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Better Contrails Mitigation - BeCoM

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D5.1

The development and calculation of robust algorithmic cost functions for climate change of H_2O, NO_x, and contrail cirrus

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Executive Summary

This deliverable and the associated work package (WP) contribute to objective (5) targeting the integration of non-CO2 effects (e.g. contrails) into current policy schemes, such as the revised EU Emission Trading System, ICAO CORSIA and EU Green Deal. For this purpose, existing and discussed policies for non-CO2 effects are reviewed. Based on the analysis, requirements are derived for the integration of non-CO2 policies into flight planning and trajectory optimization.

In our approach, a policy-driven flight planning for non-CO2 effects must consider i) what emissions aircraft release into the atmosphere, ii) where these emissions occur, and iii) how the atmosphere responds to these emissions. To address the first two questions, the policy needs to consider combustion processes of the fuel, engine and aircraft performance as well as the flight path, at least in three dimensions (latitude, longitude, altitude). The third point concerns the response of the climate system to the various non-CO2 effects, which differ greatly in their atmospheric lifetimes and meteorological conditions. This requires the application of rapid climate response models for fair calculation of CO2 equivalent emissions (CO2e). For flight planning (pre-flight mode) as well as for monitoring, reporting and verifying (post-flight mode), all stakeholders need to be able to calculate CO2e and the resulting payment obligations in an easy, transparent and predictable way. A conversion of non-CO2 effects into algorithmic cost functions for climate change (aCCC) has therefore been performed. aCCCs are simple linear equations that estimate the costs from aircraft emissions in euros per kilogram of fuel as a function of meteorological conditions at time and location of emissions. As non-CO2 effects account for 8 times more of the uncertainty in the aviation net ERF than CO2, we analyzed options for addressing uncertainties in policy measures and decision parameters for the internalization of climate effects.

To show the suitability of policy driven flight planning for reducing the climate impact of flights, we present the results of a small-scale case study considering CO2e-based accounting for both CO2 and non-CO2 effects. Without non-CO2 accounting, a climate-optimized flight planning has to balance two conflicting objective functions, the minimization of monetary costs (fuel, time, operating costs, etc.) and climate impact (emissions, ERF, ΔT, etc.). When selecting the Pareto-optimal trajectory to be flown, it is therefore necessary to balance the additional costs that are acceptable to achieve the desired savings in climate impact. Political measures can simplify the decision-making process during flight planning. The internalization of climate effects ensures that the climate-optimized flight trajectory is the most cost-effective. This creates a financial incentive for re-routing flights in a climate-optimized way. We assume that all additional costs are fully passed on to passengers. Assuming a CO2 price of 50€ per ton of CO2, the ticket prices of the analyzed routes would increase by between EUR 1 (0.5%) and EUR 7 (3.9%). With higher CO2 prices, the absolute ticket price increase would rise proportionally. These effects on passengers could be moderated by the gradual introduction of non-CO2 accounting.

These results will be extended in the second half of the BeCoM project in both WP4 and WP5.

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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 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. This will also be considered in the course of this deliverable and the scientific work in BeCoM project. Following the analysis of possible policy schemes, a conversion of non-CO_2 effects into algorithmic cost functions for climate change (aCCCs) has been performed in order to provide one-single cost optimal solution in the context of climate-optimized trajectories. In the second half of the project, uncertainties in the assessment process will be studied in particular to develop a concept for the integration of these uncertainties into aCCCs by consideration of stochastic characteristics in policy instruments.

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.

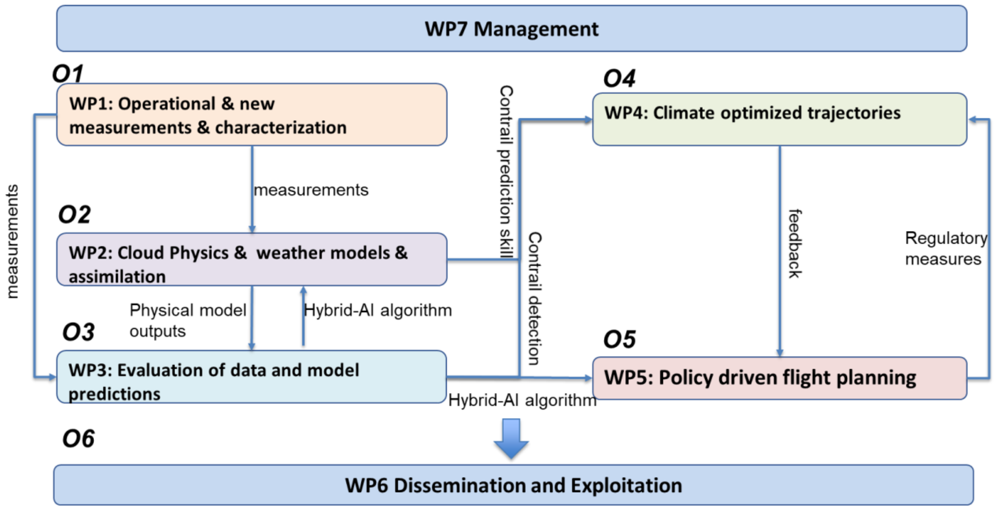

Figure 1. Work package overview of BeCoM project

This deliverable presents the results obtained in WP5 up to month 24 (M24) of the project focusing the development and calculation of robust algorithmic cost functions for climate change (aCCC) and demonstrating their applicability in a case study context. Hence, results from Task 5.1 and Task 5.2 are presented in this document (see Figure 2). Task 5.1 dealt with the review of policy instruments for implementing climate-cost-efficient routing, carried out by DLR and Envisa in the first nine months of the project. This included a review of different CO_2 equivalent (CO2e) approaches incorporating non-CO_2 effects into existing policy instruments like EU ETS or CORSIA (constant CO2e factor, distance-dependent CO2e factor, location-dependent CO2e factor, etc.) as well as a review of flanking policy instruments for non-CO_2 effects. Finally, the findings led to the deduction of specifications for integrating price-based non-CO_2 policies into flight planning and trajectory optimization. Task 5.2 consisted of evolving a methodology for integrating non-CO_2 policies into flight planning and trajectory optimization, which was performed by DLR. This included the development of an algorithmic concept characterizing weather-dependent climate charges of aircraft emissions at a given location and time (4-D cost functions for climate change, aCCCs) as well as the elaboration of a monetarization logic quantifying the amount of emission certificates to be surrendered or respectively the level of emission charge to be paid per climate impact of CO_2, H_2O, NO_x and contrail-cirrus. 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.

In the second half of the project, the focus is on the third and final task of assessing the effectiveness of the developed policy-driven flight planning approach, which will be addressed by DLR, TU Delft, Thales and Envisa. This includes the expansion of a direct operating cost model with climate charges,

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which can be fed into the trajectory optimization in close collaboration with WP4. Furthermore, a parametric analysis of the developed algorithmic cost functions will be performed to enable robust climate-sensitive flight planning. Finally, the optimization results from WP4 will be analyzed to evaluate the developed climate policy concept from both scientific as well as Stakeholders' perspective.

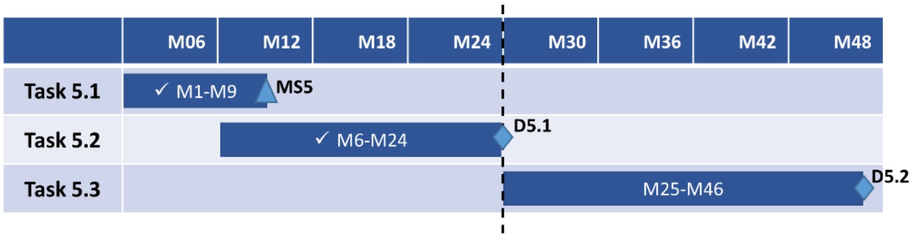

Figure 2: Gant Chart for WP5

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. On this basis, a demonstration case study is evaluated in Chapter 4, before we conclude this document with a final summary and outlook in Chapter 5.

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2 Review of policy instruments for implementing climate-cost-efficient routing

Climate-optimized rerouting approaches are based on multi-objective optimization (Pareto optimizations) that aim to minimize both monetary parameters (such as flight time, fuel consumption, and/or operating costs) and climatological variables (including 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).

