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Comparative Analysis of GHG Calculation Methodologies in Aviation

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Corresponding Author:	Yury Erofeev Leipzig University Faculty of Management Science and Economics GERMANY
First Author:	Yury Erofeev
Order of Authors:	Yury Erofeev
	Stefan Majer
	Daniela Thrän
Abstract:	The aviation sector faces mounting pressure to deliver transparent, comparable greenhouse-gas (GHG) disclosures under European Sustainability Reporting Standards (ESRS). We provide a comparison of aviation GHG methodologies spanning simple factor tools and flight-specific, lifecycle-inclusive approaches. Our approach combines a structured documentation review (retaining calculators that publish or allow derivation of emission intensity per passenger-kilometre), controlled computations for standardized short-, medium-, and long-haul profiles under each method's native assumptions (energy scope, class/cargo allocation, distance modelling, non-CO2 handling), and a documentation-based multi-criteria analysis (0–3 rubric) on boundary clarity, non-CO2 treatment, data granularity, documentation/auditability, and reporting alignment; we also record standards applicability with a binary (0/1) screen and test sensitivity to weights and thresholds. Results show modest dispersion at short haul but pronounced divergence at long haul, driven chiefly by inclusion of radiative forcing indices (RFIs) and well-to-wake (WTW) factors; methods applying RFI+WTW report systematically higher CO2e than tank-to-wake calculators. High-scoring, well-documented frameworks and European factor sets emphasizing WTW and transparent assumptions are best positioned for ESRS-style disclosures, while some tools remain useful for screening if omissions are made explicit. We find no universal monotonic link between score and emissions; the long-haul association is mechanistic (scope completeness and non-CO2 inclusion). We propose a minimum-viable ESRS-ready approach: explicit energy scope declaration, documented non-CO2 treatment with RFI sensitivity, versioned/traceable factors and allocation rules, and reproducible calculations. Limitations include partial "black-box" implementations, scope heterogeneity, and residual judgment in scoring.

Comparative Analysis of GHG Calculation Methodologies in Aviation

Yury Erofeev[a,b,*], Stefan Majer[c], Prof. Dr. Daniela Thrän[a,d]

[a]*Faculty of Economics and Management Science, Leipzig University, Grimmaische Straße 12, Leipzig, 04109, Germany*
[b]*SQUAKE GmbH, Brunnenstraße 19, Berlin, 10119, Germany*
[c]*DBFZ Deutsches Biomasseforschungszentrum gGmbH, Torgauer Str. 116, Leipzig, 04347, Germany*
[d]*Department of Bioenergy, Helmholtz Center for Environmental Research - UFZ, Permoserstr. 15, Leipzig, 04318, Germany*

Abstract

The aviation sector faces mounting pressure to deliver transparent, comparable greenhouse-gas (GHG) disclosures under European Sustainability Reporting Standards (ESRS). We provide a comparison of aviation GHG methodologies spanning simple factor tools and flight-specific, lifecycle-inclusive approaches. Our approach combines a structured documentation review (retaining calculators that publish or allow derivation of emission intensity per passenger-kilometre), controlled computations for standardized short-, medium-, and long-haul profiles under each method's native assumptions (energy scope, class/cargo allocation, distance modelling, non-CO_2 handling), and a documentation-based multi-criteria analysis (0–3 rubric) on boundary clarity, non-CO_2 treatment, data granularity, documentation/auditability, and reporting alignment; we also record standards applicability with a binary (0/1) screen and test sensitivity to weights and thresholds. Results show modest dispersion at short haul but pronounced divergence at long haul, driven chiefly by inclusion of radiative forcing indices (RFIs) and well-to-wake (WTW) factors; methods applying RFI+WTW report systematically higher CO_2e than tank-to-wake calculators. High-scoring, well-documented frameworks and European factor sets emphasizing WTW and transparent assumptions are best positioned for ESRS-style disclosures, while some tools remain useful for screening if omissions are made explicit. We find no universal monotonic link between score and emissions; the long-haul association is mechanistic (scope completeness and non-CO_2 inclusion). We propose a minimum-viable ESRS-ready approach: explicit energy scope declaration, documented non-CO_2 treatment with RFI sensitivity, versioned/traceable factors and allocation rules, and reproducible calculations. Limitations include partial "black-box" implementations, scope heterogeneity, and residual judgment in scoring.

