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Abstract: Decision parameters of an MRV scheme for integrating non-CO_2 aviation effects into EU ETS

Although about two-thirds of aviation's climate impacts are caused by non-CO_2 effects, such as ozone production or contrail cirrus formation, these effects are not yet considered in existing and currently planned policy instruments (e.g. EU ETS or CORSIA). Due to their climatological relevance, however, various economic concepts have been proposed recently to internalise non-CO_2 effects. Most of these approaches are based on the principle of equivalent CO_2 emissions (CO2e), a way of unitizing the impact of all climate agents. Several calculation methods for CO_2 equivalents are in principle available, which differ in the degree of detail and are subject to uncertainties related to atmospheric science. There are a quite a few key decision parameters for policy makers for setting up a monitoring, reporting, and verification (MRV) scheme for non-CO_2 effects. The aim of this study is therefore to analyze and discuss the most important decision parameters for the integration of non-CO_2 aviation effects into EU ETS.

Kurzbeschreibung: Entscheidungsparameter eines MRV-Systems zur Integration von Nicht-CO_2-Luftverkehrseffekten in das EU-ETS

Obwohl etwa zwei Drittel der Klimaauswirkungen des Luftverkehrs durch Nicht-CO_2-Effekte, wie beispielsweise die Ozonproduktion oder die Kondensstreifenzirrenbildung, verursacht werden, werden diese Effekte in bestehenden und derzeit geplanten Politikinstrumenten (z.B. EU-ETS oder CORSIA) noch nicht berücksichtigt. Aufgrund ihrer klimatologischen Relevanz wurden allerdings in letzter Zeit verschiedene ökonomische Konzepte zur Internalisierung von Nicht-CO_2-Effekten vorgeschlagen. Die meisten dieser Ansätze basieren auf dem Prinzip von CO_2-Äquivalenten (CO2e), einer Maßeinheit zur Vereinheitlichung der Klimawirkung der unterschiedlichen Treibhausgase. Es sind allerding mehrere Berechnungsmethoden für CO_2-Äquivalente denkbar. Diese unterscheiden sich im Detaillierungsgrad und ihren atmosphärenwissenschaftlichen Unsicherheiten. Es gibt somit eine Reihe von wichtigen Parametern, die die politischen Entscheidungsträger beim Aufbau eines Systems zur Überwachung, Berichterstattung und Verifizierung (engl. monitoring, reporting, and verification; MRV) von Nicht-CO_2-Effekten berücksichtigen müssen. Ziel dieser Studie ist es daher, die wichtigsten Parameter bei der Integration von Nicht-CO_2-Effekten des Luftverkehrs in das EU-Emissionshandelssystem zu analysieren und zu diskutieren.

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List of abbreviations

ATR	Averaged Temperature Response
CC	Contrail Cirrus
CH_4	Methane
CO_2	Carbon Dioxide
COP	Conference of the Parties
CORSIA	Carbon Offsetting and Reduction Scheme for International Aviation
ECMWF	European Centre for Medium-Range Weather Forecasts
ERF	Effective Radiative Forcing
EU-ETS	EU Emissions Trading System
GTP	Global Temperature Potential
GWP	Global Warming Potential
H_2O	Water vapor
ISSR	Ice-supersaturated Region
MRV	Monitoring, Reporting and Verification
NO_x	Nitrogen Oxides
O_3	Ozone
PMO	Primary Mode Ozone
RF	Radiative Forcing
UNCED	United Nations Conference on Environment and Development

1 Introduction

In the past decades, high annual air traffic growth rates have doubled air traffic volumes in every 15 years (Airbus, 2019). Since historical and projected annual growth rates of around 5% of revenue passenger kilometers greatly exceed annual fuel efficiency increases (1-2%) (Kharina & Rutherford, 2015), greenhouse gas emissions from international aviation have increased by 130% between 1990 and 2017 (European Environment Agency, 2019). Aviation's percentage share of total greenhouse gas emissions can therefore be expected to further increase in the future. A trend that is also reinforced by the mitigation success in other sectors: In spite of rising emissions from aviation, EU member states were able to reduce their total emissions by 23.5% between 1990 and 2017 (European Environment Agency, 2019), releasing CO_2 emission allowances for aviation.

Almost two third of aviation's climate impact is caused by non-CO_2 effects (Lee et al., 2021; Grewe et al. 2017), such as the NO_x-induced production of ozone or the formation of contrail cirrus (CC) in cold and humid regions. Contrail cirrus is currently estimated to be the largest individual contribution to total radiative forcing (RF) from aviation, while the three components CO_2, NO_x, and CC are expected to be about equally important for induced temperature change (Grewe, 2020; Ponater, Bickel et al., 2021).