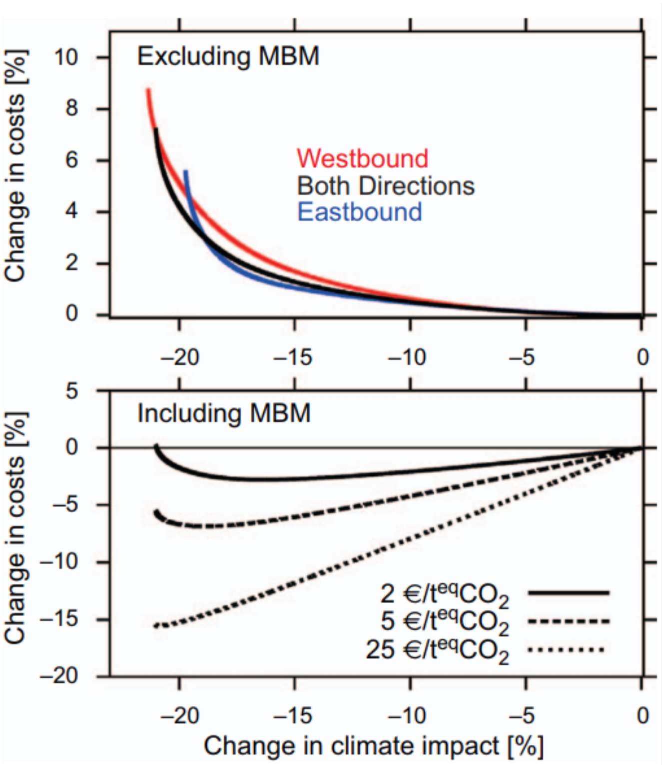

Figure 3: Top: Optimal climate-cost relations of trans-Atlantic air traffic for 5 winter and 3 summer days (averaged over the climatological frequency). West- and eastbound traffic is given relative to the climate impact of aviation flown west- and eastbound at minimum costs, respectively. Bottom: inclusion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

When selecting the Pareto-optimal trajectory to be flown, it is therefore necessary to balance the additional costs that are acceptable to achieve the desired savings in climate impact: +1% costs for -10% climate impact mitigation or +5% costs for -20% climate impact mitigation? By internalizing the climate impact (converting into costs or CO_2 equivalents), decision-making can be simplified. This requires policy instruments for non-CO2 effects.

2.1 Overview of Non-CO2 Policy Instruments

Various policy concepts for non-CO_2 effects have recently been proposed in the literature. Most concepts try to integrate non-CO_2 effects into existing market-based measures (MBMs), like EU ETS or CORSIA, based on the principle of equivalent CO_2 emissions (CO2e), a way of standardizing the climate impact of all climate agents (see Section 2). As non-CO_2 effects are not yet fully understood and still linked with medium to high uncertainties (Lee et al., 2021), no environmental policy instruments have

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yet come into force in aviation for non-CO_2 effects. Nevertheless, on December 8, 2022, the European Union decided to expand the EU emissions trading system (EU ETS) to include non-CO_2 effects. According to the amendment, non-CO_2 effects should be covered by a monitoring, reporting, and verification system (MRV) from 2025 as a first step towards full integration into the EU ETS (EU, 2022). Research is also being conducted whether non-CO_2 effects can be mitigated more effectively and efficiently by designing flanking instruments. These can be differentiated into price-based and regulatory policies, as follows.

Flanking Price-Based Policies for Non-CO_2 Effects:

Flanking price-based policies for non-CO2 effects include:

- Charge for NO_x emissions during cruise, landing, and take-off (Faber et al., 2008)
- Introduction of weather-dependent climate charges in highly climate-sensitive regions (climate-charged airspaces) as an incentive for climate-optimized rerouting (Niklaß et al., 2020, 2022)

Flanking Regulatory Policies for Non-CO_2 Effects:

Flanking regulatory policies for non-CO2 effects include:

- Cruise certification standard for NO_x emissions (Wit et al., 2004)
- Altitude restrictions for commercial aircraft for reducing the likelihood of contrail formation (Williams et al. 2002, 2003)
- Introduction of weather-dependent non-fly zones in highly climate-sensitive regions (climate-restricted airspaces; Niklaß et al., 2017, 2019)

2.2 Calculating CO_2 Equivalent (CO2e) Emissions for Non-CO_2 Effects

CO2e are a common metric for unitizing the climate impact of various climate agents. Since CO_2 is a particularly long-lived greenhouse gas, its climate impact is well understood. Therefore, it is reasonable to express the impacts of non-CO_2 effects in relation to the impacts of one kg of CO_2. For a given type and amount of a climate agent i, resulting CO2e cause the same climate response (e.g., RF or ΔT) over a specific time horizon (e.g., 20, 50, or 100 years), so that the total CO2e from CO2 and non-CO2 effects can be described as:

$$CO2e_{total} = CO_2 + \sum_i CO2e_{agenti}$$

In principle, there are several CO2e calculation methods available that are designed for different applications and differ, among other things, in the accuracy of the climate assessment. The higher the accuracy of relevant atmospheric processes can be described, the greater is the incentives for climate mitigation. But, however, more accurate CO2e approaches will also require a higher amount of data for monitoring, reporting, and verification. The selection of a CO2e calculation method is therefore a trade-off between high climate mitigation incentives and low efforts for MRV activities.

Key criteria for choosing a CO2e method are therefore:

- CO2e factors must provide incentives for actually reducing non-CO_2 effects (not simply adding costs but providing the possibility to reduce climate impact and the cost of operation)
- CO2e factors should be easily calculable, predictable, and transparent

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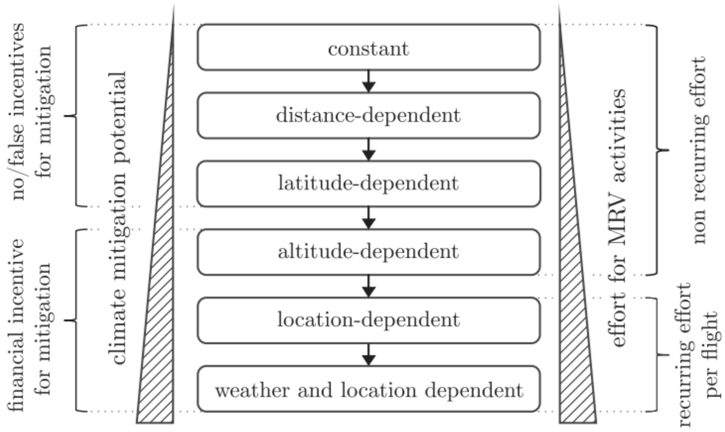

Figure 4. Mitigation benefit and effort for monitoring, reporting and verification (MRV) activities of different CO2e calculation methods (adapted from Niklaß et al., 2020, p. 43)

Simple CO2e factors (constant, distance- or latitude-dependent, see Figure 4) are heavily criticized and proven to be inappropriate since they further increase the focus on CO_2 reduction, might create false incentives (an incentive to fly higher rather than lower), and "penalize" climate-cost-efficient routings (due to the increased fuel burn) (Forster et al., 2006; Niklaß et al., 2020; Dahlmann et al., 2021). In order to avoid misguiding incentives, at least the altitude dependency of non-CO_2 effects has to be considered in the CO2e calculation method (Faber et al., 2008; Niklaß et al., 2020). This requires at least detailed information about the aircraft trajectory (altitude profile). Significantly higher non-CO_2 mitigation incentives can be generated by location-dependent or weather- and location-dependent CO2e factor that take the entire 4D flight profile into account.

2.3 Non-CO_2 policies in European context: Revision of EU ETS and establishment of a non-CO_2 MRV system

In December 2022, a revision of the European CO_2 emissions trading system (EU ETS) was agreed at trilateral meetings of representatives of the European Parliament, the European Commission and the European Council. According to the agreement (European Union, 10 May 2023), the EU ETS is being realigned with the ambitious European climate protection target, which aims to significantly reduce emissions by 55% by 2030 compared to 1990 levels. This revision involves a multi-layered approach. Firstly, the number of emission allowances permitted each year will be significantly reduced by increasing the linear reduction factor (LRF) from the current 2.2% to 4.3% between 2024 and 2027. In addition, a rapid phase-out of the free allocation of aviation allowances (EUAA) is planned, which should be completed by the end of 2025.

Beyond CO_2 emissions, attention is also directed towards non-CO_2 climate effects of aviation. Starting from January 1, 2025, non-CO_2 aviation climate effects shall be covered by a monitoring, reporting and verification (MRV) framework as a first step towards full integration into the EU ETS. From this date, member states must ensure that aircraft operators calculate and CO2e emissions per flight. Implementing an effective non-CO_2 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 shall therefore submit an assessment report on the application of the MRV framework and, if appropriate, a legislative proposal to mitigate the non-CO_2 impacts of aviation by extending the scope of the EU ETS to non-CO_2 impacts of aviation.

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2.4 Requirements for integrating non-CO_2 policies into flight planning and trajectory optimization

From the literature analysis, we derive the following requirements for non-CO_2 policies in aviation:

- **Consideration of various Non-CO_2 Effects:** The approach should account for various non-CO_2 effects, including contrail-induced cloudiness (CiC), NO_x emissions, and water vapor emissions, among others.
- **Weather dependency consideration:** Given the strong dependency of non-CO_2 effects on weather conditions, particularly CiC, the approach should integrate weather data and forecasts into its optimization algorithms.
- **Generation of financial incentives:** The approach should incentivize airlines to reduce both CO_2 and non-CO_2 emissions by incorporating financial mechanisms that reward environmentally friendly practices.
- **International and regional applicability:** It should be feasible to implement the approach on both international and regional scales, ensuring compatibility with existing regulatory frameworks such as EU-wide policies.
- **Simplicity in monitoring, reporting, and verification:** The approach should facilitate straightforward processes for monitoring, reporting, and verification, ideally leveraging automation to streamline these tasks.
- **Ease of understanding, predictability, and transparency:** It should be easy for stakeholders to comprehend the rationale behind the approach, predict its outcomes, and ensure transparency in its application and results.
- **Adaptability to scientific understanding:** Given the inherent uncertainties in climate science, the approach should be adaptable to accommodate evolving scientific knowledge and uncertainties, allowing for adjustments based on new findings or improved understanding.

