CLIMATE CHANGE
29/2024

Final report

DLR Review of an EASA Report requested by the European Commission

„Updated analysis of the non-CO_2 climate impacts of aviation and potential policy measures pursuant to EU Emissions Trading System Directive Article 30(4)"

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Abstract: DLR Review of an EASA Report requested by the European Commission

Aircraft operations contribute to climate change by emissions of carbon dioxide (CO_2), nitrogen oxides (NOx), sulfur oxides (SOx), water vapor (H_2O), aerosols, and the formation of contrails and contrail cirrus. Since 2012, aviation's CO_2 emissions have been regulated by the European Emission Trading System (EU ETS). All flights within the European Economic Area (EEA) are subject to this scheme. According to Article 30(4) of the revised EU ETS Directive 2018/410, 'the Commission shall present an updated analysis of the non-CO_2 effects of aviation, accompanied, where appropriate, by a proposal on how best to address those effects (before January 2020).' Against this background, the EU Commission commissioned a study to EASA in 2019. Three main questions had to be investigated: Question 1: What is the most recent knowledge on the climate change effects of non-CO_2 emissions from aviation activities? Question 2: What factors/variables have had an impact on those effects? What is the level of that impact? Do these factors/variables exhibit trade-offs or interdependencies between different emissions? Question 3: What research has been undertaken on potential policy action to reduce non-CO_2 climate impacts? What are the pros and cons of these options in terms of implementation? What knowledge gaps exist?' As of November 2020, the full report investigating these tasks has been published (European Commission, 2020). In December 2020, the German Environmental Agency (UBA), mandated the German Aerospace Center (DLR) with a study on proving/testing monitoring and reporting methods for non-CO_2 climate impacts of aviation in the EU ETS. One important work package within this DLR-study was the review of the EASA study by the European Commission (2020). This review has been conducted with the emphasis on currently remaining research questions, on a risk management analysis and on measures implementable as pilot project(s). The main results of this review are presented in this report.

Kurzbeschreibung: DLR Review des von der Europäischen Kommission beauftragten EASA Berichts

Der Luftverkehr trägt durch den Ausstoß von Kohlendioxid (CO_2), Stickoxiden (NOx), Schwefeloxiden (SOx), Wasserdampf (H_2O), Aerosolen und die Bildung von Kondensstreifen und Zirrusfahnen zum Klimawandel bei. Seit 2012 werden die CO_2-Emissionen des Luftverkehrs durch das Europäische Emissionshandelssystem (EU-ETS) reguliert. Alle Flüge innerhalb des Europäischen Wirtschaftsraums (EWR) fallen unter dieses System. Gemäß Artikel 30 Absatz 4 der überarbeiteten EU-EHS-Richtlinie 2018/410 "legt die Kommission eine aktualisierte Analyse der Nicht-CO_2-Effekte des Luftverkehrs vor, gegebenenfalls zusammen mit einem Vorschlag, wie diese Effekte am besten reduziert werden können (vor Januar 2020)." Vor diesem Hintergrund hat die EASA im Auftrag der EU-Kommission eine Studie erarbeitet. Es wurden drei wesentliche Fragen untersucht: Frage 1: Was sind die neuesten Erkenntnisse über die Effekte der Nicht-CO_2-Emissionen des Luftverkehrs auf den Klimawandel? Frage 2: Welche Maßnahmen/Technologien haben sich auf diese Nicht-CO_2-Emissionen ausgewirkt? Wie groß ist deren Einfluss? Gibt es gegenseitige Abhängigkeiten zwischen den verschiedenen Emissionen? Frage 3: Welche Forschungsarbeiten wurden zu möglichen politischen Maßnahmen zur Verringerung der Nicht-CO_2-Emissionen durchgeführt? Was sind die Vor- und Nachteile dieser möglichen Maßnahmen im Hinblick auf ihre Umsetzung? Welche Wissenslücken bestehen? Im November 2020 wurde der vollständige Bericht der EASA veröffentlicht (Europäische Kommission, 2020). Im Dezember 2020 beauftragte das Umweltbundesamt (UBA) das Deutsche Zentrum für Luft- und Raumfahrt (DLR) mit einer Studie zur Erprobung von Monitoring- und Reportingmethoden für Nicht-CO_2-Emissionen des Luftverkehrs im EU-ETS. Ein wichtiges Arbeitspaket innerhalb dieser DLR-Studie war der Review der EASA-Studie (2020). Dieser Review wurde mit dem Schwerpunkt auf derzeit noch offenen Forschungsfragen, auf einer Risikomanagementanalyse und auf als Pilotprojekt(e) umsetzbaren Maßnahmen durchgeführt. Die wichtigsten Ergebnisse dieser Überprüfung werden in diesem Bericht vorgestellt.

