy.
- **Integrated climate effects**. Some participants pointed out the necessity of simultaneously addressing at least the three main aviation-related emissions, i.e., CO_2 (including life cycle emissions), NO_x, and contrails, to avoid solutions that target only one specific impact while potentially exacerbating others. For example, integrating life cycle emissions into the assessment of climate-optimized re-routing might reduce the expected climate benefit of contrail avoidance, as the additional fuel burn also increases upstream CO_2 emissions (including processes as extraction, refining, transport, etc.) by roughly +30% for conventional fossil-based Jet A-1. The overall goal should be to minimize the net effective climate impact. Some participants argued

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that the real objective would be to find a balance between the certain impact related to CO_2 reduction and still unsure non-CO_2 mitigation impact, a yet unresolved question.

Conclusion and next steps

The workshop provided valuable insights and feedback from participants. Key points included:

- Diverging views on market-based measures, with some advocating for cautious use due to uncertainty, and others emphasizing their flexibility and potential benefits.
- Broad support for starting with regulatory or incentive-based approaches, especially for "no-regret" options.
- Uncertainty should not prevent action but must guide prudent and flexible policy design.
- Recognition that non-CO_2 effects are complex and need better data, with MRV seen as a crucial first step.
- Interest in using MRV data not only for compliance, but also for scientific research and informed policymaking.
- Emphasis on the need for international coordination, while recognising that regional measures (e.g. in Europe and North Atlantic) can have significant impact.
- Integrating climate costs into operational decisions (e.g., flight routing) could lead to win-win outcomes if well designed.

The discussion was productive and valuable, with plans to share quantitative results from the BeCoM project with stakeholders for further feedback. The next steps will involve a larger stakeholder event foreseen for late 2025 (November-December) to include authorities, ANSPs, airlines, weather services, and researchers, to take place in Brussels, Delft, Frankfurt, Hamburg or at another place convenient to reach for most participants.

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Better Contrails Mitigation - BeCoM

Appendix 4

BeCoM Final Stakeholder Workshop: Summary of Discussions

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AGENDA FINAL STAKEHOLDERS WORKSHOP

22 January 2026 | In person (and online)

Meeting date:	22 January 2026
Meeting place/venue:	TU Delft Campus, Aerospace Engineering Faculty, Delft, NL + Teams meeting *Plenary sessions: **Lecture room B*** *Break-out morning session (11.30-12.30): **Meeting room Falco** (max 20 people)* *Break-out afternoon session (Meeting 13:30-14:30): **Meeting room Orion** (max 12 people)*
Participants:	Stakeholders + Consortium partners + Advisory Board members
Contact(s)	Feijia Yin (Scientific Coordinator) | F.Yin@tudelft.nl | +31(0)645 474 809 Oana Trifan (Project Coordinator | o.trifan@tudelft.nl | +31(0) 648 216 211

Thursday 22nd of January 2026

10.00 – 10.30		**Welcome/Coffee/Start of the meeting**	
10.30 - 11.00		Brief presentations of the BeCoM project	
Break-out round I	11.00 12.30	A. Brief presentations of main results so far in the following areas: 1. Measurements 2. Weather models 3. Contrail observation B. Break-out discussions	Philippe Keckhut (UVSQ | Latmos |online) Alexander Cress (DWD) Teodora Petrisor (THALES)
12.30 - 13.30		**Lunch break**	
Break-out round II	13.30 14.30	A. Brief presentations of main results so far in the following areas: 4. Trajectory optimisation 5. Policy instruments B. Break-out discussions	Feijia Yin (TU Delft) Malte Niklass (DLR)
14.30 - 15.30		Plenary: Conclusions by each group / exchange of ideas between groups	
15.30 - 16.30		Recommendations for application/implementation	
17.00	**End of workshop**		

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Summary of discussions

Breakout Group 1: Measurements

The discussion focused on the improvement of water vapour measurements onboard aircraft, which deliver information allowing to better locate contrail formation risk areas. It was noted that such sensors are not the only way to identify and avoid ice-supersaturated regions; however, additional sensors will provide more real data for numerical weather forecast (NWP) and thus help to improve forecasts.