For policy-driven flight planning, the following additional requirements shall be fulfilled:

- **Applicability for various Non-CO_2 Policies**: The approach should be flexible and adaptable to accommodate different types of non-CO_2 policies proposed for aviation.
- **Ease of applicability in daily operations:** The approach should enable operators to perform environmentally friendly flight planning and execution under realistic conditions (e.g. congested airspace) and avoid penalizing them for operational behavior they cannot influence.

These general requirements have been derived in the course of the project in parallel to the EU decision to revise the EU ETS. Despite the fulfillment of these requirements, we focus on the alignment of policy driven flight planning (WP5 in BeCoM) and the European non-CO_2 MRV framework.

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3 Schematic for integrating price-based CO2e in operational flight planning

For integrating non-CO_2 climate effects of aviation into climate policies and 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, we 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, the flight path of the aircraft must be taken into account, at least in three dimensions (latitude, longitude, altitude), 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 fair calculation of CO_2 equivalent emissions (CO2e).

For flight planning (pre-flight mode) as well as for monitoring, reporting and verifying (post-flight mode), all stakeholders need to be able to calculate CO2e in an easy, transparent and predictable way (Section 2.4). In order to reduce the additional effort to a minimum, all necessary calculation steps should automatically be performed by a standardized CO2e software (see Figure 5), possibly provided directly by the regulatory authority (e.g. the EC in case of non-CO2 MRV) or by an approved higher-level organization.

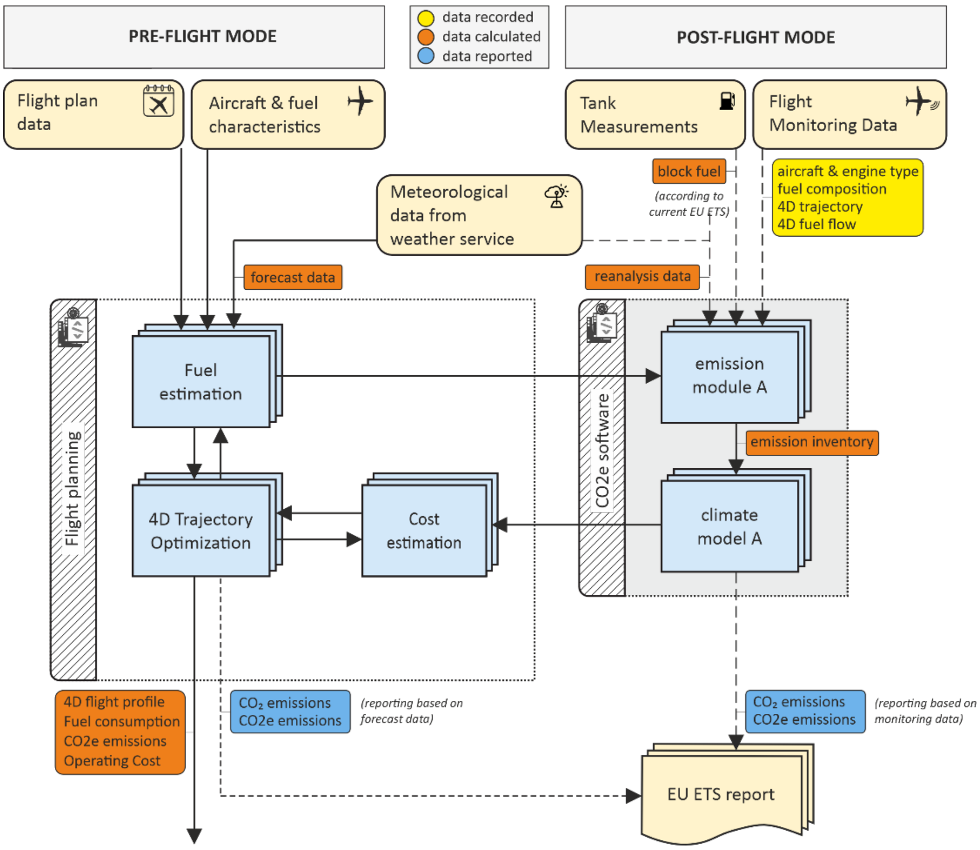

Figure 5. Flowchart for integrating non-CO2 aviation effects into flight planning procedures (pre-flight mode) and monitoring and reporting processes (post-flight mode) of aircraft operators. In order to reduce the operational MRV effort to a minimum, all necessary CO2e calculation steps need to be performed by a standardized CO2e software, possibly provided by a higher-level authority.

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During flight planning, aircraft operators (AOs) use weather forecast data to estimate fuel consumption and operating costs in order to fly the safest and most cost-effective route possible. To enable AOs to estimate CO2e, the standardized software should therefore include

(1) an emissions module that provides emission inventories along the flight path for CO2, H2O and NOx, and
(2) a climate response module for the CO2e estimations of the flight for H2O, NOx, 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)

Analogous to the CO_2 monitoring in EU ETS and under CORSIA, different calculation methods might be made available for both modules. We recommend that AOs can choose between two options: a 'minimum effort solution' based on a climatological model approach regardless of the actual weather situation and a 'full potential solution' offering larger climate mitigation potential, in particular weather-based avoidance of contrail formation and of NO_x effects.

For climate response modelling, a number of different climate models are available, 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). For the minimum effort solution, AirClim could be a suitable model. For a full potential solution, aCCFs for all climate forcers or CoCiP for consideration of contrail cirrus effects could be applicable models.

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. ATR50, GWP100) and the share of calculated CO2e that is monetized (e.g. based on uncertainty intervals). The monetarization is done by multiplying the accounted CO2e value with a carbon price, e.g. for emissions allowances (EUAA).

3.1 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 trajectory and emissions modelling
(3) Uncertainties in climate impact modelling

Weather-related uncertainties can be addressed by incorporating different forecasts or ensembles of meteorological data sets (e.g. available from European Centre of Medium Range Weather Forecast, ECMWF). The standard deviation for persistent contrail formation for ten ensemble data sets areas is displayed in Figure 6 based on an evaluation of algorithmic climate change functions in the project FlyATM4 (Dietmüller et al. 2023, Simorgh et al. 2023). The figure shows large areas without persistent contrail formation (standard deviation of zero) as well as small areas where contrails form in every of the ten considered meteorological ensembles. Especially at the boundaries of these predicted areas of persistent contrail formation, we observe higher standard deviations as the ensembles differ in the prediction of persistent contrail formation areas based on variations in temperature and relative humidity. The uncertainties can be considered and investigated in the CO2e-pricing of non-CO_2 effects, for instance by considering different weather ensembles in the analysis. In a very conservative approach, consideration of CiC effects can, for instance, be reduced to areas of contrail formation in all considered ensembles.

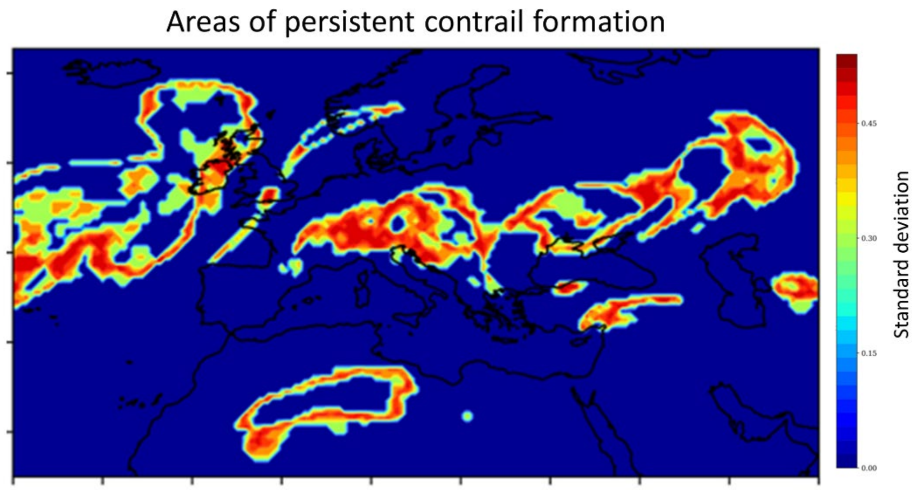

Figure 6: Standard deviation for areas of persistent contrail formation calculated with Clim-ACCF library resulting from FlyATM4E project (according to Simorgh et al. 2023)

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. Typically, 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, 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 CO2 and H2O, emissions of nitrous oxides (NOx) are a by-product caused by oxidation of nitrogen contained in the air, under high combustion temperatures. Hence, NOx 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 NOx 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 & 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. These fuel flow correlation methods are associated with uncertainties of approximately up to +/- 10% for NOx emissions during cruise (Schaefer & Bartosch 2013). We will exclude these uncertainties from assessing policy-driven flight planning, since they are significantly smaller than meteorological and climate assessment uncertainties. 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.

