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Integrating aviation's non-CO_2 effects into EU ETS: Impact of CO_2e accounting on operational and technological climate mitigation measures

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Abstract

To comply with defined ambitious climate goals, technical and operational improvements are required to reduce the climate impact of aviation. Non-CO_2 emissions contribute to a majority of aviation's total effect and a reduction of the associated climate impact is often associated with an increase in fuel consumption and CO_2 effects. These trade-offs typically result in higher operating costs, which create a lack of economic incentive to pursue such measures, ultimately slowing implementation. Therefore, this study investigates implications from a market-based policy scheme designed to support the implementation of climate mitigation strategies by internalizing non-CO_2 effects. An extension of the EU ETS to account for non-CO_2 effects in terms of CO_2 equivalents is modeled and resulting climate mitigation potentials and operating cost changes are analyzed. The results demonstrate the suitability of an extension of the existing accounting to non-CO_2 effects as this reduces cost in relation to the reference without measure implementation. Furthermore, benefits of operational climate mitigation measures are demonstrated in comparison to the use of sustainable fuels. Technical efficiency improvements can further help to increase mitigation potentials and reduce operating cost, while reduced accounting shares can help to limit cost and ticket price increase.

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Keywords: air transport; non-CO_2 effects; CO_2 equivalents; accounting; climate mitigation; EU ETS

1. Introduction

In contrast to other modes of transport, the climate impact of aviation is not only determined by its CO_2 but also by its non-CO_2 effects which are estimated to contribute to a majority of the total effective radiative forcing (Lee et al., 2021). These effects result from the emissions of nitrogen oxides (NO_x), water vapor (H_2O) and particulates, that influence the radiative balance of the atmosphere via different direct and indirect effects. For instance, H_2O acts

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as a direct greenhouse gas as well as through the formation of contrails and contrail-induced cloudiness (CiC). NO_x emissions lead to the formation of atmospheric ozone (O_3) with a warming effect as well as methane (CH_4) depletion with a cooling effect. While the climate effect from CO_2 emissions is directly related to fuel consumption, non-CO_2 climate effects do not only depend on emission quantities but also on emission location, altitude and time. A quantification of these non-CO_2 effects is associated with a lower level of scientific understanding leading to approximately eight times higher uncertainties compared to CO_2 (Lee et al., 2021).

In order to reduce anthropogenic radiative forcing, a variety of different climate mitigation measures is required to ensure compliance with ambitious climate goals that have been defined, e.g. in context of the Paris Agreement (Grewe et al., 2021). Different approaches from both technical and operational side as well as from a regulatory perspective can help to reduce the climate impact of aviation. While current technological advancements such as new engine or aircraft types focus the reduction of fuel consumption thus mainly reduce CO_2 climate effects, operational approaches are also suitable to reduce non-CO_2 effects by exploiting laterally, vertically and temporally varying climate sensitivity of these emissions. In these cases, a reduction of non-CO_2 climate effects is typically associated with a rise in fuel burn and CO_2 effects. Due to higher uncertainties of non-CO_2 climate effects, the trade-off between increasing certain CO_2 effects and reducing uncertain non-CO_2 effects needs to be considered. Moreover, a deviation from economically efficient operations increases operating cost hindering aviation stakeholders to implement such climate mitigation measures. Therefore, policy measures come into place to support the implementation of climate mitigation approaches and to reduce possible implementation barriers. Such regulatory measures can be categorized into voluntary measures, e.g. Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA), market-based measures, e.g. European Union Emission Trading System (EU ETS), and regulatory measures, e.g. environment standards for NO_x emissions (Niklaß, 2019). In course of the current revision of the EU ETS, which previously considered CO_2 effects only, non-CO_2 climate effects from aviation are covered by a European monitoring, reporting, and verification framework (MRV). This represents a first step towards a full integration of non-CO_2 effects into the EU ETS. As of 2025, aircraft operators are required to report CO_2 equivalent emissions (CO_2e) considering the climate impact of non-CO_2 effects. On this basis, the European Commission plans to investigate the opportunity to prepare a legislative proposal on how to comprehensively mitigate aviation's climate effects by extending the scope of the EU ETS to non-CO_2 emissions (European Union, 2023).