- Both the IAGOS and the AMDAR programme include these measurements. IAGOS is more research-oriented with a higher sensor quality, whereas AMDAR's focus is on improving the detection over a larger altitude profile.
- Today, only a few airlines and routes participate, not sufficient to obtain global coverage.
- It is important to always record cruise altitude with the measurement data; the measurements should be fed into a meteorological assimilation tool.
- Sensors and equipment need to be adapted to everyday airline operation conditions, rather than requiring handling like a research lab experiment.
- It was discussed which minimum number of aircraft with humidity sensors would be needed for global coverage; EUMETNET estimated around 50 aircraft were largely sufficient to cover Europe if the route coverage were selected carefully. For comparison, 10 IAGOS aircraft operate worldwide today, equipped with the ICH sensor (IAGOS capacitive hygrometer). In Europe, 9 aircraft are equipped with AMDAR WVSS II sensors (water vapour sensing system), and about 130 aircraft in the US.
- Airlines require equipment with minimum weight and volume; one airline mentioned that in the past they decided against mounting the equipment because it would have made them lose a passenger seat. Regular maintenance efforts are also not to be neglected.
- This analysis can be different between aircraft types and airlines; it should be identified which operators would provide best benefit. The initial selection of IAGOS operators and routes was made depending on scientific interest and may be different for wider deployment.
- Airlines should be incentivised with other benefits, such as a package of weather sensors including e.g. turbulence detection. Coordination amongst airline alliances to identify most effective routes would be helpful.
- Optimisation of a global ground measurement network (e.g. with Lidar sensors) is a much more complicated task and requires separate discussions. However, some reference stations with multi-wavelengths Lidar measuring both contrail altitude and water vapour as demonstrated by BeCOM could be interesting as Calibration/Validation tools.

Recommendations

- Identify an optimal route network for airborne humidity measurements with global coverage, encourage worldwide participation of airlines

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- Provide onboard measurement equipment with optimised weight and size, best combined with other weather info (e.g. turbulences)
- Identify public funding opportunities, e.g. through Innovation Fund

Breakout Group 2: Weather Models

- Use of weather data for trajectory optimization:
    - Weather forecast data are 4-dimensional, such that the position, extent and movement of ice-supersaturated regions (ISSRs) can be derived.
    - They do not include contrails, so no ambiguity between contrail cirrus and natural cirrus in weather prediction.
    - They are passed to a trajectory optimizer. There different levels of complexity are possible, each requiring different amounts of NWP data, from simple ISSR avoidance over also considering the Schmidt-Appleman-Criterion to even trying to give an estimate of contrail radiative impact. As a simple proof-of-concept, the trajectory optimizer in BeCoM considers ISSRs only in clear sky and then decides based on the extent of the ISSRs, whether rerouting is possible.
    - “Clear sky” is a questionable term, as the transition between clear sky, subvisible cirrus and visible cirrus is smooth. Thresholds can be set for ice water content and/or ice crystal number density to define, what is to be considered a cloud and what a visible cloud. The radiative impact of a contrail is reduced with increasing optical depth of the surrounding cloud.
    - A recent study has found that most contrails occur within some kind of cirrus.
- Any information on upper tropospheric humidity can in principle be assimilated into the weather model and helps to improve the forecast of ISSRs. In-situ (e.g. aircraft) measurements are preferable due to their high resolution.
- There was a request for a comparison of the different available weather models, to find a most reliable source of weather data for trajectory optimization and further improving of the MRV reporting.
    - We are working on a comparison between the DWD two-moment scheme and the DIPS one-moment scheme developed within BeCoM.
    - A comparison of humidity relevant parameters of different NWP weather models between different weather centres is planned within the upcoming SESAR CICONIA Met project.
- Output of DWD’s ICON version with two-moment scheme are currently available for MRV reporting, but
    - the model version is not yet run operationally. So, there is a risk that sometimes data may be unavailable. It was nevertheless noted that for the year 2025 all needed weather data have been made available for the MRV.
    - ICON is still being adapted to the new scheme. The forecast is not yet tuned optimally. The integration of the of the 2-moment cloud ice micro physic scheme

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into the ICON model looks difficult. Hence DWD will integrate the scheme instead into a special version of ICON.
    - the special ICON version including 2-moment scheme is planned to become fully operational by the end of 2026, implying better performance compared to current version.
- Data of the DIPS scheme, developed within BeCoM, are not available for MRV reporting. If weather centres are interested, it might become part of an operational weather model in the future.