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Furthermore, there are major uncertainties in modeling the climate impact of non-CO_2 effects. This is primarily due to the fact that the atmosphere is an extremely complex system 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 is providing best estimates of the effective radiative forcing (ERF) for all relevant climate effects and the 5-95% confidence intervals, respectively.

The confidence interval of each climate agent could be factored into the CO2e accounting to incorporate uncertainties in climate impact modeling in policy measures. This means that emitters must provide allowances for all non-CO_2 effects with a confidence level of e.g. greater than 80%. In this case, only the 20% percentile of the climate impact of the respective trace substance is included in the CO2e accounting. To implement this approach, we have estimated the probability density function for cirrus contrails (see Figure 7) and nitrogen oxides (see Figure 8) assuming a Gaussian normal distribution and a Pearson distribution, respectively. According to the assumed distributions, we obtain an ERF of 37.0 mW/m^2 for CiC (64% of the median value of 57.4 mW/m^2) and an ERF value of 8.8 mW/m^2 for NO_x (56% of the median value of 17.5 mW/m2) at a 20% percentile, which could be used for the following assessment of uncertainty effects.

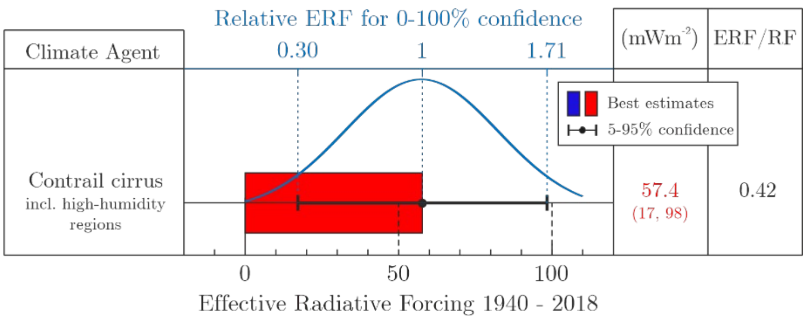

Figure 7 : Estimated probability density function for cirrus contrails assuming a Gaussian normal distribution (derived from Lee et al., 2021)

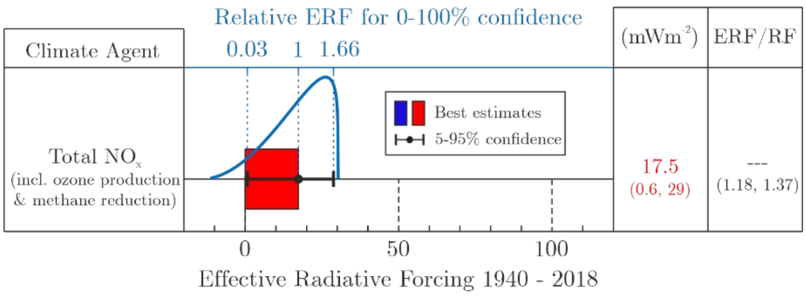

Figure 8 : Estimated probability density function for nitrogen oxides assuming a Pearson distribution (derived from Lee et al., 2021)

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3.2 Key parameters for internalization of climate effects

For the integration of non-CO_2 climate effects of aviation into policy measures, the following decision parameters must be defined, which strongly influence the amount of allowances to be surrendered, the level of climate charge to be paid or the number of offsets to be purchased:

- **Selection of climate agents**:

CO2 and non-CO2 are significant contributors to climate impact of aviation. Despite substantial improvements in the level of scientific understanding of non-CO2 effects, it is their nature, i.e., the dependence on meteorology, that largely limits the reduction of uncertainties. Therefore, risk assessments are essential to better understand how these uncertainties affect the calculation of non-CO2 effects and the potential for setting inappropriate incentives. The selection of individual climate agents greatly influences the level of CO2 equivalents (climate impact assessment) as well as the resulting effort for operationalization (required dataset for MRV scheme). A stepwise integration of various non-CO2 effects is generally feasible; however, the most significant climate agents should be included from the outset. Excluding them would remove the incentives for mitigating their climate impact. Focusing only on the mitigation of a single non-CO2 effect would risk increasing the total climate impacts caused by unintended interactions. It is therefore not only the level of uncertainty that should decide whether an agent should be integrated into a policy measure or not, but also its share to the total climate impact and a clear knowledge of its direction (warming or cooling).

- **Selection of climate metrics**:

Climate metrics can be described as a combination of 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 choice of time horizon depends significantly on the specific question being addressed (Grewe et al., 2015). If the goal is to mitigate climate change in the near future, a short time horizon, such as 20 years, would be appropriate. Conversely, for long-term sustainable aviation, a longer time horizon, such as 100 years (as used in the Kyoto Protocol), would be necessary. When assessing the impact of a single flight, it is recommended to use pulse emissions as the emission scenario. In contrast, constant emissions are preferred for analyzing the mitigation potential of new aircraft technologies used over several years to decades. The choice of emission scenario significantly influences the weighting between short- and long-lived climate agents. Selecting pulse emissions with a long-time horizon emphasizes long-lived species (e.g., CO2), whereas constant emissions with shorter time horizons focus on short-lived species (e.g., contrail cirrus, O3) as their significant impact is more immediate.

- **Accounting options for CO2e:**

Different accounting options are conceivable, 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 modeling climate impacts into policy measures, also the confidence interval of each climate agent could be included in the CO2e accounting. For this we see the following options, which will be investigated as part of the project:

a. Full accounting where uncertainties are not considered, i.e. emitters hold permits for all calculated CO2e

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b. Gradual introduction of CO2e accounting, i.e. emitters hold permits for, e.g., 20% of calculated CO2e in the first year after the introduction, and increasing shares for the following years
c. CO2e accounting within a confidence interval to account for significant uncertainties in the assessment of non-CO2 effects, i.e. emitters hold permits for all non-CO2 effects within a certain confidence level of e.g. 80%.

Moreover, the certificate price influences the cost per CO2e, thus the relation of climate cost compared to operating cost. Higher CO2 prices are expected to lead to higher trajectory adaptations. In the EU ETS, prices of emissions allowances (EUAA) have fluctuated greatly since 2012 when the aviation sector was included. From 2012 to 2019, the price remained well below 20 euros, then rose to around 80 euros in 2022, fluctuated around this value from 2022 to 2023, and dropped to around 50 euros in April 2023. Future prices of EUAAs are hard to predict as they reflect the interaction between supply and demand. In view of the revision of the EU ETS with an increasing Linear Reduction Factor (LRF), expiring free allocations, and the potential integration of non-CO2 effects, a further price increase seems most likely. If non-CO2 effects shall be integrated into the EU ETS, they can either be included under the current emissions limit (cap) and counted against CO2 limits or managed under a separate for non-CO2 effects. In both cases, it must be decided if and by how much the overall emissions limit should it be increased. A policy decision that might highly influence the prices of emissions allowances.

- **Geographical scope of the policy:**

The geographical scope must be defined taking into account political, legal and climate impact reduction considerations. For instance, debates are ongoing between a full scope integration of non-CO2 effects into the MRV scheme including all flights from and to the EU and a regional integration limited to intra-European flights. A full scope would include long-distance flights with higher mitigation potentials which are legally more complex to address. These aspects are not covered in the course of the BeCoM project.

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4 Demonstration of policy driven flight planning

To show the suitability of policy driven flight planning for reducing the climate impact of flights, the following chapter presents the results of a small-scale case study considering CO2e-based accounting for both CO_2 and non-CO_2 effects. These results will be extended in the second half of the BeCoM project in both WP4 and WP5.

4.1 Case study definition

Due to a focus on the European region, we analyzed the intra-European flight schedule based on Sabre Market Intelligence data base (Sabre MI). We apply filter to the aircraft type (set to Airbus A320 or A320neo) and a minimum flight distance of 750 km. We pre-select routes based on the covered traffic volume in terms of available seat kilometers (ASK) as indicated in 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 9) over a sample of possible analysis days considering the respective weather situation.