In context of the Horizon Europe project *Better Contrail Mitigation (BECOM)*, the concept of extending existing accounting schemes by non-CO_2 effects is investigated. In this context, Niklaß et al. (2025) focus on the influence of extending the EU ETS on climate-optimized flight planning and examined sensitivities towards possible policy design parameters. While business-as-usual trajectory optimization results in a pareto front illustrating the opposing goals of climate impact mitigation and cost minimization, the introduction of CO_2e pricing leads to an adjusted cost-optimal solution with increased direct operating cost overcompensated by a reduction of climate effect accounting cost. The study confirms the suitability of such a pricing scheme to motivate climate-optimized flight planning. Based on the conceptual analysis in Niklaß et al. (2025), the following study investigates the influence of an extended accounting scheme on different climate mitigation approaches. Thereby, we aim to address the research objective of comparing different technical and operational mitigation measures in context of assuming a CO_2e-based accounting considering both CO_2 and non-CO_2 effects. To this end, this study combines findings from the current state of literature for different climate mitigation measures regarding mitigation potentials with the assessment of direct operating cost changes through the consideration of non-CO_2 effects in a market-based policy scheme.

2. Method

This section describes the assessment method, including CO_2e accounting of non-CO_2 effects (Sec. 2.1), climate impact calculation from flight trajectories (Sec. 2.2), and the overall study design (Sec. 2.3).

2.1. Pricing of non-CO_2 effects

CO_2e emissions combine the effects of CO_2 and non-CO_2 emissions into a single metric, expressing the amount of CO_2 (in kg) that would cause the same climate impact as the considered emission species. This allows for consistent climate impact assessment using metrics like radiative forcing, global warming potential, or average temperature response (ATR), over time horizons such as 20, 50, or 100 years. ATR100 is commonly used due to its direct link to global temperature change and low dependence of the considered time horizon (Megill et al., 2024; Niklaß et al., 2025).

We apply a pulse scenario for single-flight analysis (pATR100) and a future emissions scenario (F-ATR100) for overall mitigation. CO_2e for species i are calculated by multiplying their relative climate impact (compared to CO_2) with the CO_2 emissions of that flight, resulting from the CO_2 emission index EI_{CO_2} and the associated fuel burn m_{fuel}. CO_2e_{total} sums contributions from all species.

$$CO_2e_i = \frac{ATR_{100,i}}{ATR_{100,CO_2}} \cdot m_{fuel} \cdot EI_{CO_2} \tag{1}$$

$$CO_2e_{total} = \sum_i CO_2e_i = CO_2e_{CO_2} + CO_2e_{H_2O} + CO_2e_{NO_x} + CO_2e_{CiC} \tag{2}$$

Based on calculated CO_2e, a pricing according to European Union Aviation Allowances (EUAA) can be assumed, which changes the direct operating cost (DOC) of a flight mission in dependence of fuel burn (m_{fuel}), flight time t and flight distance d to the adjusted DOC ($aDOC$) considering the total CO_2e with a EUAA price (p_{EUAA}).

$$aDOC = \underbrace{f(m_{fuel}, t, d)}_{DOC} + \underbrace{CO_2e_{total} \cdot p_{EUAA}}_{Climate\ cost} \tag{3}$$

The change in adjusted DOC ($\Delta aDOC$) can also be calculated per passenger (n_{Pax}) indicating a possible increase in ticket prices when assuming a price elasticity of zero.

2.2. Emissions and climate impact modeling

To obtain the climate impact in ATR100 and the change in operating cost, flight mission modeling and climate impact assessment are required. For this purpose, an established modeling chain named *integrated Trajectory Calculation Module (iTCM)* is applied as depicted in Figure 1 (Zengerling et al., 2024).

First, flight trajectories are generated for a combination of given origin-destination pairs and aircraft type. The trajectory calculation provides relevant flight performance parameters such as forces (drag, thrust), speeds, accelerations and fuel consumption along four-dimensional flight trajectories based on aircraft and engine specific flight performance parameters. Second, emission flows are determined based on the calculated fuel flow along the generated trajectories. While emission quantities for CO_2 and H_2O are assumed to be proportional to fuel consumption, NO_x emissions are calculated applying DLR's fuel flow correlation method according to Schäfer and Bartosch (2013). Third, geo-spatially resolved emission flows for the considered emission species are fed into the climate impact assessment. The iTCM comprises the opportunity to evaluate the climate impact from in-flight emissions with *algorithmic climate change functions (aCCFs)*, that estimate climate sensitivity of different species in dependence of meteorological boundary conditions at location and time of emission (*meteorological approach*; Dietmüller et al., 2023). Alternatively, the climate impact can be assessed in a *climatological approach* with the non-linear climate chemistry response model AirClim (Dahlmann et al., 2016), which directly builds on emission outputs from the iTCM via a gridding interface (Linke et al., 2017).