Breakout Group 3: Contrail observation

Topics discussed:

- How to best exploit satellite sensors and link them to post-flight analysis (2 tools pointed out that could help reduce manual scanning through flights)
- Discussion about MTG performance with respect to MSG and about the utility of combining with ground/other sensors
- How far can we go with radiative effect estimation and what can be done about very thin/short contrails missed by satellite sensors.
- An ANSP raised the question of looping back to predictions and how it is key to go beyond individual contrails and towards climate sensitive areas (the impact on network/sector capacity is very high and needs to be taken into account)

During the restitution session afterwards, a lot of discussions turned around this ANSP perspective and the need for the aviation sector to work on better automatising the flow between ATM, Network Manager and the other stakeholders.

The accuracy level of the predictions and the available capacity of analysing satellite data for large numbers of flights was also brought up again (in reference to D-KULT). However, for a proper validation of climate response models and their predictions regarding the effects of contrails, it is required to analyse a considerable number of flights and a corresponding amount of satellite data.

Breakout Group 4: trajectory optimization

The discussion focused on the trajectory optimization for climate impact mitigations. The following aspects were discussed:

- Two possible means of contrail avoidance were discussed, i.e., closing certain airspaces vs. optimising certain flights. The former appeared easier in procedure but is heavily dependent on the airspace capacity. For the latter, identifying the saturation effects of contrails for individual flights is essential.

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- The "100 flights" initiative of the D-KULT project performed trial flights for contrail avoidance. While the outcome is being analysed, this procedure, first in its kind, required intensive coordination between different stakeholders. This demonstrated the complexity of large-scale implementation, and the need for automatised flight planning tools to upscale trajectory optimisation.
    - This is interesting since during the shadow mode trial in CONCERTO, only limited effects on operations were observed (the airspaces considered have low/medium traffic though)
- While contrails are one driving parameter for operational mitigation measures, the impact on other effects, e.g., CO_2 and NO_x, requires robust evaluation.
- Airspace capacity differs per airspace, hence also the mitigation potential. It was noted that contrail avoidance appears as a cost-effective measure over certain regions and flight corridors,

Recommendations:

- Assess the network constraints (as an additional type of airspace constraints, similar to, e.g., turbulence-prone zones) in trajectory optimizations to avoid contrail/climate sensitive regions.
- Climate-optimized trajectories depend heavily on different climate models. The quality of the models requires thorough evaluation, for instance, using real life flight performance data.
- Contrail avoidance can also change the climate impact from other species, for instance, CO_2/NO_x. It is essential to consider such interdependency during flight trajectory optimizations to minimize the mitigation risk.

Breakout Group 5: Policy instruments

An engaged discussion took place on the model assumptions and the robustness of the previously presented simulations of policies on non-CO_2 emissions and cost burdens.

- There was agreement that reducing non-CO_2 climate impact is important, but that it involves a trade-off between more certain long-term CO_2 effects and more uncertain short-term non-CO_2 effects, which implies that a metric needs to be chosen (GWP100 with efficacy applied was mentioned as example), this being ultimately a political rather than a purely technical choice. In conclusion, it was thus noted that reduction of both CO_2 and non-CO_2 should be pursued in parallel.
- Emissions trading is usually the most efficient way to address negative externalities, but uncertainty about non-CO_2 effects means that other policies should be taken into account as well.
- There are many policies in place, and although non-CO_2 policies alone may not impose a large burden on airlines, the cumulative effect of multiple climate policies could be significant. It would therefore be interesting to analyse all policies jointly.
- The geographical scope and the question of where to start were discussed.

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- There was agreement that data and information exchange between airlines and researchers is important and will be pursued in order to improve modelling.
- Note that fuel burn penalties to avoid contrails increase the use of energy and CO_2 emissions (lifecycle to be considered) plus they increase NO_x and PM emissions from the aircraft, which would be against the basic principle of environmental protection.

Summary of final plenary discussions

For each of the 5 breakout groups, the moderator gave a summary of the outcome, followed by a plenary discussion on the topic.