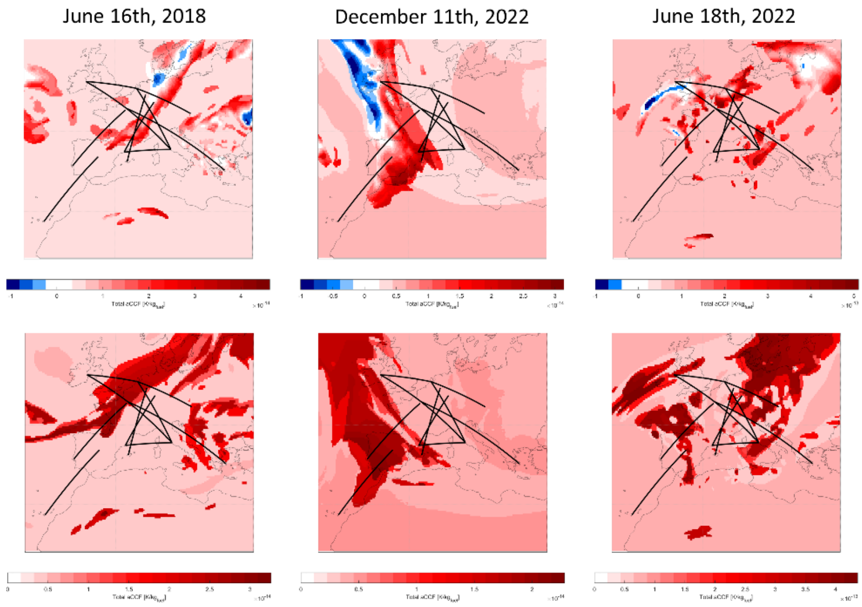

Figure 9: Top-10 routes for selected days and times (day-time and night-time).

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 9 shows a large area of contrail formation along the route during daytime (12 UTC) and no contrail formation during night time (00UTC).

The climate impact assessment in this context will be performed based on algorithmic climate change functions (aCCFs) in Version 1.0A (Matthes et al. 2023, Dietmüller et al. 2023). In addition to CO2, we will consider H2O, NOx, and CiC as non-CO2 climate forcers. The operating cost assessment is based on a direct operating cost model developed in the context of the ClimOP project. It is extended with CO_2 and non-CO_2 accounting terms assuming a CO_2 price of 50€ per ton of CO_2, which is equivalently used for CO2e from non-CO_2 climate forcers. This represents the carbon price according

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to EEX for April 2023[1]. Moreover, we consider different accounting options, i.e. full accounting (the emitter requires certificates for 100% of CO2e from non-CO_2 effects) and gradual accounting for accounting shares of 20%, 40%, 60% and 80%. The CO2e are based on pATR100 as a climate metric. Further details on the applied method can be found in section 4.2.

4.2 Models

Demonstrating the applicability of aCCCs is in the following demonstrated for the above-mentioned case study. The climate impact assessment is in this context based on algorithmic climate change functions (aCCFs) as developed in previous European projects ATM4E and FlyATM4E (see Figure 10). Nevertheless, the concept of aCCCs can also be transferred to any other climate modelling, though aCCFs have been shown to be especially suitable in flight planning and trajectory optimization with regard to climate. The optimizations are performed with DLR LV's trajectory optimization module in python (pyTOM).

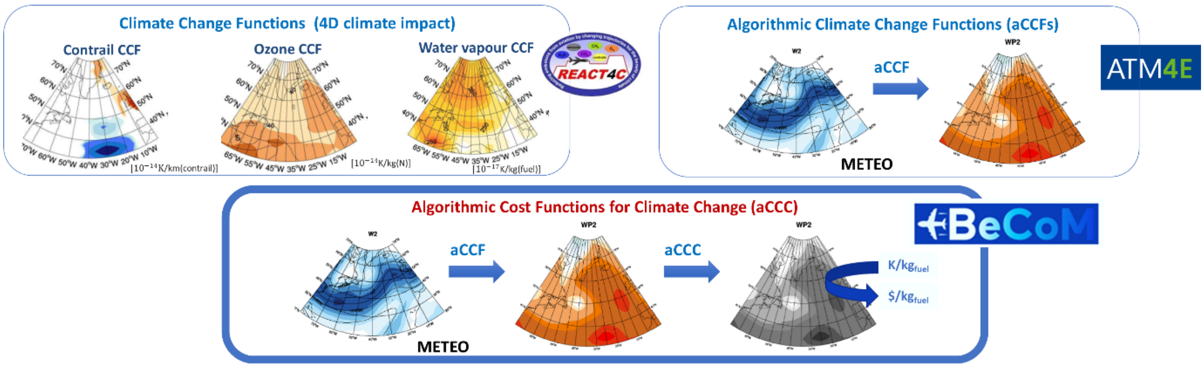

Figure 10: Concept of deriving aCCC from aCCF

aCCFs & Meteorological data

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 & Grewe 2019, Yamashita et al.2020, Dietmüller et al. 2023). Since extensive climate simulations are not feasible for application in flight planning and trajectory optimization, 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, NO_x-induced Ozone (O3) and methane (CH4) changes as well as contrail-induced cloudiness can easily be evaluated with the forecasted or reanalyzed 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). The results can be transferred to other climate metrics by applying simple scaling factors.

These aCCFs can be used to estimate the climate impact from CO2 and non-CO2 species and hence can be applied to calculate the CO2 equivalent emissions (CO2e) for the aCCCs. CO2e can be obtained as the temporal integral of algorithmic climate change functions (aCCFs, Yin et al. 2023) multiplied with the associated emission flows for CO2, H2O, and NOx or the true airspeed v_{TAS} in the case of CiC:

[1] https://www.eex.com/en/market-data/environmentals/eu-ets-auctions

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

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:

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

The merged aCCF ($aCCF_{merged}$) represents the climate impact from the considered non-CO_2 emission species H_2O, NO_x, and CiC (Dietmüller et al. 2023). Algorithmic cost functions for climate change (aCCC) can then be calculated by multiplying the CO_2e values with the carbon costs:

$$aCCC = CO_2e(x,t) \cdot c$$

As indicated in Figure 11, both carbon price and metric significantly influence the aCCC. On the one hand, the considered metric (as exemplarily shown for different time horizons) influences the gradient of the aCCC due to different weightings of the different species effects. For instance, CiC has a relatively high impact for shorter time horizons while it is weaker for longer time horizons. On the other hand, the carbon price influences the price level in general, thus also the relation of climate cost in relation to other operating cost.

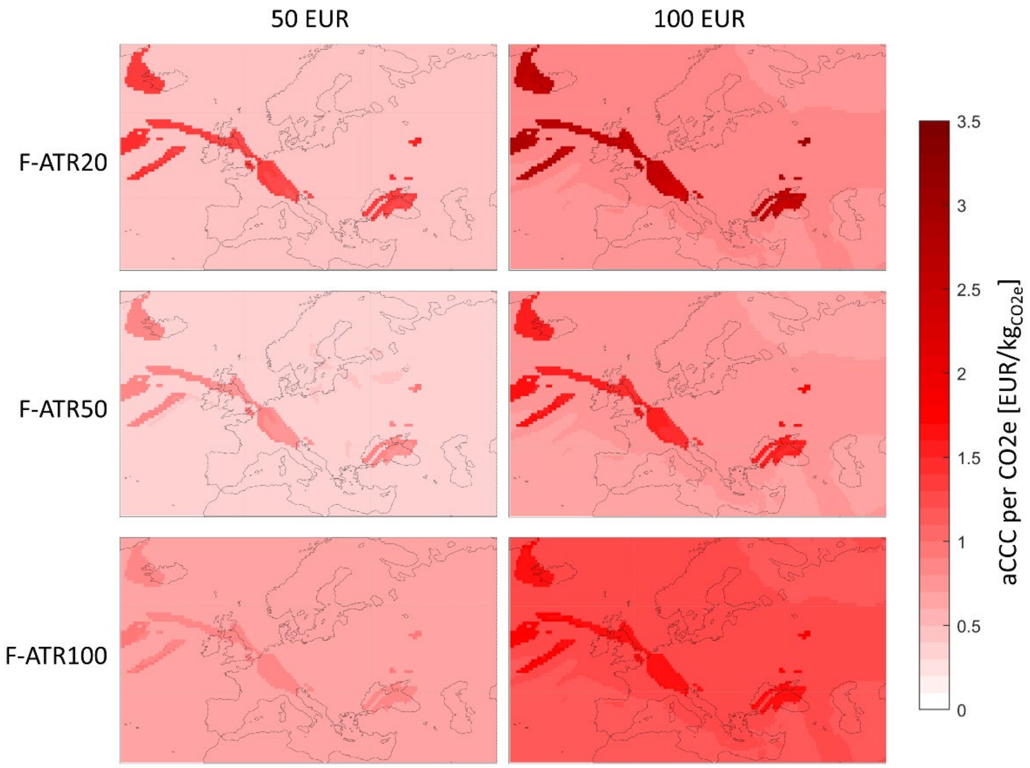

Figure 11: aCCC per CO2e, exemplary over European region on June 16th, 2018 at a constant pressure altitude of 200 hPa

If non-CO2 climate effects are considered in flight planning based on CO2e 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 as well as a cost term accounting for the climate impact of this flight.

$$C_j = f_{DOC}(m_{fuel,j}, t_j, d_j) + CO_2e_j \cdot c$$

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Trajectory optimization and emission calculation

In this work, we apply DLR's Trajectory Optimization Module in python (pyTOM), which detects eco-efficient trajectories based on optimal control techniques (Lührs et al., 2016). In pyTOM, 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 5) 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 cost functional J 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):

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

Where t is the time, d the distance, and m_{fuel} the burnt fuel of the aircraft. The continuous optimal control problem is transformed into a nonlinear programming problem (NLP) and solved using standard NLP solvers. The Pareto optimal set is found by varying the weights $\left(c_{fuel}, c_{clim}\right) \in [0;1]$ with $c_{fuel} + c_{clim} = 1$.