In addition, a direct operating cost (DOC) assessment is performed based on a simplified method developed in course of the EU Horizon 2020 project ClimOP (Zengerling et al., 2023). As displayed in equation 3, mission-specific DOC are calculated in dependence of the parameters mission distance, fuel burn and flight time.

2.3. Study design to assess different climate mitigation measures

The changes in operating cost due to the implementation of CO_2e accounting are assessed and compared for different climate mitigation measures. The final analysis comprises of a mission specific comparison of different climate mitigation approaches from the technical and operational domain regarding their climate mitigation potential as well as cost changes. The changes in operating cost can be analyzed in relation to the reference without CO_2e

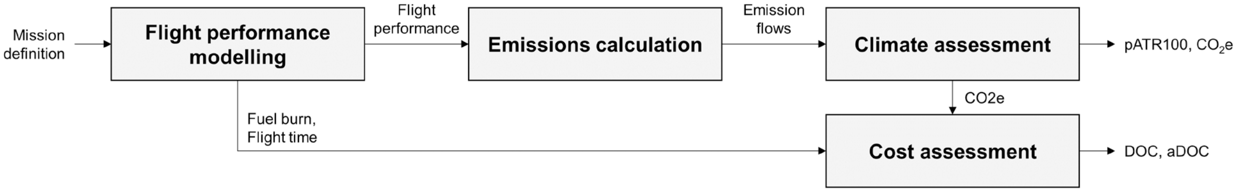

Fig. 1. Assessment workflow to assess climate mitigation potential along individual flight missions

accounting as well as the reference with CO_2e accounting. Finally, we aim to estimate overall climate mitigation potentials in relation to additional cost in course of implementing a CO_2e pricing scheme. The detailed assessment focuses on the following operational climate mitigation approaches:

- Flying lower and slower to benefit from reduced climate sensitives of non-CO_2 effect at lower flight altitudes while compensating higher fuel burn with reduced speeds according to Zengerling et al. (2023)
- Lateral rerouting to avoid climate sensitive areas laterally.
- Climate-optimized intermediate stop operations (ISO) to benefit from higher fuel efficiency through an intermediate stop for refueling. Intermediate stop airports and flight altitudes in this case are selected from Zengerling et al. (2022).

In an extended analysis, formation flight is also considered in the comparison based on literature results, as flying in formation leads to the reduction of fuel burn from aerodynamic advantages as well as reduced climate impact based on saturation effects (Marks et al., 2021). From the technological perspective, we additionally consider the use of sustainable aviation fuels leading to a net reduction of CO_2 effects over the fuel life cycle as well as in-flight reduction of non-CO_2 effects regarding the formation of cirrus clouds (Teoh et al., 2022). We also consider technical improvements enhancing fuel efficiency and reducing NO_x emission indices in a parameter study (cf. Table 1).

Table 1. Modeling assumptions and data sources

	Reference value (Data source)
Cost	
CO_2e price	0.084 €/kg, based on average values from 2023 (European Energy Exchange, 2024)
Fuel price (Jet A1)	0.82 €/kg, average value from 2023 (EASA, 2024)
Fuel price (SAF)	2.78 €/kg, average value from 2023 (EASA, 2024)
Trajectory modeling	
Seat load factor	84%, based on European average in 2023 (IATA, 2023)
Emissions & climate impact	
Fuel efficiency increases (technical)	Variation between 0 and 15%
NO_x emission reduction (technical)	Variation between 0 and 15%
Impact from SAF	Reduction in contrail climate impact by 45% (Teoh et al., 2022) and by 80% in net CO_2 (Grewe et al., 2021), no effect on NO_x and direct H_2O effects (Harlass et al., 2024) No change in flight time and fuel consumption
Impact from formation flight	Reduction in climate impact by 6% of CO_2, by 23% in NO_x effects, by 8% in H_2O and by 40% in CiC (Marks et al., 2021)

This assessment focuses on the long-range segment due to its high share of traffic volume (in available seat kilometers, ASK) and climate impact. Unlike short-haul routes, long-haul aviation lacks viable alternatives to fuel-based propulsion in the mid-term, as hydrogen or electric-powered aircraft are expected to enter the market primarily on short routes. Conventional aircraft will remain dominant for long-haul flights. The analysis targets flights to and from the ECAC area, using 50 representative missions that capture key traffic flows, distances, geographical regions, and aircraft types.