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List of abbreviations

ATR	Averaged Temperature Response
BDL	German Aviation Association (Bundesverband der Deutschen Luftverkehrs-wirtschaft)
CAEP	Committee on Aviation Environmental Protection
CO_2	Carbon Dioxide
COP	Conference of the Parties
DLR	German Aerospace Center (Deutsches Zentrum für Luft- und Raumfahrt)
EASA	European Union Aviation Safety Agency
EC	European Commission
EINOx	Emission Index of Nitrogen Oxides
EU ETS	EU Emissions Trading System
EEA	European Economic Area
ERF	Effective Radiative Forcing
GHG	Greenhouse Gas
H_2O	Water vapour
ICAO	International Civil Aviation Organization
IEIR	Independent Experts Integrated Review
IPCC	International Panel on Climate Change
LTO	Landing and Take-off
nvPM	Non-volatile Particulate Matter Emissions
NO_x	Nitrogen Oxides
OPR	Overall Pessure Ratio
RF	Radiative Forcing
RQL	Rich-quench-lean
SAF	Sustainable Alternative Fuels
SO_x	Sulfur Oxides
UBA	German Environment Agency (Umweltbundesamt)
UNFCCC	United Nations Framework Convention on Climate Change
WLTP	Worldwide Harmonized Light-Duty Vehicles Test Procedure

1 Background and objective

Aircraft operations contribute to climate change by emissions of carbon dioxide (CO_2), nitrogen oxides (NO_x), sulfur oxides (SO_x), water vapor (H_2O), aerosols, and the formation of contrails and contrail cirrus. According to the International Panel on Climate Change (IPCC), the total climate impact by aviation is two to four times larger than the effect of its past CO_2 emissions alone (IPCC, 1999 and 2007). In 2009, Lee et al. (2009) estimated for the year 2005 that aircraft-induced CO_2 contributed 1.6 % to the total anthropogenic radiative forcing while the total aviation effect, i.e., the sum of the CO_2 and the non-CO_2 effects, amounted to 4.9 %. However, uncertainties concerning the impact of some of these species, especially NO_x emitted on high altitudes, and cloud effects are still large (Lee and Fahey, 2016 and Lee et al., 2009).

Since 2012, aviation's CO_2 emissions have been regulated by the European Emission Trading System (EU ETS). All flights within the European Economic Area (EEA) are subject to this scheme. According to Article 30(4) of the revised EU ETS Directive 2018/410, 'the Commission shall present an updated analysis of the non-CO_2 effects of aviation, accompanied, where appropriate, by a proposal on how best to address those effects (before January 2020).'

Against this background, the EU Commission commissioned a study to EASA in 2019. Three main questions had to be investigated by a team of international experts:

'Task 1: What is the most recent knowledge on the climate change effects of non-CO_2 emissions from aviation activities?

Task 2: What factors/variables have had an impact on those effects (e. g. technology/design, operations, fuel, market-based measures)? What is the level of that impact? Do these factors/variables exhibit trade-offs or interdependencies between different emissions?

Task 3: What research has been undertaken on potential policy action to reduce non-CO_2 climate impacts? What are the pros and cons of these options in terms of implementation? What knowledge gaps exist?' (European Commission, 2020).