Non-CO_2 effects are not yet fully understood and still linked with medium to high uncertainties (Lee et al., 2020). This is one reason why no environmental policy instruments have yet been established in aviation for non-CO_2 effects. Due to their climatological relevance, however, various economic concepts have recently been proposed for non-CO_2 effects (i.a. Williams et al., 2002, 2003; Wit et al., 2004; Faber et al., 2008; Scheelhaase et al., 2016; Niklaß et al., 2017, 2020, 2021). The majority of ideas integrate non-CO_2 effects directly into existing (or planned) market-based instruments, such as EU ETS or CORSIA, based on the principle of equivalent CO_2 emissions (CO2e), a way of unitizing the impact of all climate agents. Since the climate impact of CO_2 is well understood due to its independence of emission source and location, it is reasonable to compare 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, resulting CO2e would cause the same climate response over a specific time horizon (e.g. 20, 50 or 100 years) as CO_2. In this concept, the total amount of CO2e that results from all considered non-CO_2 effects will therefore define the amount of emission allowances to be surrendered or the amount of emission levy/tax to be paid. This paper focuses on the climate-relevant evaluation of various design parameters for the implementation of non-CO_2 effects; analyses of actual cost impacts on airlines and resultings impacts on competition are outside the scope. Several calculation methods for CO2e are in principle available, which differ in the degree of detail and are subject to uncertainties related to atmospheric science. There a quite a few key decision paramters for policy makers for setting up a monitoring, reporting and verification (MRV) scheme for non-CO_2 effects. The most important decision parameters for the integration of non-CO_2 aviation effects into EU ETS are discussed in this study:

- Selection of climate agents (Section 2.1)
- Selection of climate metrics (Section 2.2)
- Selection of the calculation methodology for CO_2 equivalents (MRV scheme; Section 2.3)
- Development of a way to deal with atmospheric uncertainties (Section 2.4)
- Development of a roadmap for CO2e accounting (Section 2.5)

2 Decision parameters for Policymakers

When implementing a climate policy, there are several decisions that need to be made, which require a collaborative process involving policymakers and scientists. An overview of these key decisions is given in Table 1 and discussed below for the integration of non-CO_2 effects into EU ETS.

Table 1: Key decisions for integrating non-CO_2 effects into EU ETS

Key decision	Options
Integrated climate agents	{CO_2, H_2O, NO_x, CC, sulphate aerosol, soot aerosol, …}
Integrated climate metrics	{ATR, GWP, GTP, …} over {20, 50, 100…} years
Integrated CO2e calculation method	{Constant, distance-dependent, location-dependent, …}
Way to deal with atmospheric uncertainties	{no action; risk specific implementation}
Roadmap for CO2e accounting	{MRV only; stepwise implementation of obligations, …}

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2.1 Selection of climate agents

CO_2 and non-CO_2 are important contributors to aviation‘s climate impact. Although the level of scientific understanding (LOSU) of non-CO_2 effects has been greatly increased, it is their nature, i.e., the dependence on meteorology, that largely limits the reduction of uncertainties. Risk assessment is therefore required to better understand the impact of uncertainties on the calculation of non-CO2 effects and thereby on the potential of setting wrong incentives (see Section 2.4).

In case it is not intended to integrate all non-CO_2 effects into the EU ETS at once, the selection of individual climate agents significantly determines the fidelity of CO_2 equivalents (climate impact assessment) as well as the resulting effort for operationalization (required dataset for MRV scheme). A stepwise integration of different non-CO_2 effects seems to be generally possible. However, the most important climate agents should be included from the very beginning, since their exclusion would also eliminate their incentive for climate impact mitigation. Focusing only on the mitigation of a single non-CO_2 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 EU ETS or not, but also its share to the total climate impact and a clear knowledge of its direction (warming or cooling).

The largest individual contribution to the total effective radiative forcing (ERF) of aviation is currently attributed to contrail cirrus (CC; ERF of 57.4 mW/m^2), which are triggered by aerosol and water vapor emissions in the hot exhaust of aircraft engines at low ambient temperatures. If the ambient air is ice supersaturated, contrails can persist over a longer time period otherwise they disappear within minutes. Long persisting contrails might change shape due to wind shear until they can no longer be visually distinguished from natural clouds. Since CC are the only non-CO_2 effect visible to the human eye, contrail cirrus might play a special role in the public awareness. Generally, it is possible to use weather forecasts for the prediction of ice-supersaturated regions (ISSR). If flights are re-routed around ISSRs (e.g. by flying lower), the climate impact of CC can be effectively mitigated (see i.a. Luehrs et al., 2016, 2021; Matthes et al. 2020). However, there are still high uncertainties in the accuracy of weather forecasts as well as climate impact assessments.