Keywords: Aviation emissions, Greenhouse gas accounting, Scope 3 emissions, Business travel, Non-CO_2 climate effects, Sustainability reporting

1. Introduction

Climate change poses a profound challenge to sustainable development, jeopardizing future generations' ability to meet their needs while addressing the present's demands. Aviation, a critical enabler of global connectivity and economic growth, is a significant contributor to GHG emissions, accounting for approximately 2-3% of global CO_2 emissions in 2019 (Lee et al., 2021). As air travel demand continues to grow, emissions are projected to increase, necessitating the development of accurate methodologies for GHG accounting. Transparency in emissions accounting is a fundamental first step toward improving the aviation industry's overall climate performance, as it enables stakeholders to identify, understand, and act on emissions reduction opportunities. Therefore, transparent, robust, and comparable reporting methodologies are crucial for supporting the sector's compliance with stringent environmental regulations and advancing progress toward global climate targets.

The aviation sector's climate impact extends beyond CO_2 emissions, encompassing non-CO_2 effects such as contrails and nitrogen oxide emissions, which significantly amplify atmospheric warming (Lee et al., 2021; Myhre et al., 2017). Radiative forcing, a metric that captures these combined effects, highlights the disproportionate impact of high-altitude emissions on climate systems. Despite technological advancements like SAF and emerging innovations in electric and hydrogen-powered aircraft, decarbonizing aviation remains a complex and resource-intensive endeavor (Gössling et al., 2019; Gkoumas et al., 2021). Targeted infrastructure upgrades, e.g., SAF production and distribution facilities, airport electrification, and charging systems for alternative propulsion, (Meindl et al., 2023; El Zein et al., 2025) combined with policy harmonization around emission accounting standards and market-based measures, as well as substantial investments in decarbonization technologies and reporting systems, are essential to reduce aviation's environmental footprint and ensure alignment with emerging frameworks like the CSRD.

The Corporate Sustainability Reporting Directive (CSRD) mandates use of the European Sustainability Reporting Standards (ESRS), which set the detailed disclosure requirements. Under the CSRD, organizations are mandated to disclose detailed non-financial data, which encompasses emissions from

*Corresponding author's e-mail: yury.erofeev@squake.earth

business travel (European Commission, 2023). This directive fosters corporate accountability, encouraging businesses to adopt robust carbon accounting practices and align with environmental sustainability goals.

Accurate emissions reporting is essential with regard to the CSRD (Nuotio, 2025), which mandates transparent and verifiable environmental disclosures for companies operating within the EU. Since the late 1990s, more than 15 different aviation emission calculation methodologies have been developed to support climate reporting, policy development, and carbon offsetting. These include international frameworks such as the Travel Impact Model, the ICAO Carbon Emissions Calculator (ICEC) and IATA CO_2 Connect, followed by governmental models like Department for Environment Food and Rural Affairs (DEFRA) – UK, Environmental Protection Agency (EPA) – US, and French Environment and Energy Management Agency's (ADEME) Base Empreinte – France, as well as recent tools from the private sector such as GATE4 by Advito, Cirium, and RDC Aviation.

However, methodological discrepancies across these frameworks challenge the comparability of reported data. For example, methodologies vary in addressing flight distance corrections, seating class adjustments, and non-CO_2 effects, leading to inconsistencies in emissions estimates for airlines, corporate travel reporting systems, and booking platforms used by travel managers and agencies (Iken and Aguessy, 2022; Jardine, 2009).

The core focus of this research is to evaluate the comprehensibility and reliability of GHG calculation methodologies in aviation, with particular attention to their implications for CSRD compliance. Previous studies have highlighted significant methodological variations in emissions calculations. For instance, Iken and Aguessy (2022) compared six widely used protocols, including ICAO, myclimate, and atmosfair, revealing differences in distance correction factors, emission factor applications, and inclusion of non-CO_2 effects.