As of November 2020, the full report investigating these tasks has been published (European Commission, 2020).

In December 2020, the German Environment Agency (UBA), mandated the German Aerospace Center (DLR) with a study on proving/testing monitoring and reporting methods for non-CO_2 climate impacts of aviation in the EU ETS. One important work package within this DLR-study is the review of the recent EASA study by the European Commission (2020). This review shall be conducted with the emphasis on currently remaining research questions, on a risk management analysis and on measures implementable as pilot project(s) whereas by the latter important practical experiences with innovative policy measures for the limitation of aviation's climate relevant species can be gained and at least some at the moment open research questions could be answered. The main results of this review are presented in this report. It is organized as follows: In section 2, the results of the EC-study are investigated from an atmospheric point of view and an interpretation towards a risk analysis is provided. In section 3, the policy options presented in the EC-study are analyzed and evaluated towards feasibility. Finally, section 4 provides recommendations for next steps. In the following text the study commissioned to EC by the European Commission is called EC-report.

2 Review of atmospheric science results

The EC-report summarises the current status of science and remaining uncertainties of aviation's CO_2 and non-CO_2 impacts (task 1) as well as technological and operational factors for limiting or reducing non-CO_2 impacts from aviation and related trade-off issues (task 2). The report addresses current knowledge in atmospheric science well and clearly states the remaining uncertainties. While the scientific basis demonstrated in the report is robust, their interpretation and recommendations are, by nature, more based on individual preferences. Here, we will shortly summarise and briefly comment the overall findings of the report. We further extend the discussion on the interpretation and recommendations by offering alternative pathways. Thereby we change the perspective from focussing on uncertainties in atmospheric science to analysing risks and areas of consistency.

2.1 Summary on current status of science and remaining uncertainties (Task 2)

2.1.1 Aviation emissions and effects on aviation radiative forcing

The EC-report (European Commission, 2020) summarises the current knowledge on aviation emissions. It clearly states that NO_x emissions are relatively well characterised with a fleet-wise increase in the NO_x emission index (emitted nitrogen oxides per fuel used, EI-NO_x) over the last decades, while fuel efficiencies have increased. Other non-CO_2 emissions such as sulphates and soot, in terms of number of particles and mass are not as well quantified yet, though progress might be achieved on the basis of the new nvPM ICAO certification.

The EC-report further summarises the atmospheric impacts of aviation emissions and concludes that the major non-CO_2 effects arise from NO_x emissions and contrail-cirrus formation and points out that considerable uncertainties remain for quantifying either effect. Emphasis is given to the impact of the evolution of future background emissions, e.g. from industry, traffic, households, on the estimates of future aviation NO_x-RF and the large uncertainties with respect to contrail-cirrus modelling. It is pointed out that the so-called "Effective Radiative Forcing" (ERF) is a more suitable radiative metric than RF, since it better relates to the expected future temperature effects. The ERF metric is also adopted by a wider scientific community and IPCC. The impact of aviation soot particles on natural ice clouds is identified as a potentially large cooling effect, however, the sign and magnitude of the forcing is not known with confidence. Similarly, it is concluded that emissions leading to changes in the aerosol concentrations potentially alter low-level clouds and are likely to lead to a cooling with a low confidence in the magnitude.

DLR review:

The EC-report provides a very comprehensive and thoughtful status of the current understanding of the atmospheric impacts of aviation emissions. A large part of the summary is based on the findings of Lee et al. (2021) and for net NO_x-RF on Skowron et al. (2021), rounding it off by addressing other recent literature, leading to the more general conclusion that "the largest of these effects are the forcing from the current-day net NO_x effect and contrail cirrus."

While this conclusion and also the discussion on uncertainties can in general be largely supported, unfortunately, the conclusions are not addressing how to deal with these uncertainties and how these uncertainties can be considered to allow for a de-risking strategy for reducing non-CO_2 climate effects.