NO_x emissions have an indirect effect on the climate caused by an increase in ozone concentration (O_3; ERF of 48.6 mW/m^2; warming) and a reduction in methane concentration (CH_4; ERF of −21.1 mW/m^2; cooling; Lee et al., 2020), which are both important greenhouse gases. A reduced CH_4 concentration in turn reduces ozone production; an additional effect known as primary mode ozone (PMO) or long-lived ozone. The lifetime of the ozone perturbation is in the order of weeks, while the lifetime of a CH_4 and PMO perturbation is about 12 years. The relative short lifetime of ozone greatly reduces its global distribution. Therefore, the climate impact of O_3 is more dependent of the emission location than the impact of CH_4.

As the three components (CO_2, NO_x and CC) clearly increase global temperate and might be about equally important for the induced temperature change (Grewe, 2020; Ponater, Bickel et al., 2021), latter two should be integrated from the early beginning into EU ETS.

2.2 Selection of climate metric

Climate metrics are used for quantifying the contributions of emissions of different agents to climate change. In general, climate metrics can be described as a combination of a climate indicator (e.g. RF or ΔT), emission scenario (emission course, background emissions, etc.) and time horizon (often 20, 50, 100 or 500 years) (see e.g. Fuglestvedt et al., 2010).

Most common climate indicators are radiative forcing (RF), global warming potential (GWP), global temperature potential (GTP) and average temperature response (ATR), which differ in their dependency on the time horizon (weak dependence for ATR and GWP) as well in their consideration of thermal inertia (e.g. ATR, GTP) (Dahlmann, 2011). It is also important to choose an indicator which is less dependent of the selected emissions scenario (e.g. ATR, GWP). A direct relation to the resulting temperature response e.g. (e.g. ATR, GTP) might enhance the comprehensibility of the selected indicator.

The selection of emission scenario describes the development of emissions over time (e.g. pulse or sustained emissions). When measuring the impact of a single flight, it is recommended to use pulse emissions, while constant emissions are the preferred choice for analyzing the mitigation potential of new aircraft technologies. Choosing an emission scenario can also influence the weighting between short- and long-lived climate agents. The selection of pulse emissions with a large time horizon focus on long-lived species (e.g. CO_2), rather than constant emission with shorter time horizons that focus on short-lived species (e.g. CC, O_3) as the large impact is dominant at the beginning.

The choice of time horizon is strongly dependent on the concrete question to be answered (Grewe and Dahlmann, 2015). Asking for mitigating the climate change in the near future would imply short time horizons of e.g. 20 years. The requirement for sustainable aviation would imply longer time horizons of, e.g., 100 years. For the Kyoto protocol, for instance, which is applied to long-lived greenhouse gases, a time horizon of 100 years was decided.
As it takes about 30 years for the atmosphere and ocean to adjust to a new radiative balance, a time horizon of more than 30 years is reasonable when using a climate indicator based on ΔT (ATR, GTP). In particular, for climate metrics that measure the climate change in one point in time (e.g. RF, GTP) based on pulse emissions, the selection of the time horizon is a weighting between long- and short-lived climate agents. For short time horizons the impact of short-lived species dominates, while for larger time horizons the impact of long-lived species dominates, as the impact of short-lived species is already gone.

Regarding the inclusion of non-CO_2 aviation effects into EU ETS, the selection of a climate metric defines the ratio between CO_2 and non-CO_2 effects and therefore the quantity of CO_2

equivalents to be surrendered. The setup of the MRV scheme, however, is independent of this choice. In a pilot phase, CO_2 equivalents could therefore be calculated for different climate metrics.

2.3 Selection of the calculation methodology for CO_2 equivalents (MRV scheme)

For integrating non-CO_2 effects into existing policy instruments, aircraft operators and authorities have to collect and monitor additional flight data for CO2e calculation (see Step 1 in Figure 1). This will probably increase their administrative effort. The level of these additional expenses will be strongly depending on the chosen CO2e calculation method, which differ in the degree of detail and are subject to uncertainties related to atmospheric science (see Figure 2). The higher the accuracy of relevant atmospheric processes, the greater the incentives for climate mitigation. But, however, more accurate CO2e approaches will also require a higher amount of data for monitoring, reporting and verification (see Table 2). 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:

- 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 cost of operation)
- CO2e factors should be easily calculable, predictable and transparent

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; Scheelhaase et al., 2016). This requires at least detailed information about the aircraft trajectory (altitude profile). However, if aircraft flight path data must be monitored, significantly higher non-CO_2 mitigation incentives can be generated by taking the entire 3D or 4D flight profile into consideration (location-dependent or weather- and location-dependent CO2e factor).