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:

$$J = min\left\{f_{DOC}\left(m_{fuel}, t, d\right) + CO_2e_j \cdot c\right\}$$

4.3 Results

Figure 12 and Figure 13 show the reference missions for both cases, i.e. with and without contrail formation along the flight from BCN to FRA. The reference case (business as usual, BAU) is characterized by the cost optimal solution including an accounting of CO_2 effects only. We observe that both vertical and lateral plot of trajectories only vary marginally for the two considered weather situations in the cost optimal case.

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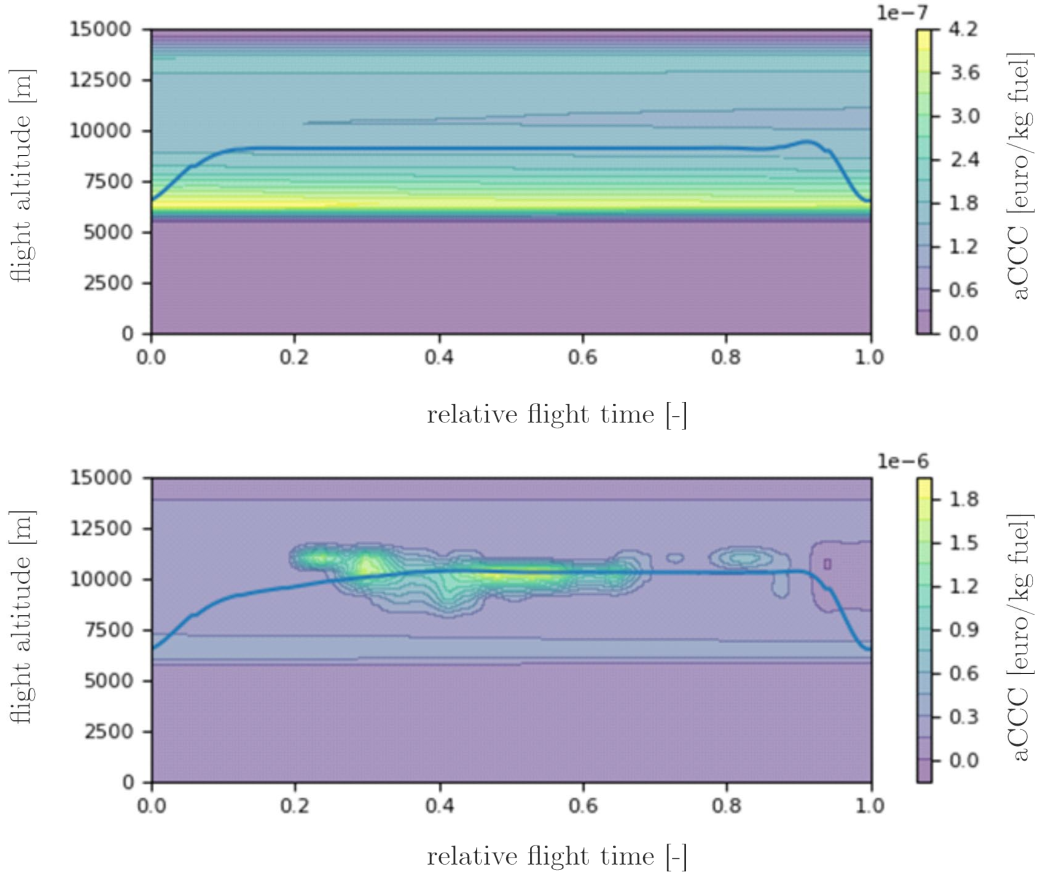

Figure 12: Vertical Plot of reference trajectories (no non-CO_2 accounting) for an exemplary A320 mission from BCN to FRA and two weather situations: without persistent contrail formation (top) and with persistent contrail formation (bottom). The color code indicates the algorithmic costs for climate change (aCCC) in euros per kg of fuel in case of non-CO2 accounting.

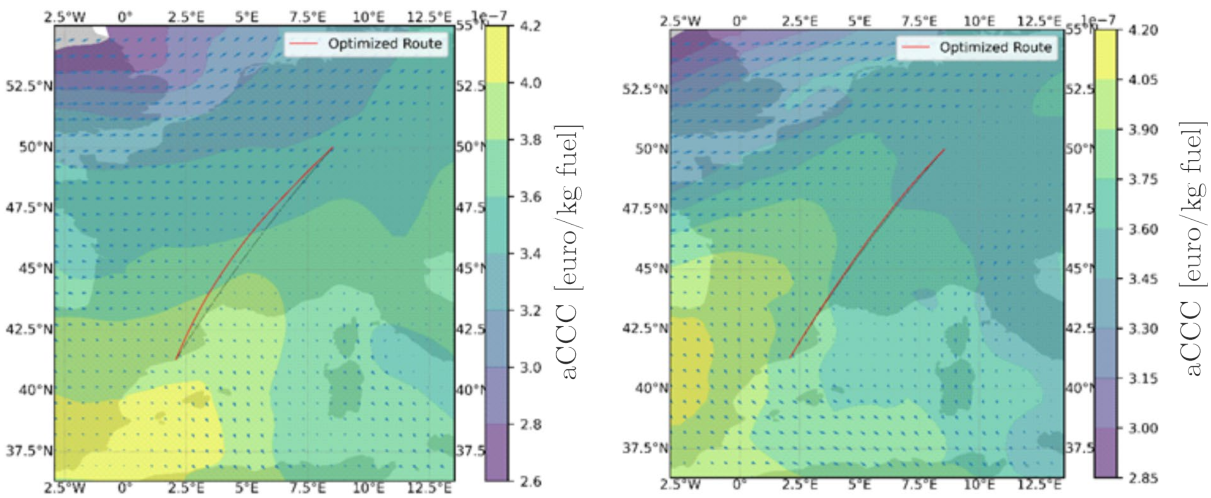

Figure 13: Lateral Plot of reference trajectory (no non-CO_2 accounting) for an exemplary A320 mission from BCN to FRA and two weather situations: without persistent contrail formation (left) and with persistent contrail formation (right). The color code indicates the algorithmic costs for climate change (aCCC) in euros per kg of fuel in case of non-CO2 accounting.

When additionally considering CO2e from non-CO2 effects in the accounting, the cost-optimized routes results vary significantly from each other for both weather situations, as displayed in Figure 14. The flight mission without persistent contrail formation only changes marginally compared to the reference without accounting for non-CO2 effects. In this case, we only see minor adjustments in the flight altitude to exploit altitude-dependent effects of NOx-induced O3 and CH4 changes.

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Simultaneously, the CiC intensive mission changes significantly compared to its reference routing. To avoid the area of contrail formation with high climate impact and high aCCCs, the flight path deviates primarily vertically, which greatly reduces the average cruising altitude along the mission. By doing so, the climate impact can be reduced by 56.5% in this case compared to the cost optimal solution (reference case) while it only decreases by 2.5% for the CiC-free mission.