Exemplarily, Dahlmann et al. (2016) provided one strategy to address uncertainties in non-CO_2 aviation impacts arising from atmospheric science, in decision making for mitigation options. Hence, an analysis is required which analyses the risks of disbenefits when implementing non-CO_2 aviation effects. Undoubtedly, reducing uncertainties in atmospheric science is important and to be pursued, however, the EC-report might be interpreted in a way to first reduce scientific uncertainties before acting. From DLR point of view, a roadmap should rather be developed how to consider risks in decision making and to derive e.g. robust or no-regret measures with a relatively low risk of failure.

In general, NO_x and contrail-cirrus have both warming and cooling effects, i.e. also likely for individual flights (see e.g. Grewe et al., 2014 their Fig. 8). Though, either overall radiative effect is estimated to be a warming one. Any risk assessment could benefit from considering these effects in their spatial and temporal inhomogeneity. Additionally, a revision of the analysis technique in determining the total NO_x-RF might also be required as indicated in Section 2.2.3 of the EC-Report, as there are very strong statements published on preferring so-called tagging or contribution methods, when assessing the contribution of aviation NO_x to RF[1]. This method fully decomposes anthropogenic contributions to atmospheric concentrations and avoids attributing ozone from other sectors to aviation as otherwise would be done when using the so-called perturbation approach. This way, the contribution calculation becomes less sensitive to changes in background concentrations (Grewe et al. 2012) and changes in the sign of the RF-NO_x for future background emissions become more unlikely.

2.1.2 Metrics and equivalent CO_2

The EC-Report provides an overview on the climate metrics and their use to derive equivalent CO_2 emissions for non-CO_2 effects. An emphasis is given on the different lifespans of CO_2 (long) and non-CO_2 (short) effects, which complicates a clear evaluation of trade-offs since those are dependent on the time horizon. A clear statement is made that temperature-based metrics and GWP* are potentially representing the temperature targets of the Paris Agreement best. A recommendation of individual metrics is not provided since that would imply a user's choice and a political debate on climate objectives and other socio-economic factors.

DLR review:

The EC-report provides a state-of-the-art discussion on climate metrics and the conversion into equivalent CO_2 emissions. However, while there is an agreement that science cannot provide best climate metrics, which are equally valid for all research and political questions, there is also the possibility to select dedicated climate objectives from the debate between policies and science and relate these objectives to adequate and distinct climate metrics (Grewe and Dahlmann, 2015). This potentially facilitates an easier decision process on the choice of climate metric, since it better discriminates between the more political decision on the climate objective and the more scientific decision, which climate metric suits the climate objective. There are two obvious climate objectives related to the Paris Agreement and the 1.5°C-IPCC report:

[1] However, this study demonstrates that when the relationship between emissions and concentrations is nonlinear, sensitivity approaches are not suitable to retrieve source contributions", Clappier et l. (2017); "The simplest approach based on increments (incremental approach) is often not suitable ", Thunis, 2019; "We demonstrate the utility of ozone source attribution as a powerful model diagnostic tool", Bulter et al., 2020; "This leads to an underestimation of the contribution of specific emission sources to ozone if these impacts are used for source attribution", Mertens et al. 2020. "Nevertheless, tagging is particularly helpful when answering the question as to how overall changes can be attributed to different emission sectors, and hence represents an attribution method that treats individual sectors more uniformly", Matthes et al., 2021

- Limiting long-term climate change: What long-term climate reduction can be achieved by a regarded measure in order to support the target of limiting climate change in the light of the Paris Agreement? (objective 1)
- Avoiding tipping points: What short-term climate reduction can be achieved by a regarded measure in order to support the target of limiting overshooting effects in the light of the Paris Agreement? (objective 2)

Considering the contribution of a measure to climate change hence requires an estimated future scenario (F), where the respective measure is applied on a daily basis. The average temperature response can serve as a basis for estimating the mean climate impact over a given time horizon of, e.g., 20 and 100 years for objective 1 and 2, respectively. This could lead to a proposal of climate metrics for

- Limiting long-term climate change: 100 year averaged temperature response (ATR) of a future (F) air traffic scenario including the respective measure: *F-ATR100*
- Avoiding tipping points: 20 year averaged temperature response (ATR) of a future air traffic scenario (F) including the respective measure: *F-ATR20*

As discussed in the EC-Report GWP* with a time horizon of 100 years or 20 years are similar to the respective potential on the basis of F-ATR metrics since they are both addressing temperature changes and are closer related to objectives with respect to the Paris Agreement. It is important to note that the impact of the choice of the metrics (here: potential of F-ATR vs. GWP*) is small as long as they target the same climate objective.