A good compromise between high mitigation incentive of non-CO_2 impacts and slightly reduced MRV effort (no ECMWF[1] data required) could initially be a location-dependent CO2e factor, which still relies on climatological mean data (evaluated over the annual mean or for individual seasons) for climate impact assessment. In this case, the CO2e value is estimated individually for each flight, but regardless of the actual weather. If an aircraft flies the same 3D flight profile on the same route every day, the estimated CO2e level remains identical. As a result, the climate impact of a single flight might be over- or underestimated for individual weather situations. However, the route-specific CO2e estimate of all flights over the reference period (e.g., year, season) is reasonably accurate, as extreme weather events of single days are compensated.

A Stepwise implementation of weather- and location-dependent CO2e factors is also possible, with a location-dependent factor as the first implementation step. This requires intermediate evaluations.

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[1] European Centre for Medium-Range Weather Forecasts

Figure 1: Monitoring and reporting steps for integrating non-CO$_2$ aviation effects into EU ETS

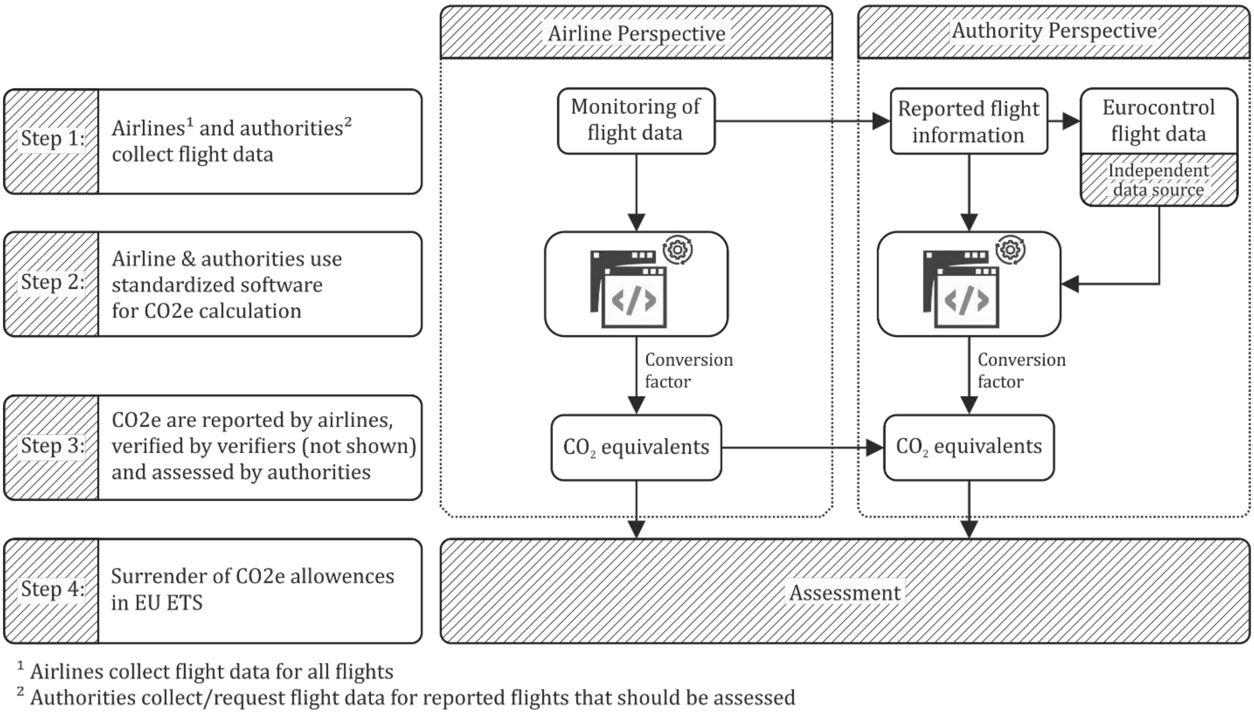

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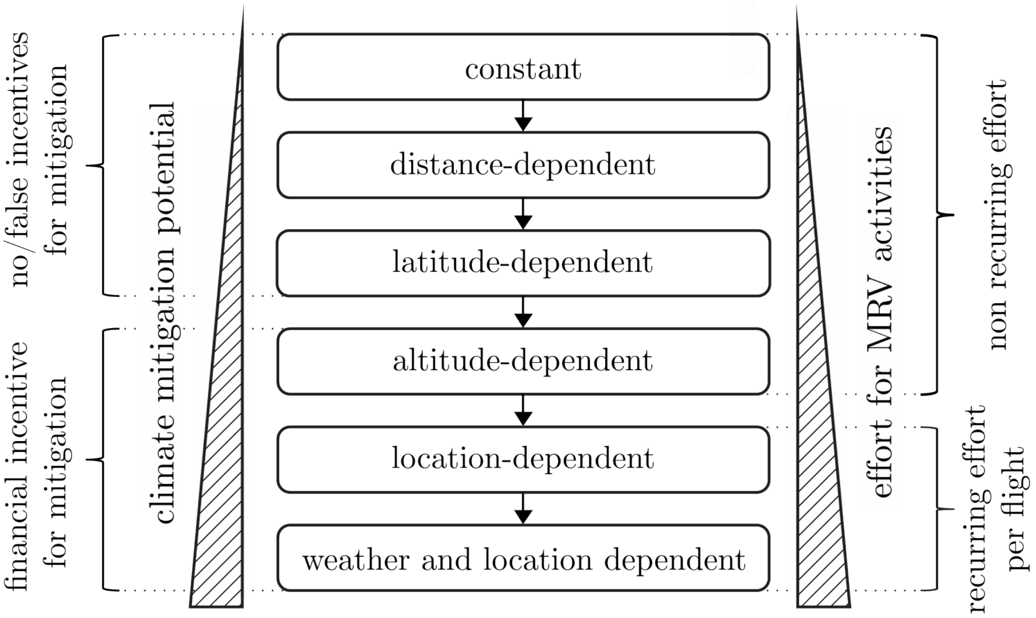
Figure 2: Mitigation benefit and effort for monitoring, reporting and verification (MRV) activities of different CO2e calculation methods



© Niklaß et al., 2020, p. 43 (adapted)

Table 2: Overview of the properties of various CO2e calculation methods. Gray text indicates data/information that is identical to simpler calculation methodologies

CO2e calculation method	Data to be monitored	Data to be reported	Additional MRV effort	Accuracy in climate assessment	Mitigation incentive	Possible applications
Constant	Fuel consumption	Origin-Destination Frequency Fuel consumption CO_2 equivalents	To be neglected	very low	non	ecological footprint assessments
Distance-dependent	Fuel consumption	Origin-Destination Frequency Fuel consumption CO_2 equivalents	To be neglected	Low	non	ecological footprint assessments
Latitude-dependent	Fuel consumption	Origin-Destination Frequency Fuel consumption CO_2 equivalents	Standardized software needed	realistic representation on a yearly basis	non	compensation market