Similarly, Filimonau (2012) identified inconsistencies in online carbon calculators, emphasizing the need for methodological standardization. However, to date, no comprehensive update or follow-up to Filimonau (2012) has been conducted, leaving an important gap in the literature. This research seeks to address this gap by providing an updated and systematic evaluation of current methodologies, reflecting both methodological developments over the past decade and the evolving regulatory context shaped by reporting frameworks like the CSRD.

Most existing studies have focused on comparing numerical outcomes across aviation emissions calculators (Althaus and Cox, 2019; Migault; Iken and Aguessy, 2022), but few have systematically analyzed the underlying system boundaries and methodological dimensions. These approaches are often tailored to specific policy contexts or voluntary offsetting schemes, which may not align with the mandatory and standardized reporting requirements under the CSRD. As a result, the applicability of their findings to corporate compliance remains limited.

For example, methodologies diverge in their treatment of short-haul versus long-haul flights—some apply broad multipliers, while others use detailed distance bands or route-specific data (Barret, 2020). Non-CO_2 effects such as NO_x and contrail-induced cirrus also vary: DEFRA or CO2 emissiefactoren, for instance, use a fixed radiative forcing index, whereas many tools omit these effects entirely (Lee et al., 2021; Barret, 2020).

Building on previous comparative efforts, this research examines the underlying assumptions and implications of different aviation GHG accounting methodologies, with a particular focus on their transparency and suitability for corporate reporting. Understanding what lies behind the diversity of methodological approaches is essential for enabling organizations to navigate the complexities of emissions reporting, avoid systematic over- or underestimation of emissions, and enhance the credibility of their disclosures. By analyzing both methodological robustness and regulatory alignment, this study contributes to improving transparency in aviation GHG accounting—an indispensable first step toward fostering comparability, accountability, and ultimately more effective climate action across the sector.

A distinctive feature of this work is its synthesis of published implementation guidance and technical documentation involved in sustainability reporting and travel emissions tracking. These perspectives are crucial for assessing the operational relevance of different methodologies and for evaluating whether harmonization is feasible in practice—an essential step toward improving transparency, comparability, and usability of emissions reporting. This study operates on the hypothesis that interpreting practice-oriented documentation alongside a systematic comparison of methodologies can reveal both the practical challenges and opportunities for aligning aviation GHG accounting practices with emerging regulatory frameworks, thereby supporting more credible and actionable corporate climate disclosures.

To frame the study's purpose and scope, we explicitly ask which aviation GHG calculation methodologies best meet CSRD-aligned requirements for transparency, completeness (e.g., treatment of non-CO_2 effects and well-to-wake (WTW) boundaries), and auditability—and why; how and by how much emissions estimates diverge across methodologies over representative flight profiles (e.g., short-, medium-, long-haul and booking classes), and which modelling choices (e.g., distance corrections, RFIs, lifecycle scope, load/cargo allocation) drive these differences; and what the practical trade-offs are for corporate reporters between methodological rigor and implementability (data demands, documentation quality, reproducibility), as well as what constitutes a minimum viable approach that remains CSRD-ready. Guided by these questions, our objective is to develop a transparent, multi-criteria evaluation and to synthesize published guidelines into actionable recommendations for harmonized, credible aviation emissions reporting under the CSRD.

2. State of the Art

2.1. GHG Calculation Frameworks

GHG calculation methodologies in aviation have evolved over the past decades to meet the increasing demand for accurate, transparent, and comparable carbon accounting. These methodologies underpin climate reporting, policy development, and voluntary offsetting schemes, and they vary significantly in their assumptions, scope, and data requirements. Generally, the methodologies can be grouped into two broad categories: simplified approaches based on average factors and detailed approaches incorporating flight- and airline-specific data. Simplified methods are easier to apply and widely accessible, but risk underestimating or overestimating emissions due to their generalizations. In contrast, detailed methods offer higher precision at the cost of greater data demands and complexity.