The EC-report characterises the differences between climate metrics and discusses the challenges for calculating CO_2-equivalences based on those climate metrics. By this, the report touches upon requirements for climate metrics to enable the calculation of CO_2-equivalences for non-CO_2 effects. However, a clearer description of these requirements would have been more useful to foster any inclusion of non-CO_2 effects into regulations and assessments, though certainly challenging. Based upon the report, we suggest the following list of requirements that a suitable climate metric might fulfil:

- Technology dependence: Changes in, e.g. the emission index of NO_x should be included in the e-CO_2 calculations.
- Emission growth dependence: The growth of emissions should be included in the calculation of the e-CO_2 emissions, since they largely control the impact of short-term, i.e. non-CO_2 effects. Since technologies evolve differently for individual emitted species, growth (or decline) of CO_2 and other emissions, e.g. NO_x, should be treated separately.
- Update frequency: The dependence on the emission growth, might make it necessary to update equivalent ratios on, e.g., an annual basis with a well-defined procedure.
- Dependence on regional emissions: Since non-CO_2 effects have a temporal and spatial dependency, i.e., the location and time of emissions largely influence the climate impact of those emissions, a consideration of a local dependency of the e-CO_2 emission might be required. Currently, dependencies from a more climatological point of view to weather dependent calculations are discussed in science (Niklaß et al. 2019).
- Forward looking climate impact: As clearly discussed in the EC-Report, values from, e.g. Lee et al. (2021) for different climate metrics are based upon past aviation operations and technologies. Therefore, they are not a suitable basis for e-CO_2 calculations which target the assessment of current and future emissions and technologies.

- Relation to the Paris Agreement: A climate metric might generally follow the target provided by the Paris Agreement and by that resemble temperature targets. The EC-report suggests temperature-based metrics (AGTP, ATR) and GWP*.
- Stability: Temporal changes in the CO_2-equivalence calculations are envisaged to account for future technology and socio-economic changes. Short-term fluctuations, however, should be limited to allow for a robust and predictable evolution of CO_2-equivalences, which is also addressed in the EC-report (3rd key point of Section 2.3).

Note that this list might be extended.

2.1.3 Summary on technology and operational factors for limiting or reducing non-CO_2 impacts from aviation and related trade-off issues (Task 2)

Emissions:

The EC-report summarises in more detail the knowledge on non-CO_2 emissions. In general, due to the ICAO regulations' historical focus on air quality, the LTO emissions (take-off, climb, approach, taxi/idle) are well characterised, whereas for cruise conditions emission data are not required to be certified and hence are not known to the same degree of accuracy. The regulation relates thrust specific NO_x emissions to the overall pressure ratio (OPR). More stringent certification levels led to $EINO_x$ improvements at constant OPR. However, since OPR and thereby fuel efficiency increased over time, the fleet-averaged $EINO_x$ has actually increased, though NO_x emissions per passenger-kilometer decreased. The report stresses, however, that more research into cruise NOx emissions is required to understand the relation between $EINO_x$ at surface conditions and cruise conditions, especially for future engine developments and their reduction potentials. Non-volatile particulate matter emissions (nvPM) are now better characterised in mass and number based on the new ICAO regulation. However, also more research is required for nvPM estimates at cruise conditions. In the future, a significant reduction of nvPM emission is expected since recent low-emission engine technologies (lean burn and advanced RQL) will increase their market share.