Altitude-dependent	Fuel consumption 3-D position Fuel flow Aircraft mass (optional) Ambient temperature	Origin-Destination Aircraft & Engine type Flight number Fuel Consumption CO_2 equivalents Take-off mass (opt.)	Standardized software needed	realistic representation on a yearly basis	Low to medium	compensation market, emission trading
Location-dependent	Fuel consumption Aircraft mass (optional) 3-D position Fuel flow Ambient temperature Ambient humidity (opt.)	Origin-Destination Aircraft & Engine type Flight number Fuel consumption CO_2 equivalents Take-off mass (opt.)	Standardized software needed	Best estimate on a seasonal or yearly basis	Medium	emission trading

CO2e calculation method	Data to be monitored	Data to be reported	Additional MRV effort	Accuracy in climate assessment	Mitigation incentive	Possible applications
Location- & weather-dependent	Fuel consumption 4-D position Fuel flow Aircraft mass (optional) Ambient temperature Weather forecast data	Origin-Destination Aircraft & Engine type Flight number Fuel consumption CO_2 equivalents Take-off mass (opt.)	Standardized software needed	Best estimate on a daily basis	High	emission trading

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For reducing MRV effort, a standardized CO2e software (step 2 in Figure 1), possibly provided directly by the European Commission for airlines (monitoring & reporting) as well as verifiers & authorities (verification and assessment), could automatically perform all necessary calculations to determine CO2e. This includes the emission calculation (CO_2, H_2O, NO_x) along the flight route as well as the estimation of the CO2e factor of the flight. The emissions calculation procedure could be based on the Boeing Fuel Flow Method 2 (DuBois & Paynter, 2014), a process that can be completely automated by software using in-flight measurement of fuel flow data. Climate response models for computing CO_2 equivalents per flight are not yet publicly available, but a number of European research institutions could provide this capability. As an example, an open source version of DLR's software *AirClim* (Dahlmann et al, 2016) is currently being developed. Another possibility to reduce the MRV effort of aircraft operators is to have only the most necessary data reported. Authorities should retrieve relevant information from independent sources, whenever possible. For instance, flight profile data could be obtained directly from EUROCONTROL (see Figure 1 & Table 2). It would also be possible to estimate the fuel flow along the flight profile. The standardized CO2e software used by the authorities would have to be expanded accordingly.