The assessment is based on the assumptions in Table 1. We apply EUROCONTROL's Base of aircraft data, version 4.2 (BADA4; Nuic and Mouillet, 2012) and emission indices from ICAO Engine Emissions Databank (ICAO, 2023). Meteorological conditions are provided by ECMWF ERA5 reanalysis data sets (Hersbach et al., 2020) and aircraft category dependent unit costs are derived from 2018 average airline cost data (Zengerling et al., 2023).

3. Results

Section 3.1 compares mitigation measures by climate and cost effects. Section 3.2 examines sensitivities to technical improvements and accounting shares.

3.1. Comparing different climate mitigation measures assuming CO$_2$e accounting

The suitability of extending CO$_2$e pricing is demonstrated for operational measures based on the above-mentioned assumptions along a reference mission from Paris (CDG) to Boston (BOS) with a Boeing 777 assuming realistic meteorological conditions (reference day Dec 11, 2018) and following a meteorological climate impact assessment approach. The implementation of different climate mitigation measures reduces the cost compared to a reference without measure implementation when assuming CO$_2$e accounting (cf. Figure 2). For instance, selecting the best cruise altitude and speed without CO$_2$e accounting is typically a trade-off decision between cost and climate impact. Implementing a CO$_2$e-based pricing scheme simplifies the decision as an altitude reduction of 4,000 ft (Figure 2, yellow square in the center) in this example leads to the highest cost decrease (–2.3 %) and a climate mitigation potential of 10.5 %. While a comparison of cruise altitude and speed reduction (–6,000 ft, –10 %; Figure 2, blue circle on the left) leads to the highest mitigation potential, we do not observe marked changes in aDOC compared to the reference case.

Furthermore, climate-optimized ISO (Figure 2, red triangle) shows no aDOC improvement compared to the reference, making it unsuitable in this example. The resulting rise in operating cost also affects customers. Assuming a full cost transfer to passengers, ticket prices increase between 61 and 84 € depending on the chosen mitigation measure, while the reference case without measure implementation leads to a ticket price increase of approx. 74.1 € due to

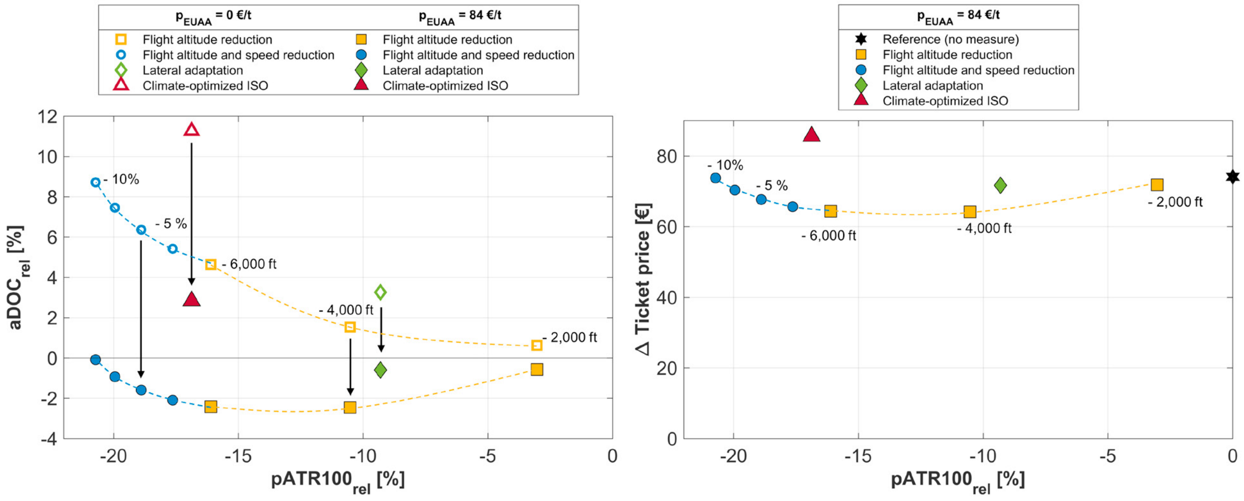

Fig. 2. Climate mitigation potential in relation to cost changes (left) and ticket price increases (right) from different climate mitigation measures assuming CO$_2$e accounting for an exemplary long-range mission. Changes on the left are relative to a reference case without measure implementation assuming different accounting approaches, changes on the right are relative to a reference without measure implementation and without any CO$_2$e accounting in place ($p_{EUAA} = 0$ €/t)

the additional non-CO_2 pricing. The most cost-effective option results in a 61.4 € increase for the assessed long-haul mission.