Several prominent frameworks illustrate the diversity of approaches in the field. The ICAO Carbon Emissions Calculator, widely used for passenger flight emissions, calculates emissions based on Great Circle Distance (GCD), corrects for actual flight paths, and applies passenger-to-freight allocation factors. Its focus on accessibility facilitates broad application but may oversimplify flight-specific parameters, affecting precision (ICAO, 2024).

DEFRA's method incorporates radiative forcing indices (RFI) of 1.7 to account for non-CO_2 climate impacts, making it more comprehensive. It also includes fuel uplift factors to address operational inefficiencies. While its detailed reporting supports nuanced assessments, it can be resource-intensive (Bramwell et al., 2024).

The Dutch CO_2 emissiefactoren methodology emphasizes comprehensiveness by incorporating both CO_2 and non-CO_2 emissions by inclusion of RFI of 1.7, differentiating by distance and class, and applying a detailed lifecycle approach. This robustness comes at the cost of requiring extensive data inputs (Milieu Centraal, 2022).

ADEME focuses on integrating emissions from various lifecycle stages of aviation. This methodology aligns well with France's sustainability mandates but is less adaptable to global contexts due to its region-specific assumptions (Ministry for an Ecological and Inclusive Transition, 2019).

The Base Empreinte methodology, developed and maintained by ADEME, provides a comprehensive database of emission factors and inventory datasets for assessing the environmental impacts of products, services, and projects. It integrates emissions from multiple lifecycle stages, combining GHG with and without contrails (with the approximate factor of 1.8) and other environmental indicators to support both organizational carbon accounting and environmental labeling in France. Base Empreinte reflects France's regulatory and policy priorities, emphasizing transparency, documentation, and multi-criteria impact assessment. While highly detailed and robust for French and EU contexts, its region-specific assumptions, such as regulatory baselines, energy mixes, and methodological conventions, may limit its direct applicability to global settings without careful adaptation (ADEME, 2025).

Chalmers University of Technology employs LCA and incorporates RFI of 1.7. Its emphasis on both upstream and downstream emissions highlights its robustness, but the reliance on extensive datasets may limit scalability (Larsson and Månsson, 2024).

The Travel Impact Model (TIM), developed by Travalyst and Google's Travel Sustainability team, provides detailed estimations of carbon emissions for individual flights. It integrates flight-specific factors such as fuel burn, operational details, and seating configurations, aiming to offer travelers transparent sustainability information, aligned with EEA guidelines (Google, 2023).

Umweltbundesamt's TREMOD methodology integrates lifecycle emissions, offering a detailed breakdown of tank-to-wake (TTW), well-to-tank (WTT), and additional non-CO_2 factors. It considers national and international contexts, making it suitable for region-specific applications. TREMOD also includes a higher RFI of 2.4, acknowledging the substantial warming effects of non-CO_2 emissions such as NO_x and contrails (Allekotte et al., 2021; Knörr et al., 2012).

The International Council on Clean Transportation (ICCT) employs a robust approach to aviation emissions accounting, leveraging detailed operational data and fuel consumption statistics (Graver et al., 2020). While not regionally constrained, it offers granular insights but lacks explicit per-passenger metrics suitable for compliance with frameworks like CSRD.

Manatū Mō Te Taiao methodology incorporates radiative forcing and lifecycle considerations but is heavily tailored to the New Zealand context. While its comprehensive inclusion of non-CO_2 effects offers valuable insights, it is less relevant for global or European use cases (Ministry for the Environment, 2024). The RFI is 1.7, similar to DEFRA's approach.

The methodology and results presented in this study were developed under the Framework Service Contract EEA/ACC/18/001/LOT 1, commissioned by the European Environment Agency (EEA). This contract facilitated the preparation of a robust, transparent, and replicable framework for assessing greenhouse gas efficiency indicators across transport modes in Europe. Conducted by Fraunhofer ISI and CE Delft, the study supports the EEA's strategic objective to monitor and report GHG efficiency in a consistent and policy-relevant manner. The findings of this report, while reflecting the state of knowledge at the time of completion in 2020, also highlight the dynamic nature of emissions accounting and the need for ongoing methodological refinements. The work under EEA/ACC/18/001/LOT 1 thus contributes significantly to enabling the EEA to provide comparable, mode-specific indicators that inform both policy development and stakeholder decision-making within the EU context (CE Delft and Fraunhofer ISI, 2020).