2.4 How to deal with uncertainties in atmospheric science

By a better understanding of (micro-)physical and chemical processes of the atmosphere, the LOSU[2] of aviation's non-CO_2 effects has been greatly increased. Nevertheless, non-CO_2 effects still account for 8 times more of the uncertainty in the aviation net ERF than CO_2 (Lee et al., 2021). Non-CO2 effects largely depend on meteorology, showing a large daily variability. This variability contributes to a large level of uncertainty of non-CO_2 effects and largely limits their potential in reducing uncertainties. Following the decision of the 1992 United Nations Conference on Environment and Development (UNCED) that a "lack of full scientific certainty shall not be used as a reason for postponing cost-effective measures to prevent environmental degradation" (United Nation, 1992, Annex 1, Principle 15), strategies are required to cope with them.

To better understand the impact of uncertainties on the calculation of non-CO_2 effects and thereby on the potential of setting wrong incentives, risk assessments are required for selected climate agents. First, the climate mitigation potentials of specific strategies have to be verified. Here, the risk assessment clarifies that at a high probability (e.g. >95%) any mitigation measure leads on average to a climate impact reduction of CO_2 and non-CO_2 effects, but may allow for individual cases adverse effects. This kind of risk assessment may include Monte Carlo simulation or similar tools that consider uncertainties and propagate them for various climate mitigation options to uncertainties in gained reductions of CO_2 equivalents. Second, reported CO2e values have to represent estimated climate impact of aviation on average. Here, the risk assessment clarifies that at a high probability (e.g. >95%) the simplified methodologies for CO2e calculations sufficiently describes on average aviation's climate impact on the basis of higher fidelity models and measurements. This requires a solid data base, including flight information, fuel consumption as well as CO_2 equivalents from numerous flights. Necessary data could be collected in a pilot MRV scheme (see Section 2.5), in which non-CO_2 effects are already monitored and reported, but are not yet subject to monetary internalization.

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[2] The LOSU index for each forcing agent relies on an assessment of the nature of assumptions involved, the prevailing uncertainties about the processes that drive the forcing, and the resulting confidence in the estimated numerical value (IPCC 2001).

2.5 Roadmap for CO2e accounting

For the implementation of CO2e accounting, a variety of options of a transition period are conceivable, varying in the choice of (i) geographic scope of application, (ii) time horizon, (iii) climate agents, (iv) climate metrics, (v) CO2e calculation methodology, as well as the (vi) share of accounted CO_2 equivalents.

A pilot MRV phase, focusing only on monitoring and reporting of CO2e, could be used to test and to improve MRV procedures. The data collected in the pilot MRV phase could also be applied to risk assessments to reduce misaligned mitigation incentives as well as to perform analyses of actual cost impacts on airlines and resultings impacts on competition.

The geographic scope of application has to be defined, considering both political and legal perspectives.

In accordance with the results of the risk and impact analyses, actual obligations either to surrender allowances or to buy offsets would start in a 2nd transition phase. 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. For this we see the following options:

- Stepwise enhancement of additional CO2e surrender or offsetting obligations over time (e.g. 20%, 40%, 60%, ... at different years)
- Individual CO2e surrender or offsetting obligations for each species depending on specific uncertainties (e.g. only 20%, 40%, 60%, 80% depending on uncertainties)