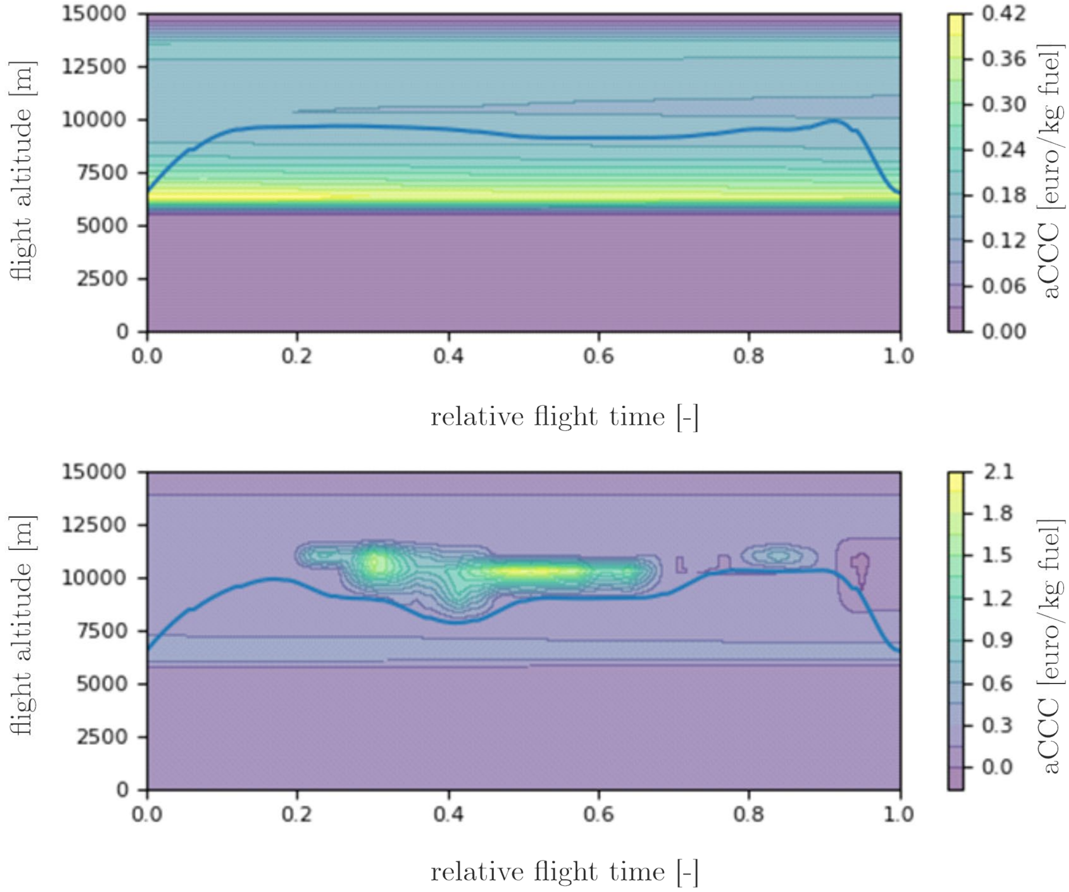

Figure 14 : Vertical plot of optimized trajectories considering a full accounting of non-CO_2 effects with a carbon price of 50 euro per ton of CO_2, for an exemplary A320 mission from BCN to FRA and two weather situations: without persistent contrail formation (top) and with persistent contrail formation (bottom). The color code indicates the algorithmic costs for climate change (aCCC) in euros per kg of fuel in case of non-CO_2 accounting.

Nevertheless, both cases demonstrate the suitability of the accounting to reduce climate effects with policy-driven flight planning. However, the potentials are significantly lower for the mission without CiC effects (see Figure 15). Figure 15 and Figure 16 illustrate the concept of non-CO_2 accounting and its suitability for reducing the climate impact along flight missions with cost-optimal solutions. The underlying data is additionally displayed in Table 1 and Table 2 at the end of this chapter.

Without non-CO_2 accounting, a climate-optimized re-routing (black dots in Figure 15 & Figure 16) has to balance two conflicting objective functions, the minimization of monetary costs (fuel, time, operating costs, etc.) and climate impact (emissions, ERF, ΔT, etc.). When selecting the pareto-optimal trajectory to be flown, it is therefore necessary to balance the additional costs that are acceptable to achieve the desired savings in climate impact. As higher climate mitigation potentials (in terms of relative CO_2 equivalents) are associated with higher operating costs, we have a 'win-lose' situation in case of trajectory-optimization without an accounting of non-CO_2 effects.

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However, if a policy scheme incorporating pricing of non-CO_2 effects is introduced, decision-making during flight planning can be simplified. As the climate-optimized solution (green pentagon) is more cost-effective than the reference solution (green square), there is a financial incentive to re-route flights in a climate-optimized way ('win-win situation').

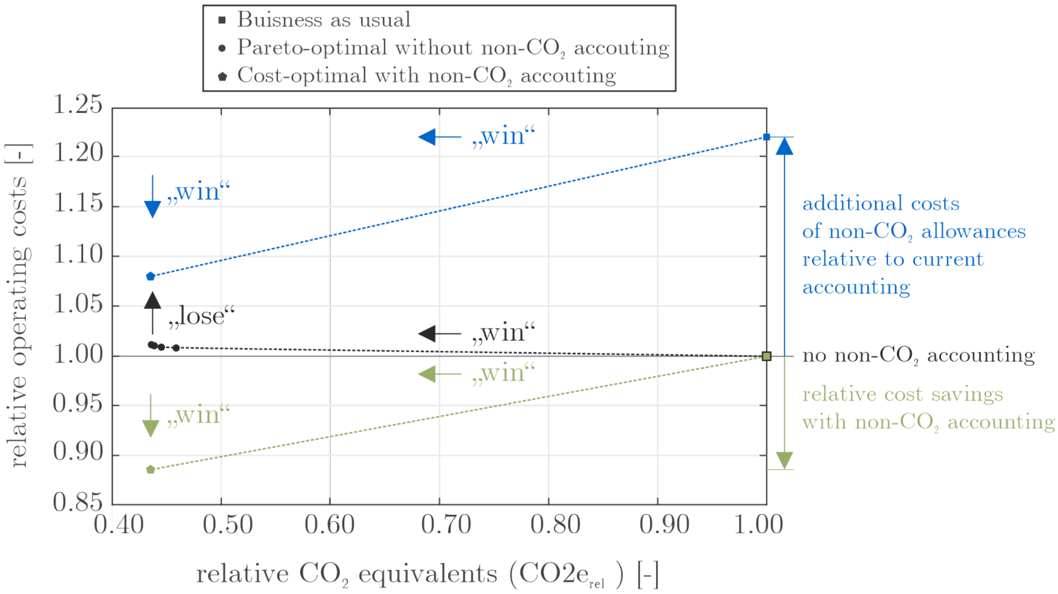

Figure 15: Relative results from trajectory optimization considering different accounting approaches for CiC-intensive mission from BCN to FRA

While the climate-optimized solution associated with a mitigation potential of 56% led to approximately 1% of additional operating cost without non-CO_2 accounting, the cost can be reduced by approximately 11% with an introduction of CO_2 accounting for the CiC intensive mission. For the mission without persistent contrail formation, the numbers are significantly lower both regarding climate-mitigation potential and cost changes. Obviously, the absolute cost decrease is due to the changed reference in the non-CO_2 accounting case. In relation to the original operating cost without non-CO_2 accounting, the cost increase is due to an additional cost term introduced. While the cost increase is around 22% above the reference without accounting if the route is not changed, a policy-driven flight planning avoiding areas of high climate cost only leads to a cost increase of approximately 8% in the CiC intensive case.

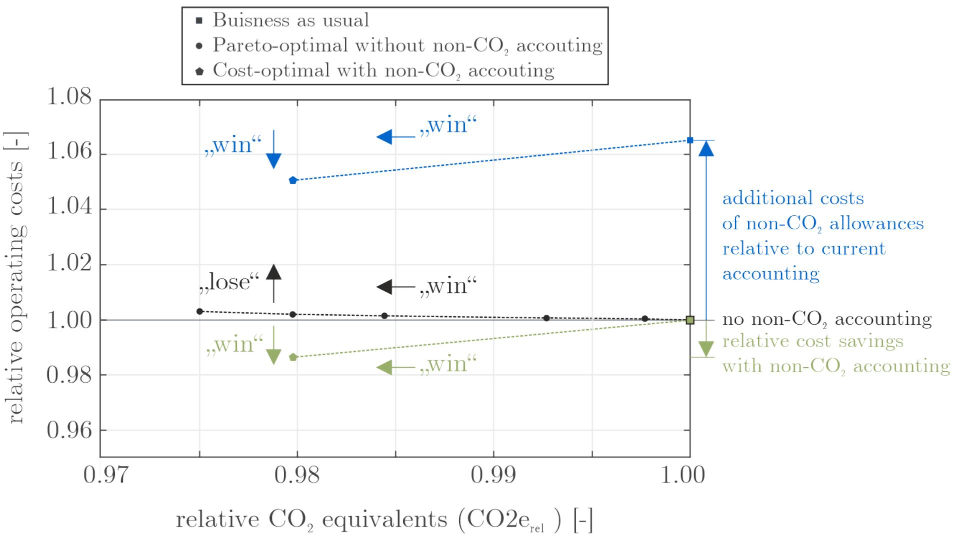

Figure 16: Relative results from trajectory optimization considering different accounting approaches for mission without CiC from BCN to FRA

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Based on the assumption that the additional cost resulting from the additional non-CO_2 accounting, are directly transferred to the passengers leading to an increase in ticket prices, Figure 17 and Figure 18 provide the results for the investigated exemplary routes with varying contrail intensity. We observe that the additional ticket price strongly depends on the selected accounting share, i.e. a gradual introduction of non-CO_2 accounting would moderate the effects for passengers. In general, the additional ticket prices for the considered routes vary between 1 EUR and 7 EUR, which remains below 5% of the ticket price for the considered missions (178.11 EUR for BCN-FRA, 196.51 EUR for DUS-PMI).