Across these methodologies, several recurring challenges emerge. Variations in treatment of flight distance—e.g., broad multipliers versus detailed distance bands—can lead to discrepancies in emissions estimates. Similarly, non-CO_2 effects, including NO_x and contrail-induced cirrus, are inconsistently accounted for, with some methodologies applying fixed RFIs and others omitting them entirely (Lee et al., 2021; Barret, 2020). Furthermore, boundaries of assessment (e.g., tank-to-wake vs. well-to-wake) and assumptions about operational inefficiencies differ markedly, affecting the comparability of results. While some methods prioritize ease of use and transparency, others aim for comprehensiveness and scientific rigor, which often increases complexity and data requirements.

These methodological discrepancies present challenges not only for voluntary offsetting schemes but also for compliance with emerging regulatory frameworks such as the CSRD. Although the CSRD is not the focus of this study, its emphasis on transparency and comparability underscores the importance of understanding what lies behind different GHG accounting approaches, particularly for corporate stakeholders aiming to produce credible and actionable emissions disclosures (Farinelli, 2024; Kılıç et al., 2019; Gulko et al., 2024).

Overall, the state of the art in aviation GHG methodologies reflects a trade-off between accessibility and precision, simplicity and comprehensiveness. This diversity highlights the necessity for systematic evaluation and potential harmonization of methods to enable more transparent, comparable, and robust emissions reporting.

2.2. Data Gaps

Despite the proliferation of GHG calculation methodologies in aviation, several significant data gaps remain that hinder the precision, comparability, and transparency of emissions estimates. A central issue is the widespread reliance on aggregated or average data rather than detailed flight-specific inputs. Many calculators apply generic emission factors per passenger-kilometer or assign flights to broad distance classes without accounting for operational realities such as specific aircraft type, seating configuration, airline operational efficiency, or prevailing weather conditions (Andrejiová et al., 2020; Seymour et al., 2020). Such generalizations risk masking the substantial variability in emissions between different flights and carriers, thereby limiting the usefulness of reported figures for decision-making and regulatory compliance.

Aircraft type is a particularly important determinant of emissions, as differences in fuel efficiency between, for example, an A320neo and a B737-800 can amount to more than 15% for the same route (Kühn and Scholz, 2023). Similarly, assumptions about load factor are often fixed to industry averages, whereas actual occupancy can vary significantly, particularly on routes with seasonal demand patterns or where premium cabins dominate capacity. Furthermore, real-world flight routing often diverges from the theoretical GCD due to air traffic management, weather avoidance, or holding patterns; yet, many methodologies ignore such deviations, potentially underestimating emissions for longer, less direct paths.

Non-CO_2 effects, including those from contrails and NO_x, introduce another layer of complexity. While it is well-established that these high-altitude effects amplify the climate impact of aviation beyond direct CO_2 emissions (Lee et al., 2021; Scholz, 2023; Mattausch, 2024), their treatment in calculation methodologies is inconsistent. Some frameworks apply a Radiative Forcing Index (RFI) as a simple multiplier, with values ranging from 1 (ignoring these effects) to about 2.7 (Jungbluth and Meili, 2019), but no universally accepted RFI standard exists. Differences in RFI assumptions alone can more than double the reported emissions, undermining comparability across calculators.

Another notable gap concerns the system boundaries applied. Some methodologies consider only the tank-to-wake (TTW) phase of emissions, i.e., combustion of fuel during flight, while others include well-to-wake (WTW) emissions, accounting for upstream processes such as fuel extraction, refining, and transport. Lifecycle emissions can increase total GHG estimates by approximately 20–30% (Mattsson and Sterneus, 2024), yet they remain inconsistently integrated across calculators. Similarly, end-of-life emissions associated with aircraft model, as captured in full LCA-based approaches, are rarely considered, despite their relevance to understanding aviation's complete climate impact.