Trade-offs:

Trade-offs are discussed for CO_2 and NO_x emissions, pointing out that increasing the NO_x stringency below the CAEP/8 standard may come at the expense of some specific fuel consumption deterioration. However, it is also discussed in the Independent Experts Integrated Review (IEIR) that in the past, this trade-off was only very limited. No trade-off of between NO_x and nvPM emissions was observed for recent engine technologies (lean burn and advanced RQL) since both emission types are reduced with respect to earlier rich burn engines. However, trade-offs might appear for future improvements of these engines. Anyway, further CO_2 reductions are envisaged due to commercial incentives, aerodynamic improvements and weight savings technologies which lead to simultaneous reductions in NO_x and nvPM.

Operational measures and fuels:

The EC-Report discusses the options of avoiding climate-sensitive regions and states that contrail avoidance involves flying at sub-optimal conditions and hence is associated with fuel penalties. Sustainable alternative fuels (SAF) have shown to reduce soot particle emissions and thereby to reduce the contrail climate impacts. However, the greenhouse gas life-cycle of SAF has to be analyzed carefully, especially with respect to land use changes to balance the net environmental benefits.

DLR review:

The EC-Report largely stresses the trade-offs between fuel use (and therefore CO_2 emissions) on the one side and non-CO_2 effects and emissions such as NO_x emissions on the other side, regarding future technologies, contrail avoidance or more general climate-optimized flying. However, the trade-offs largely depend on the reference chosen. For example, when analyzing the advancements of fuel use and NO_x emissions over time both were reduced and the IE stated that the fuel penalty for NO_x reductions was low, i.e. in the range of 0% to 0.5% and hence also the trade-off was weak. Whereas taking an engine technology and optimizing that given technology for a NO_x reduction might have a much stronger trade-off. Potential trade-offs between NO_x and nvPM might be hidden by the fact that all current in-service engines were developed with no nvPM regulation existing and therefore optimized for low NO_x and fuel burn only (with the smoke number standard being only a plume visibility limit). Future developments might therefore show more distinct trade-offs. However, this might be a more academic view. Similar for contrail avoidance. Papers like Grewe et al. (2017) or Matthes et al. (2020) presume an academic and ideal cost optimal scenario. And hence avoidance of either contrails or climate sensitive regions – by definition – lead to a fuel penalty. However, current ATM is not performed fuel optimal nor cost optimal and hence there are possibilities to reduce both fuel use and non-CO_2 climate impact, so-called win-win situations. In addition, the fuel optimal flight altitudes for current aircraft are broad enough to be able to cover a range of appropriate flight levels. Hence the fuel penalty for contrail avoidance is largely dependent on the reference, and more research is required to identify situations with minimal trade-offs between non-CO_2 effects and fuel consumption. In addition, a combination of SAF and avoidance of climate sensitive regions might lead to considerable reductions in both CO_2 and non-CO_2 climate impacts.

Other operational improvements, such as formation flight (Marks et al. 2021, Dahlmann et al. 2020), intermediate stop operations (Linke et al. 2017), or climate North-Atlantic Track Systems might have an overall climate benefit, though dependent on the climate objective and metric.

3 Review of policy option results

As explained above, this section investigates the recent EC-Report (European Commission, 2020) concerning the potential policy measures to reduce non-CO_2 climate impacts. Special focus will be on their feasibility of implementation.

After considering a broad range of possible measures, the EC-Report concentrated its analysis on six potential policy options:

- NO_x charge
- Inclusion of aircraft NO_x emissions in the EU ETS
- Reduction in maximum limit of aromatics within fuel specifications
- Mandatory use of SAF (Sustainable Aviation Fuels)
- Avoidance of ice-supersaturated areas by operational measures
- Climate Charge.

EC-Reports' main results indicate that the first two measures investigated (NO_x charge and the inclusion of aircraft NO_x emissions in the EU ETS) would lead to financial incentives for both aircraft/engine manufacturers and airlines to reduce NO_x emissions. Moreover, the trade-off between optimizing aircraft fuel burn (and thus CO_2 emissions) and NO_x emissions will also have to be kept in mind by the manufacturers and airlines. However, the EC-Report underlines a number of out-standing atmospheric science-related research questions towards making such financial measures implementable. Against this back-ground, the EC-Report estimates that both measures could potentially be implemented in the medium term, i.e. in 5 to 8 years.