3 Summary

- CO_2 and non-CO_2 are important contributors to aviation‘s climate impact.
- The understanding of non-CO_2 effects has been largely increased. The nature of non-CO_2 effects, i.e. the dependency on meteorology largely limits reduction in uncertainties.
- The selection of climate agents largely determines the fidelity of CO_2e (climate impact assessment) as well as the effort for operationalization (required dataset for MRV scheme).
- A stepwise integration of various effects seems possible. However, the most important agents beside CO_2 should be included from the very beginning, since the exclusion of CC and NO_x would also eliminate their incentive for climate impact mitigation. The integration of further effects (aerosol effects, etc.) should be possible at any time.
- The selection of a climate metric defines the ratio between CO_2 and non-CO_2 effects and therefore the quantity of CO_2 equivalents to be surrendered. The setup of the MRV scheme, however, is independent of this choice. In a pilot phase, CO_2 equivalents could be calculated for different climate metrics.
- Several calculation methods for non-CO_2 effects are in principle available, which differ in the degree of detail and are subject to uncertainties related to atmospheric science.
- Choosing a CO2e method is a trade-off between high climate mitigation incentives and low efforts for MRV activities.
- CO2e calculation methodology should provide incentives for actually reducing non-CO_2 effects
  1. not a constant factor, but depending on e.g. technology and operations
  2. not simply adding costs, but providing the possibility to reduce climate impact and cost of operation
- Effort for operationalization (MRV scheme) is strongly dependent on the chosen CO2e approach. It defines the dataset to be monitored, reported and verified.
- A gradual implementation of detailed CO2e calculation methods is possible. A location-dependent CO2e factor seems to be an initial good compromise between high mitigation incentive of non-CO_2 impacts and slightly reduced MRV effort (no ECMWF data required).
- Risk assessment is required to better understand the impact of uncertainties on the calculation of non-CO_2 effects and thereby on the potential of setting wrong incentives:
  1. Climate mitigation potentials of specific strategies have to be verified. This kind of risk assessment may include Monte Carlo simulation or similar tools that consider uncertainties and propagate them for various climate mitigation options to uncertainties in gained reductions of CO_2 equivalents
  2. Reported CO2e values have to represent estimated climate impact of aviation on average. This requires a solid data base, that could be collected in a pilot MRV scheme, in which CO2e are already monitored and reported, but are not yet subject to monetary internalization.
- In accordance with the results of the risk analysis, actual obligations either to surrender allowances or to buy offsets would start in a 2nd transition phase. 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.

4 List of references

European Environment Agency (2019). Annual European Union greenhouse gas inventory 1990–2017 and inventory report 2019 (EEA/PUBL/2019/051). Submission under the United Nations Framework Convention on Climate Change and the Kyoto Protocol

Dahlmann, K. (2011). Eine Methode zur effizienten Bewertung von Maßnahmen zur effizienten Bewertung von Maßnahmen zur Klimaoptimierung des Luftverkehrs. Dissertation Ludwig-Maximilians-Universität, München, Dezember 2011.

Dahlmann, K., Grewe, V., Frömming, C., Burkhardt, U., 2016. Can we reliably assess climate mitigation options for air traffic scenarios despite large uncertainties in atmospheric processes? Transp. Res. D.-TR E 46, 40–55. http://dx.doi.org/10.1016/j.trd.2016.03.006.

Dahlmann, K., Grewe, V., Matthes S., & Yamashita, H. (2021): Climate assessment of single flights: Deduction of route specific equivalent CO2 emissions, Int. Journal of Sustainable Transportation, https://doi.org/10.1080/15568318.2021.1979136.

DuBois, D., & Paynter, G. (2014). 'Fuel flow method 2' for estimating aircraft emissions (SAE Technical Paper 2006-01-1987). Society of Automotive Engineers (SAE).

Faber, J., Greenwood, D., Lee, D., Mann, M., de Leon, P. M., Nelissen, D., Owen, B., Ralph, M., Tilston, J., van Velzen, A., & van de Vreede, G. (2008). Lower NOx at higher altitudes. Policies to reduce the climate impact of aviation NOx emission. CE Delft.

Fuglestvedt, J. S., Shine, K. P., Berntsen, T., Cook, J., Lee, D. S., Stenke, A., Skeie, R. B., Velders, G. J. M., & Waitz, I. A. (2010). Transport impacts on atmosphere and climate: Metrics. Atmospheric Environment, 44(37), 4648–4677. https://doi.org/10.1016/j.atmosenv.2009.04.044.

Grewe, V., & Dahlmann, K. (2015). How ambiguous are climate metrics? And are we prepared to assess and compare the climate impact of new air traffic technologies? Atmospheric Environment, 106(1), 373–374. https://doi.org/10.1016/j.atmosenv.2015.02.039.

Grewe, V., Dahlmann, K., Flink, J., Frömming, C., Ghosh, R., Gierens, K., Heller, R., Hendricks, J., Jöckel, P., Kaufmann, S., Kölker, K., Linke, F., Luchkova, T., Lührs, B., van Manen, J., Matthes, S., Minikin, A., Niklaß, M., Plohr, M., …Ziereis, H. (2017). Mitigating the climate impact from aviation: Achievements and results of the DLR wecare project. Aerospace, 44(3), 1–50. https://doi.org/10.3390/aerospace4030034.

Grewe, V. (2020). Aviation emissions and climate impacts. In Aviation and climate change. Taylor and Francis Group. ISBN:9781472479174

IPCC, 2001: Climate Change 2001: The Scientific Basis. Contribution of Working Group I to the Third Assessment Report of the Intergovernmental Panel on Climate Change [Houghton, J.T., Y. Ding, D.J. Griggs, M. Noguer, P.J. van der Linden, X. Dai, K. Maskell, and C.A. Johnson (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Kharina, A., & Rutherford, D. (2015). Fuel efficiency trends for new commercial jet aircraft: 1960 to 2014. White paper of the International Council on Clean Transportation (ICCT).