- **Group 1 – Measurements**
  - It was discussed if the benefit of additional airborne humidity measurements justified the extra cost and effort of equipping more aircraft. The benefit of these measurements was widely seen, while not considered a necessity. The CICONIA project is investigating the usefulness of more comprehensive humidity data in weather models; further studies might be necessary in this context.
- **Group 2 – Weather models**
  - Weather forecast output does not include any contrails, since NWP models do not have any information about flight plans. This is not necessary, since contrails have limited influence on the evolution of the weather (cf. Schumann & Seifert, 2025, https://doi.org/10.5194/egusphere-2025-4512).
  - DWD's two-moment scheme will be available for full operational use by end of 2026.
- **Group 3 – Contrail observation**
  - In the D-KULT project, TF100-flight trial, some post-flight analyses of satellite images were done.
  - Various available tools, e.g. MCAST (MIT) and Contrails Explorer (Google) provide similar info.
  - ANSPs stressed the importance of real-time data collection and processing for entire airspace sectors.
  - Avoiding contrails can lead to up to 60% capacity reduction, with often high manual workload for ANSP and an impact on the network manager, especially in the beginning of such practices.
  - Note that many ISSRs have an inhomogeneous thickness distribution, with an average thickness above 4000 ft.
  - Newly developed climate response tools need validation; a methodology for this is currently under development, with a need for some agreed reference ("ground truth").
- **Group 4 – Trajectory optimisation**
  - Flight trial campaigns are being planned for the near future. What would the size of blocked airspace be? This would determine options for detours, under- and overflying.
  - In D-KULT, a collaboration chain was established, including weather data (DWD/DLR) and new models and flight planning tools in a real-life experiment. In results interpretation, characterisation of unavoided contrails (when deviation was not possible

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– so-called observer flights) is as important as successful contrail avoidance. Such flights offer the opportunity to test the prediction quality of the underlying processes, including meteorological data and climate response models.
- Work with 9 ANSPs showed large differences in capability for contrail avoidance, depending on airspace capacity. The CONCERTO project works on automation of avoidance.

- **Group 5 – Policy instruments**
  - The different time horizons of climate impact of CO_2 and contrails need to be kept in mind.
  - Implementing the non-CO_2 MRV is mandatory. However, while ETS is considered by various experts to be a promising policy instrument for regulating non-CO_2 impact, other policies should be investigated as well.
  - ICAO is doing extensive work on non-CO_2 emissions:
    - Standard development for cruise NOx reduction,
    - White papers by the Impact Science Group (ISG),
    - A large symposium on non-CO_2 emissions in 2024, which raised awareness in wider parts of the world,
    - Investigation of the feasibility of a concept of “non-CO_2 as a commodity”,
    - (No MRV concept at global level yet).
  - Relevant initiatives in Europe that were mentioned in the discussion:
    - Aviation Non-CO_2 Expert Network (ANCEN), sponsored by EASA
    - UK ATI report on contrails
    - Swiss work on measurement and technical reduction of NOx and particulate matter (PM).

Final recommendations

- **Group 1 - Measurements**
  - Improve (weather prediction through enhanced humidity measurements onboard aircraft
    - Cost-benefit analysis for additional measurements
    - Identify optimal flight route coverage, encourage worldwide airline participation
    - Provide optimised (low-weight, low-volume) measurement equipment, best combined with other weather info (e.g. turbulences)
    - Public funding, e.g. through Innovation Fund
- **Group 2 – Weather models**
  - Intercomparison of weather models between weather centres
  - Scheme developed at DLR to be offered to weather services beyond DWD, including ECMWF
- **Group 3 – Contrail observation and modelling**
  - Promote further the link between models and observations
    - Life-trial campaigns

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    - Scalability of models

- **Group 4 – Trajectory optimisation**
  - Develop and promote use of automatised flight planning tools that integrate non-CO_2 mitigation
  - Check feasibility of optimised trajectories (e.g. from DLR study)
  - Enhance validation and verification of simulations vs observations,
    - Not only to check if contrails were successfully avoided, but also if predicted contrails were actually created (false & true positive / negative)
  - Include effect of other emission species (NOx, PM) in tools to determine climate-optimised flights
  - Use of non-CO2 MRV data available from 2026
- **Group 5 – Policy instruments**
  - Collaborate with airlines
    - Share data for modelling
  - Extend analysis from single flights to full airspace
  - Include more policy options in addition to those studied (“climate charges” and closure of airspace portions)
  - Identify and involve organisation in charge of collecting climate impact parameters (ICAO? WMO?)