Moreover, data availability itself poses challenges. High-quality, disaggregated operational data at the flight level (e.g., actual fuel burn, passenger and cargo allocation, routing) is often proprietary and not publicly accessible. Many companies must rely on approximations provided by third-party calculators or industry averages, which limits transparency and introduces uncertainty (Gössling et al., 2025). For organizations required to report under stringent standards, such as the CSRD, the lack of granular, verifiable data makes compliance more challenging and may lead to either under- or overestimation of emissions.

3. Methodology

This study adopts a comparative research design centred on (i) a structured search and documentation review of aviation GHG methodologies, (ii) controlled computation of emissions across representative flight profiles, and (iii) a multi-criteria analysis (MCA) to appraise methodological suitability for reporting. We first compiled candidates through targeted searches of regulator/agency guidance, academic literature, and public method notes, then applied inclusion criteria: the method must be widely used or policy-relevant, methodologically distinct, publicly documented, and publish or allow derivation of an emission intensity per passenger-kilometre (e.g., kg CO_2e/pkm) to enable a holistic, normalized comparison across frameworks. The final set includes ICAO, DEFRA, ADEME, CO_2 emissiefactoren, TIM, TREMOD, Base Empreinte, and additional research- or industry-based approaches mentioned elsewhere in this article (e.g., TU Chalmers, IATA CO_2 Connect), spanning simplified factor-based to lifecycle- and non-CO_2-inclusive models.

For each methodology, we assembled official documentation (method notes, factor tables, scope definitions), peer-reviewed studies, and publicly available methodological guidelines. From these sources, we extracted: system boundaries (TTW/WTW), treatment of non-CO_2 effects (e.g., RFI), distance modelling (GCD and corrections), allocation rules (passenger/cargo), class splits, aircraft/seat-density assumptions, data provenance/versioning, and whether intensity metrics per pkm are explicitly provided or reproducibly derivable. Where calculators are black boxes, we recorded the visible input–output behaviour and published assumptions to replicate calculations as closely as possible; all judgments were made from documentation only.

To enable like-for-like comparisons, we defined representative flight profiles spanning short-, medium-, and long-haul distances; economy/premium/business classes; and typical passenger/cargo allocation scenarios. For each methodology, CO_2 or CO_2e per passenger was computed under two boundary settings when available (TTW and WTW). Non-CO_2 effects were modelled according to each methodology's convention (e.g., fixed/optional RFI), with sensitivity tests across plausible RFI ranges to reflect uncertainty (Lee et al., 2021). GCD was calculated using the Haversine formula, with documented distance corrections applied where specified. Seating-class adjustments, load-factor assumptions, and passenger–cargo allocation rules followed each method's guidance to avoid cross-contamination of assumptions. Where a method provides or enables pkm intensities, we used those to produce route-normalized comparisons and cross-checks.

MCA is used to evaluate methodological suitability where multiple criteria are relevant and potentially conflicting (Dodgson et al., 2009; Kiker et al., 2005). We operationalized the MCA as follows. First, criteria were defined from best practices in carbon accounting and transport LCA reporting: (1) *system boundary clarity* (explicit TTW vs. WTW and provenance), (2) *treatment of non-CO_2 effects* (presence, transparency, and rationale for RFI handling), (3) *data granularity* (flight-/airline-/aircraft-specific vs. aggregated factors; class and cargo allocation), (4) *documentation quality and auditability* (completeness, reproducibility, version control), and (5) *alignment with recognized reporting frameworks* (e.g., GHG Protocol, CSRD/ESRS). Second, each methodology was scored on a 0–3 ordinal scale per criterion using decision rules derived strictly from what is reported and documented: 0 = absent/unclear; 1 = limited/implicit (e.g., global-average factor only, no class/cargo detail); 2 = partial/conditional (e.g., regional or distance-band averages, optional parameters, or indirect treatment); 3 = explicit/comprehensive (e.g., flight-/airline-/aircraft-specific treatment, full TTW/WTW with factor provenance, or booking-class–specific application). Third, we applied two weighting schemes: (a) equal weights as the main specification, and (b) an alternative scheme reflecting priorities emphasized in practice-oriented guidance (auditability and lifecycle coverage); no primary stakeholder data were collected (weights normalized to 1). Two raters independently scored all items; inter-rater reliability was quantified with weighted Cohen's κ (quadratic weights) prior to reconciliation and indicated substantial agreement. Disagreements were then resolved via item-by-item discussion against the written decision rules; where needed, we adopted the more conservative (lower) category. Sensitivity analyses covered (i) alternative weighting vectors, (ii) scoring thresholds (e.g., merging 2/3), and (iii) criterion inclusion/exclusion to test ranking stability.