Reducing aromatics within fuel and the mandatory use of Sustainable Aviation Fuels (SAF) (measures three and four listed above) would reduce aviation's emissions of soot particulates and the radiative effects of contrail cirrus clouds. Reducing aromatics content of fuel would require kerosene producers to adapt their production processes. In addition, this production process change has to be monitored. The mandatory use of SAF could be enforced by introducing a blending quota which should be at least on European level. This quota would specify a certain percentage of SAF of total jet fuel sold which could be gradually increased. If well designed, this quota would lead to simultaneous reductions in nvPM and sulphur emissions and CO_2 emissions. At this point, the EC-Report indicates a number of atmospheric science issues which have to be solved before the implementation of fuel-related measures (see section 2). Against this background, the EC-experts conclude that reducing aromatics with-in fuel could potentially be implemented in the mid- (i.e. 5 to 8 years) to long-term (i.e. 8+ years) and the mandatory use of SAF could be implemented in the short- (i.e. 2 to 5 years) to mid-term (i.e. 5 to 8 years).

The measures five and six listed above (avoidance of ice-supersaturated areas and a "climate charge") aim at incentivizing climate friendly aircraft operations. By optimizing individual flight trajectories to avoid ice-supersaturated areas and other regions considered climate-sensitive, the formation of contrail-cirrus clouds could be reduced. In contrast, a climate charge would address all non-CO_2 effects (NO_x, water vapor, soot, sulphates, contrails) simultaneously. However, the EC-Report raises a large number of partly 'significant' research issues in the field of atmospheric science that would have to be addressed before the implementation of any such measure. Due to these open research questions, any measure to avoid ice-supersaturated areas could potentially be introduced only in the mid-term, i.e. 5 to 8 years. And a climate charge could only be introduced in the long-term, i. e. 8+ years, according to the EC-Report.

DLR review:

The EC-Report provides a comprehensive and broad analysis of possible measures for the limitation of aviation's non-CO_2 effects. Therefore, an extensive and thorough literature review has been conducted. Different types of policy measures (financial incentives/market-based measures, rules and regulations, quotas, operational measures) have been considered. This selection comprises most types of potential policy measures suitable for the reduction of air transport's climate relevant species.

Unfortunately, none of the investigated potential policy measures seems to be ready for implementation in the short run. According to the EC-Report, this is predominantly the case due to a great number of currently unsolved research questions in atmospheric science. At best, selected measures could be implemented after an additional research effort in atmospheric science of 2 – 8 years (as estimated by the EC-Report for the mandatory use of SAF). In the last resort, some measures would need 8+ years of further research before their implementation (as estimated for a climate charge).

From DLR point of view, the EC-Report argues too tentative and lacks economic analysis. The (between EC and DLR) undisputable fact that further research in atmospheric science is needed does not automatically lead to the conclusion that the design and implementation of any policy measure will have to wait until further natural scientific knowledge has been gained. In fact, both further research in atmospheric science and at least pilot projects for selected measures addressing aviation's non-CO_2 effects should be conducted in the short-term. By doing so, important experiences and knowledge could be achieved simultaneously.

At this point it will be important to select promising policy measures first. A selection criterion inter alia could be that the respective policy measure does not raise "significant" atmospheric science related question. According to the EC-Report, this applies to measures number one to four listed above (NO_x charge; Inclusion of aircraft NO_x emissions in the EU ETS; Reduction in maximum limit of aromatics within fuel specifications and Mandatory use of SAF (Sustainable Aviation Fuels). Another potentially promising policy measure would be to include selected non-CO_2 species in the EU ETS. This has been investigated by Niklaß et al. (2019) on behalf of the German Environment Agency (UBA) focussing on operational feasibility.