Lee, D. S., Pitari, G., Grewe, V., Gierens, K., Penner, J. E., Petzold, A., Prather, M. J., Schumann, U., Bais, A., Berntsen, T., Iachetti, D., Lim, L. L., & Sausen, R. (2010). Transport impacts on atmosphere and climate: Aviation. Atmospheric Environment, 44(37), 4678–4734. https://doi.org/10.1016/j.atmosenv.2009.06.005.

Lee, D. S., Fahey, D. W., Skowron, A., Allen, M. R., Burkhardt, U., Chen, Q., Doherty, S. J., Freeman, S., Forster, P. M., Fuglestvedt, J., Gettelman, A., De León, R. R., Lim, L. L., Lund, M. T., Millar, R. J., Owen, B., Penner, J. E., Pitari, G., Prather, M. J., …Wilcox, L. J. (2020). The contribution of global aviation to anthropogenic climate forcing for 2000 to 2018. Atmospheric Environment, 244 (1), 1352–2310. https://doi.org/10.1016/j.atmosenv.2020.117834.

Lührs, B., Niklaß, M., Frömming, C., Grewe, V., & Gollnick, V. (2016). Cost-benefit assessment of 2D- and 3D climate and weather optimized trajectories. In 16th AIAA aviation. https://doi.org/10.2514/6.2016-3758.

Lührs, B.; Linke, F.; Matthes, S.; Grewe, V.; Yin, F. Climate Impact Mitigation Potential of European Air Traffic in a Weather Situation with Strong Contrail Formation. Aerospace 2021, 8, 50. https://doi.org/10.3390/aerospace8020050.

Matthes, S.; Lührs, B.; Dahlmann, K.; Grewe, V.; Linke, F.; Yin, F.; Klingaman, E.; Shine, K.P. Climate-Optimized Trajectories and Robust Mitigation Potential: Flying ATM4E. Aerospace 2020, 7, 156. https://doi.org/10.3390/aerospace7110156.

Niklaß, M., Lührs, B., Grewe, V., Dahlmann, K., Luchkova, T., Linke, F., & Gollnick, V. (2019). Potential to reduce the climate impact of aviation by climate restricted airspaces. Transport Policy, 83(1), 102–10. https://doi.org/10.1016/j.tranpol.2016.12.010.

Niklaß, M., Dahlmann, K., Grewe, V., Maertens, S., Plohr, H., Scheelhaase, M., Schwieger, J., Brodmann, U., Kurzböck, C., Repmann, M., Schweizer, N., & von Unger, M. (2020, July). Integration of non-CO2 effects of aviation in the EU ETS and under CORSIA. Climate Change: 20/2020, Umweltbundesamt. FKZ:3717-42-509-0.

Niklaß, M., Grewe, V., Gollnick, V., Dahlmann, K. (2021). Concept of climate-charged airspaces: a potential policy instrument for internalizing aviation’s climate impact of non-CO2 effects, Climate Policy, DOI: https://doi.org/10.1080/14693062.2021.1950602.

Ponater, M.; Bickel, M.; Bock, L.; Burkhardt, U. Towards Determining the Contrail Cirrus Efficacy. Aerospace 2021, 8, 42. https://doi.org/10.3390/aerospace8020042.

Scheelhaase, J., Dahlmann, K., Jung, M., Keimel, H., Nieße, H., Sausen, R., Schaefer, M., & Wolters, F. (2016). How to best address aviation’s full climate impact from an economic policy point of view? – Main results from AviClim research project. Transportation Research Part D: Transport and Environment, 45(1), 112–125. https://doi.org/10.1016/j.trd.2015.09.002.

United Nation (1992, June 3–14). Report of the United Nations conference on environment and development.

Williams, V., Noland, R. B., & Toumi, R. (2002). Reducing the climate change impacts of aviation by restricting cruise altitudes. Transportation Research Part D: Transport and Environment, 7(6), 451–464. https://doi.org/10.1016/S1361-9209(02)00013-5.

Williams, V., Noland, R. B., & Toumi, R. (2003). Air transport cruise altitude restrictions to minimize contrail formation. Climate Policy, 3 (3), 207–219. https://doi.org/10.3763/cpol.2003.0328.

Wit, R. C. N., Kampman, B., & Boon, B. (2004, October). Climate impacts from international aviation and shipping (4.4772.44/e). CE Delft