In parallel, we assessed standards compliance/applicability using a binary mapping (0/1) that records whether a method's documentation explicitly claims alignment or applicability to selected standards and regimes (e.g., Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA), International Organization for Standardization (ISO) 14083, International Air Transport Association Recommended Practice (IATA RP) 1726, French Civil Aviation Authority (DGAC), Umweltbundesamt, UK Civil Aviation Authority (CAA), GHG Protocol, CSRD/ESRS). This mapping was double-coded; Cohen's κ was computed to verify acceptable agreement before reconciliation, after which discrepancies were resolved by re-checking source citations. Totals of the binaries are reported and ranked using dense ranking (ties share a rank). This documentation-based compliance screen complements the factor-based MCA by indicating where methods position themselves for corporate disclosure contexts (especially CSRD/ESRS) (European Commission, 2023).

All computations were scripted in Python to ensure reproducibility and traceability. NumPy and Pandas were used for data handling, Matplotlib and Plotly for visualization, SweetViz for exploratory analysis, and Spyder as the IDE (Oliphant et al., 2006; McKinney et al., 2010; Hunter, 2007; Inc., 2015; Raybaut, 2009; Wang et al., 2024). Where permitted, calculations were cross-checked against SQUAKE's API to validate consistency of inputs and outputs across travel modes (see public documentation at `https://docs.squake.earth/`).

Stepwise summary for replication. Step 1 (method search & selection): identify widely used, policy-relevant, and methodologically diverse calculators that publish or enable derivation of pkm intensities. **Step 2 (evidence extraction):** code boundaries, non-CO_2 handling, distance and allocation rules, class treatment, aircraft/seat assumptions, provenance/versioning, and pkm intensity availability. **Step 3 (calculation & MCA):** compute emissions for standardized profiles under each framework's native assumptions; score and weight criteria (0–3) with inter-rater reconciliation and sensitivity checks; separately compute documentation-based compliance binaries and ranks. Together, these steps yield a transparent basis for comparing aviation GHG methodologies and their suitability for GHG reporting.

4. Results and Discussion

Figure 1 presents the comparison of CO_2 or CO_2e emissions per passenger (in tonnes) as a function of flight distance (0 to 15,000 km) across multiple carbon calculation methodologies. The plot highlights significant variability in emissions estimates, particularly for long-haul flights, driven by the methodologies' underlying assumptions regarding distance corrections, non-CO_2 effects, and data granularity.

The figure was generated by computing per-passenger emissions for GCDs from 0 to 15,000 km in 250 km increments using the Haversine formula, applying each methodology's own distance corrections where prescribed. Where only distance bands or tabulated factors are published, values were taken at band knots and linearly interpolated (visible discontinuities, e.g., DEFRA short/long-haul transitions, reflect the specification). Unless required otherwise, we assumed standard economy seating with method-specific passenger–cargo allocation and average load-factor conventions; booking-class uplifts were applied only where explicitly defined. Boundary conditions follow each framework's default (TTW or WTW), and non-CO_2 effects follow the method's recommendation (e.g., fixed RFI of