Extending the results to the representative long-range sample confirms the effectiveness of non-CO_2e accounting in supporting operational climate mitigation. This assessment uses a climatological approach, excluding route-specific weather conditions. Figure 3 illustrates the individual results per considered flight mission regarding climate mitigation potential and cost increase as well as the average over the representative flight sample in a scenario without considering CO_2e accounting.

Flying at lower altitudes yields a mitigation of –25.1 % (F-ATR100) with a 3.7 % increase in direct operating cost (DOC). Combining lower altitudes with reduced speed increases mitigation to –29.8 %, though at a higher cost (+7.2 %). This demonstrates the trade-off between cost and climate optimization. Consistent with the single-mission example, a consideration of non-CO_2 effects in aviation policy helps to mitigate this trade-off showing the highest decrease in aDOC for a reduction of flight altitude and speed (–11.1 %). Climate-optimized ISO as well as lateral re-routing appear inferior to the other considered measures.

Further climate mitigation measures are included based on literature findings. Here, we focus on the use of sustainable aviation fuels as a technological advancement and formation flight as an innovative operational approach (cf. Figure 3). We see that the use of SAF leads to a high mitigation potential of approx. 35.6 % which is associated with a significant cost increase due to the high fuel expenses (+99.5 % in DOC). This rise in operating cost can be reduced by considering non-CO_2 effects in the accounting scheme but a cost increase compared to the reference case remains (+31.1 % in aDOC). By contrast, implementing formation flight is not only associated with a reduction in the climate impact by the utilization of saturation effects but also a slight decrease in operating cost through reduced fuel consumption (Marks et al., 2021). Nevertheless, an implementation of CO_2e accounting supports the implementation of such operational measures as aDOC decrease as well.

3.2. Sensitivity towards technical improvements and policy design parameters

The implementation of CO_2e accounting leads to an overall increase in operating cost when comparing to the business-as-usual scenario without a non-CO_2 accounting scheme in place. The ticket price increase ranges between 197 € and 440 € depending on the selected measure assuming the cost increase is directly transferred to the passengers. For the reference case without measure implementation in case of CO_2e accounting, the ticket price increases by approx. 273 € for an average long-range mission (cf. Figure 4). In this course, technical advancements enhancing fuel efficiency and reducing NO_x emissions can help to reduce operating cost through reduced fuel and accounting cost, but primarily contribute to higher climate mitigation potentials. Alternatively, changes to the accounting scheme can help to limit the ticket price increase. For instance, a reduced accounting, i.e. considering only a limited constant share

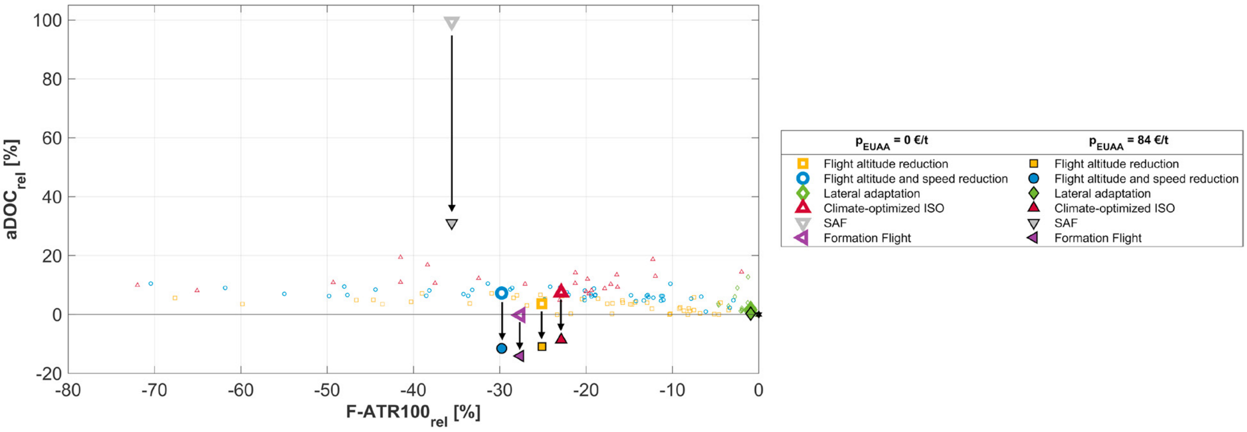

Fig. 3. Climate mitigation potential and cost changes for different climate mitigation measures representative long-distance flight scenario. Small symbols represent individual results for considered representative flight missions, large symbols illustrate average values over considered mission sample. Changes are relative to a reference case without measure implementation assuming different accounting approaches.