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Workshop participants

Breakout groups						
Morning	Afternoon	First name	Family name	Organisation	Stakeholder group	Participation
1	4	Dunya	Alraddawi	IPSL	BeCoM team	online
1	4	Sián	Andrews	NATS	ATM	online
2	5	Ignacio	Bañeres	AESA	Authorities	online
2	5	Peter	Bechtold	ECMWF	Met services	online
2	4	Björn	Beckmann	Deutscher Wetterdienst	Met services	in person
	5	Denis	Bilyarski	ENV-ISA	BeCoM team	in person
3	5	Grégoire	Boussu	Thales	BeCoM team	in person
3	5	Irène	Boyer-Souchet	Air France	Airlines	online
2	4	Federica	Castino	TU Delft	BeCoM team	in person
2	4	Victoire	Crespel	Transavia	Airlines	cancelled
2	4	Alexander	Cress	Deutscher Wetterdienst	BeCoM team	in person
3	4	Pierre	Crispel	Météo France	Met services	online
3	5	Federica	Crova	ENV-ISA	BeCoM team	online
2	5	Robin	Deransy	Eurocontrol	ANSPs	online
1	4	Christoph	Deseure	Thales AVS	ANSPs	online
1	4	Niels	Dettmann	Transport Ministry (DE)	Authorities	online
2	5	Davide	di Giusto	Thales	BeCoM team	online
1	5	Niclas	Dzikus	EC DG RTD	Authorities	online
3	4	Nellie	Elguindi	IATA	Airlines	online
1	4	Simon	Fossier	Thales	BeCoM team	in person
2	4	Cécile	Gajate	EC DG MOVE	Authorities	cancelled
2	5	Klaus	Gierens	DLR	BeCoM team	in person
1	5	Marco	Groot	KLM Royal Dutch Airlines	Airlines	in person
		Justo	Hernández Soto	DGAC (ES)	Authorities	online
3	4	Olaf	Hölzer-Schopohl	UBA /DEHSt	Authorities	online
2	4	Julian	Jene	Lufthansa	Airlines	online
1	4	Philippe	Keckhut	UVSQ/CNRS	BeCoM team	online
2	5	Kay	Köhler	UBA (DE)	Authorities	online
		Michael	Kyriakopoulos	EC DG RTD	Authorities	online
3	4	Ralph	Leemüller	DFS	ATM	online
2	5	Michael	Lunter	Infrastructure Ministry (NL)	Authorities	in person
3		Sigrun	Matthes	DLR	BeCoM team	online
3	4	Vincent	Meijer	TU Delft	BeCoM team	in person
3	5	Olivier	Meynot	DGCA (FR)	Authorities	online
1	4	Mario	Morales	AESA	Authorities	online
1	5	Malte	Niklaß	DLR	BeCoM team	in person
2	5	Dimitar	Nikov	EC DG Clima	Authorities	in person
3	4	Teodora	Petrisor	Thales	BeCoM team	in person
2	4	Matthieu	Plu	Météo France	Met services	online
1	5	Ulrika	Raab	Transport Agency (SE)	Authorities	online

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3	4	Babette	Reimann	Ministry of Economics (DE)	Authorities	online
2	4	Theo	Rindlisbacher	FOCA (CH)	Authorities	online
3	4	Ricardo	Rocha	SWISS	Airlines	in person
1	5	Thomas	Rötger	ENV-ISA	BeCoM team	in person
3	5	Martina	Sahliger	Transport Ministry (DE)	Authorities	online
3	5	Gerd	Saueressig	Lufthansa	Airlines	online
1	5	Megan	Segeren	SWISS	Airlines	in person
1	5	Leonidas	Siozos-Rousoulis	CINEA	EC	online
		Jakob	Smretschnig	TU Delft	BeCoM team	online
3	5	Lukas	Söffing	NLR	Research	in person
2	4	Dario	Sperber	DLR	BeCoM team	in person
1	5	Christoph	Todt	Tuifly	Airlines	online
1	5	Oana	Trifan	TU Delft	BeCoM team	In person
3	4	Philippe	Véry	Eurocontrol	ANSPs	online
3	5	Florian	Wozny	DLR	BeCoM team	in person
1	4	Feijia	Yin	TU Delft	BeCoM team	in person

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