As a next step, the economic impacts of different design options for the selected policy measures should be investigated. This should be done in order to identify the most efficient design in terms of costs, competitive impacts and environmental advantages for each policy measure under consideration. The need for further economic research, e. g. for cost-benefit analyses, cost estimations and their impact on European airlines and other relevant stakeholders as well as effects on competition, especially between European and non-European airlines, has also been pointed out by the authors of the EC-Report.

As a third step, pilot projects in co-operation with stakeholder from industry could be conducted for the selected, most efficient policy measures. For instance, German BDL (German Aviation Association) could be a good partner for pilot projects for the use of SAF. Airlines potentially interested in participating are LH, Air France, e. g. Both already declared their interest in the further use of SAF. As SAF is currently very expensive in comparison to traditional kerosene, economic aspects will play an important role here.

On this basis, and with additional further knowledge from atmospheric science which could have been gained in the meantime, it will be possible to design and implement innovative policy measures for the limitation of air transport's non-CO_2 species.

4 Recommendations

- The conclusion in the EC-Report that "the largest of these effects are the forcing from the current-day net NO_x effect and contrail cirrus" is supported.
- The EC-Report is lacking a strategy for managing uncertainties to derive a de-risking strategy for implementing non-CO_2 effects in decision making.
- Revisiting diagnostics with respect to NO_x-RF which include attribution techniques and temporal responses of methane contributions and having the potential to reduce uncertainties.
- The EC-Report is lacking a strategy for agreeing on climate metrics, which is currently felt as a locked-in situation between policies and science. It is noted here that a climate metric should be selected in accordance with the strategic question to be answered. Thereby, the climate metrics choices are limited.
- No climate metric is suggested in the EC-report for good and overall accepted reasons. However, still a set of climate objectives could have been proposed by the EC experts and adequate climate metrics which address these objectives could have been outlined in more detail to foster the discussion on the choice of climate metrics for the inclusion of non-CO_2 effects in regulations and assessments.
- The analysis of trade-offs might require a thorough revisiting of reference cases in the EC-report. No-regret situations, where no trade-offs exist are largely dependent on the individual reference situation. For example, the combination of using SAF and operational measures to avoid climate-sensitive regions reduces both CO_2 and non-CO_2 effects in comparison to today's operations and fuel use. Thereby, this approach constitutes a no-regret solution.
- The EC-Report provides a comprehensive and broad analysis of possible measures for the limitation of aviation's non-CO_2 effects. This selection of policy measures comprises most types of potential policy measures suitable for the reduction of air transport's climate relevant species.
- Unfortunately, none of the investigated potential policy measures seems to be ready for implementation in the short run. According to the EC-Report, this is predominantly the case due to a great number of currently unsolved research questions in atmospheric science.
- From DLR point of view, the EC-Report argues too tentative and lacks economic analysis. DLR recommends a three-step approach at this point: Firstly, to select promising policy measures, secondly, to investigate the economic impacts of different design options for the selected policy measures in order to identify the most efficient design options. Thirdly, pilot projects should be conducted with relevant stakeholders for the selected, most efficient policy measures. In parallel, atmospheric science experts should continue research on the remaining research questions identified in the EC-Report. By doing so, important experiences and knowledge could be achieved simultaneously.
- On this basis, and with additional further knowledge from atmospheric science which could have been gained in this process, it will be possible to design and implement innovative policy measures for the limitation of air transport's non-CO_2 species. First steps in this direction have already been conducted by Niklaß et al. (2019) on behalf of the German environment Agency (UBA) presenting options for implementation with varying complexity. According to Niklaß et al. (2019) it is possible to address at least some

relevant non-CO_2 species by including them into the current EU Emissions Trading System for limitation of aviation's CO_2 emissions and respective non-CO_2 effects. Hence, for practical testing, e.g., of the MRV scheme, an inclusion of non-CO_2 effects in the EU Emissions Trading System is feasible on a short time scale. However, a final selection of the way non-CO_2 effects are implemented is only recommended after a risk analysis, which takes, among others, uncertainties from atmospheric science into account.

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