of non-CO_2 effects in the accounting scheme, reduces cost increases and possible ticket price changes as displayed in Figure 4. For instance, considering 20 % of the non-CO_2 effects in the accounting reduces ticket price increases to 50.7 € for a reduction of cruise flight altitudes which is still below the ticket price increase for the reference scenario without measure implementation (ticket price increase of 54.6 €). A gradual accounting, i.e. increasing the accounting share of non-CO_2 effects gradually over time, can also help to reduce impact on aircraft operators in course of the policy implementation.

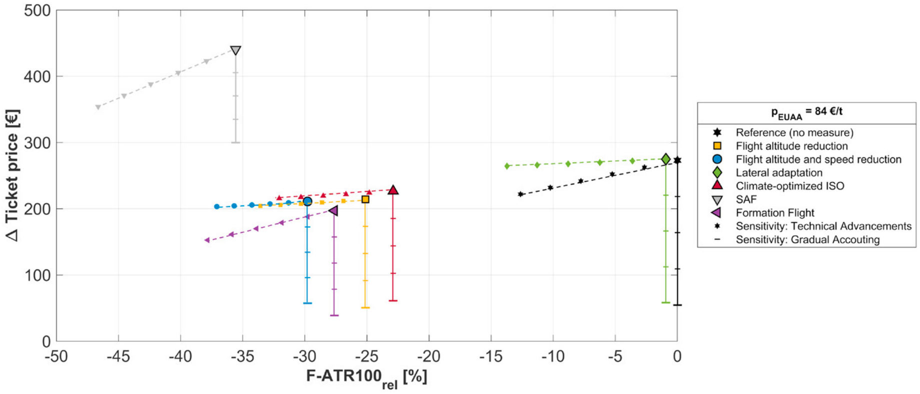

Fig. 4. Climate mitigation potential and ticket price increase for different climate mitigation measures in dependence of technical advancements and accounting share for representative long-distance flight scenario.

4. Discussion and conclusion

This study investigates the climate mitigation potential and cost increase from different climate mitigation measures in context of innovative regulatory approaches. We identify large mitigation potentials for selected operational improvements, which are associated with a high increase in operating cost. An extension of existing accounting schemes to also incorporate non-CO_2 effects of aviation can help to reduce the resulting implementation barriers. Pricing of CO_2e leads to a reduction of cost in relation to the reference case without measures implementation. Operational measures appear extremely promising when accounting for non-CO_2 effects, although leading to an increase in CO_2 effects. Use of SAF provides even higher mitigation potentials, but high fuel cost cannot be compensated with the extended accounting scheme. Further climate mitigation can be achieved from technical advancements, while a reduction of absolute cost increases compared to the business-as-usual scenario without CO_2e accounting can be addressed by the policy design, e.g. with a limited accounting share for non-CO_2 effects.

The applied modeling workflow is associated with different uncertainties and inaccuracies. This includes the estimation of climate effects from non-CO_2 emissions which are associated with eight times higher uncertainties compared to CO_2 (Lee et al., 2021). Further modeling uncertainties result from fuel flow and emission calculations as well as meteorological uncertainties. These uncertainties require further investigation to avoid falsely incentivized measure implementation. This is especially relevant in those cases where an increase in certain CO_2 effects is accepted to reduce non-CO_2 effects associated with higher levels of uncertainties.

Furthermore, the effects of a non-CO_2 accounting depend on the implementation of such a policy scheme. For instance, the selection of the respective climate metric, the price per Kilogram CO_2e as well as the accounting share influence cost changes and achievable climate mitigation potentials (Niklaß et al., 2025). Implementing CO_2e pricing within regions like the EU might also impacts passenger demand and reshape airline network dynamics, including market competition. Kölker et al. (2025) apply CO_2e simulations and passenger preference models to assess ticket price and demand changes for different geographical scopes. Moreover, a measure comparison has to incorporate further stakeholder effects beyond different cost increase. Innovative measures such as formation flight or ISO might reduce passenger comfort and increase travel times affecting airline networks. Rerouting approaches might increase air traffic density in areas of low climate sensitivity. These aspects have not been investigated in this study but require further investigation in future research.

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