Figure 18 shows the additional ticket price in relation to the mitigated climate effect in CO_2 equivalents. We find that the climate mitigation potential is less sensitive to the accounting shares, but more influenced by route characteristics and the climate impact of the reference mission. For our limited case study, we see that CiC intensive missions provide significantly higher mitigation potentials compared to less CiC intensive missions although the resulting ticket price increase remains in the same order of magnitude.

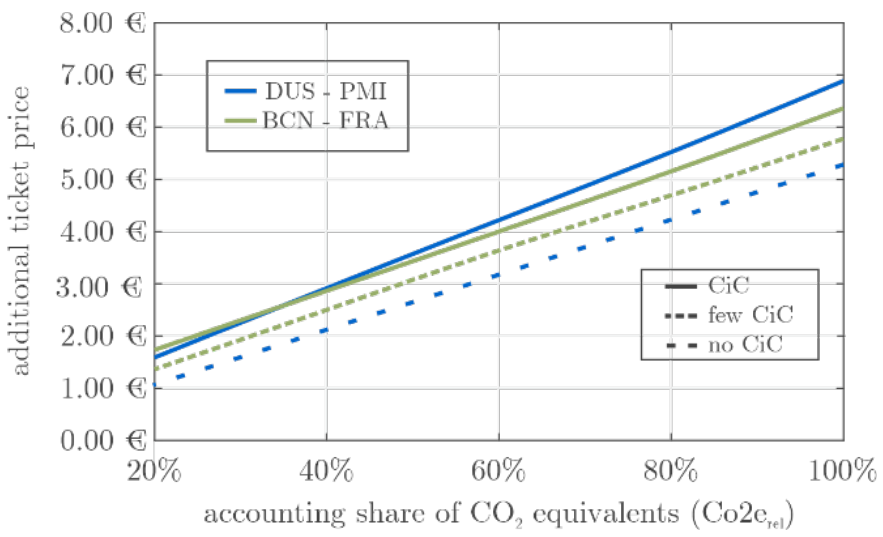

Figure 17: Additional ticket price for two exemplary missions over different accounting shares of CO2e

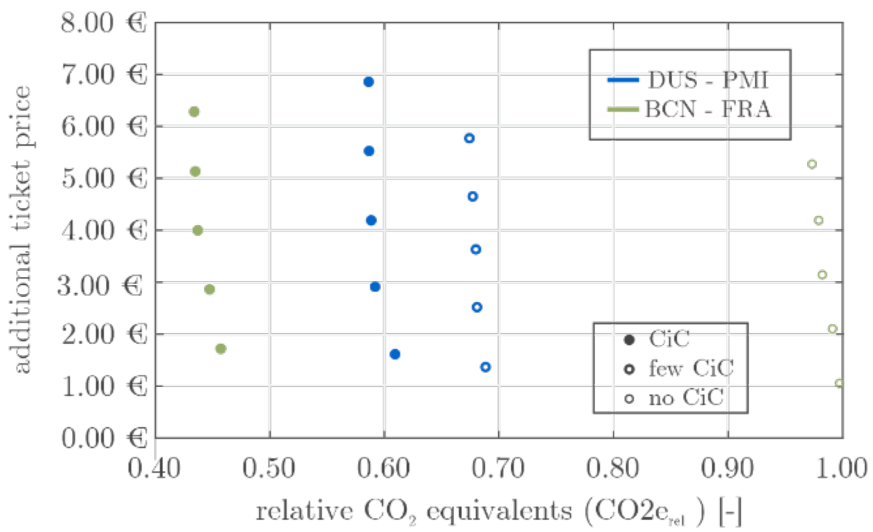

Figure 18: Pareto front over additional ticket price in relation to reduction in CO2e for different exemplary missions

In the underlying case study, we assume a constant carbon price of 50 EUR per ton of CO_2 and CO2e. Hence, the relative share of climate cost compared to direct operating cost was between 6% and 18%

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for the reference case without route optimization after accounting introduction. We assume that a higher carbon price, which lead to a higher weight of climate cost in the optimization, could influence the results and the influence of accounting on the climate impact mitigation.

Table 1: Results from trajectory optimization for different accounting shares for exemplary mission without persistent contrail formation (BCN-FRA., average ticket price of 178.11€ and 128 passengers)

Accounting share	Flight Time [s]	Fuel burn [kg]	Total Cost [EUR]	CO_2 [kg]	$CO2e_{nonCO2}$ [kg]	$CO2e_{Total}/CO2$	Add. ticket price [EUR]
0%	4621	3443	9666,00 10295.24 *	10846	12585	2.16	- 4.92 *
20%	4628	3424	9791 15	10787	12462	2.16	0.99
40%	4639	3400	9915.21	10711	12260	2.14	2.00
60%	4659	3362	10036.32	10589	11931	2.13	3.00
80%	4672	3338	10154.79	10513	11740	2.12	4.01
100%	4687	3312	10271.24	10431	11541	2.11	5.02

** Cost/price if full non-CO_2 accounting was in place*

Table 2: Results from trajectory optimization for different accounting shares for exemplary mission with persistent contrail formation (BCN-FRA, average ticket price of 178.11€ and 128 passengers)

Accounting share	Flight Time [s]	Fuel burn [kg]	Total Cost [EUR]	CO_2 [kg]	$CO2e_{nonCO2}$ [kg]	$CO2e_{Total}/CO2$	Add. ticket price [EUR]
0%	4404	3018	9049.17 11035.12 *	9505	39719	5.18	- 15.52 *
20%	4380	3193	9258.06	10059	13851	2.38	1.67
40%	4389	3187	9391.99	10039	13140	2.31	2.78
60%	4399	3176	9520.76	10004	12722	2.27	3.88
80%	4410	3155	9646.13	9938	12548	2.26	4.97
100%	4418	3143	9770.33	9899	12413	2.25	6.08

** Cost/price if full non-CO_2 accounting was in place*

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5 Conclusion & future work

This work contributes to objective 5 of the project targeting the integration of non-CO_2 effects (e.g. contrails) within current policy schemes, such as the revised EU Emission Trading System, ICAO CORSIA and EU Green Deal. We analyzed existing and discussed non-CO2 policies and derived requirements for implementation. For flight planning (pre-flight mode) as well as for monitoring, reporting and verifying (post-flight mode), all stakeholders need to be able to calculate CO2e and the resulting payment obligations in an easy, transparent and predictable way. A conversion of non-CO_2 effects into algorithmic cost functions for climate change (aCCC) has therefore been performed. aCCCs are simple linear equations that estimate the costs from aircraft emissions in euros per kilogram of fuel as a function of meteorological conditions at time and location of emissions. In the context of policy-driven flight planning and the accounting of non-CO2 effects, uncertainties play a decisive role. These uncertainties are related to uncertainties in the meteorological boundary conditions along the flight, inaccuracies in trajectory and emission modelling as well as large uncertainties associated with quantifying the climate effects from non-CO2 emissions. We present an approach on how these uncertainties could be considered in the accounting and thus prepare the assessment in the following work.

All in all, the work in the context of this deliverable shows the suitability of the developed approach of algorithmic cost functions for climate change. By incorporating non-CO2 climate effects in terms of their CO2e into the emission accounting, trajectory optimization can be performed by only considering cost (i.e. operating and climate cost). The adjusted trajectories provide both a mitigation in climate effects as well a cost reduction compared to the reference trajectory assuming accounting of CO2 and non-CO2 effects. This has been demonstrated in a small-scale case study. Although the results presented in this deliverable are based on aCCCs, which have been derived from aCCFs, the concept can also directly be transferred to other climate assessment models, as for instance the CoCiP model, implemented in pycontrails. This deliverable also demonstrates the sensitivity of the trajectory optimization in policy-driven flight planning from different parameters, such as climate metric, accounting, share, route characteristics and CO2e price. Further work will be performed in this context to extent the significance of the achieved results and systematically analyze sensitivities and dependencies from different parameters.

In general, the work performed in this deliverable needs to be related to the current work in the context of the revised EU ETS and the non-CO2 MRV starting from 2025. We expect the MRV to provide a ‘technology push’ and higher attendance for non-CO2 effects in aviation from research, political and industry side. For instance, higher data availability will help to reduce uncertainties in the assessment increasing the reliability of results. The work on policy-driven flight planning and non-CO2 accounting in the BeCoM project shall be seen as a scientific input for political decision-support. It represents conceptual work independent of the climate and emission assessment method as the approach is easy scalable to other assessment models, so that improvements and reduced uncertainties can directly be transferred to the concept in the future.

Looking out to future research, we plan to extend the scientific significance of our studies by investigating a larger set of trajectories in close collaboration with WP4 as well as extending the sensitivity analysis regarding CO2e cost, accounting method, and climate metric. The influence of uncertainties on the results will be analyzed in detail in the second half of the project. Furthermore, we are planning to incorporate Stakeholders’ perspectives. The final results will be presented in the second deliverable of WP5 in a report on the assessment of the new policy driven flight planning approach with regard to its effectiveness and feasibility.

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