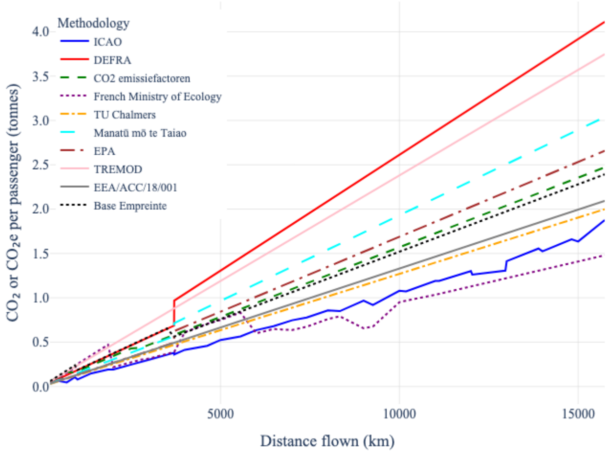

Figure 1: Comparison of CO_2 or CO_2e emissions per passenger across different methodologies as a function of distance flown.

1.7; higher ranges for TREMOD), without imposing a common multiplier. For clarity, the plot uses a color-blind–safe palette (Okabe–Ito): ICAO (navy), DEFRA (vermillion), TREMOD (purple), CO_2 emissiefactoren (green), TU Chalmers (yellow) EPA (teal), etc.

Short-haul curves (<2,000 km) cluster tightly, but beyond 5,000 km dispersion widens sharply. Relative to ICAO, DEFRA is higher by ∼94% (2,000 km), 149% (5,000 km), 142% (10,000 km), and 140% (15,000 km); TREMOD by ∼149%, 127%, 120%, and 118%; CO_2 emissiefactoren by ∼80%, 50%, 45%, and 44%; TU Chalmers by ∼33%, 21%, 18%, and 17%; and EPA by ∼40%, 61%, 56%, and 55% at the same distances. The overall max–min envelope grows from ∼2.5× at 2,000 km to ∼2.8× at 15,000 km, reflecting compounding effects of explicit non-CO_2 treatment (RFI) and WTW boundaries on long haul. Methods with RFI and/or WTW (e.g., DEFRA with RFI = 1.7; CO_2 emissiefactoren; TREMOD with higher RFI options) form the upper tier, whereas TTW-only approaches (e.g., ICAO) sit lower—though EPA exceeds ICAO by ∼40–61% across 2,000–15,000 km due to factor assumptions. Frameworks embedding flight/operational detail (e.g., DEFRA) can be more precise but are more complex to implement; TTW-only averages (e.g., ICAO) may understate long-haul impacts by omitting high-altitude effects.

Table 2 underscores the variability in standards integration among methodologies. DEFRA, ADEME, and CO_2 emissiefactoren align closely with GHG Protocol and CSRD standards, reflecting their comprehensiveness and suitability for regulatory compliance. In contrast, methodologies such as ICAO and EPA show limited integration with emerging international standards like ISO 14083, potentially affecting their broader applicability. The divergence in emissions estimates reinforces the critical role of selecting an appropriate methodology based on specific reporting requirements and regulatory contexts. For corporate stakeholders subject to CSRD, methodologies like DEFRA, CO_2 emissiefactoren, and ADEME provide the comprehensiveness necessary for transparent and reliable reporting. However, their complexity necessitates robust data management systems to handle input requirements such as flight-specific details and lifecycle emissions.

ESRS under the CSRD requires disclosure of Scope 3 Category 6 (business travel) emissions where material, together with a clear description of methods, boundaries, key assumptions, data sources, and estimation uncertainty; they do not prescribe a single aviation calculator nor a mandatory inclusion of radiative forcing. Nevertheless, CSRD's emphasis on completeness and auditability (European Commission, 2023) favours approaches that (i) make system boundaries explicit (TTW vs. WTW), (ii) document the handling of non-CO_2 effects, and (iii) provide traceable factors, allocation rules, and versioning. ISO 14083 further strengthens expectations on calculation transparency and reporting structure for transport operations. Read against these requirements, frameworks that include WTW options, publish rationale for non-CO_2 treatment, differentiate class and cargo allocation, and provide robust documentation (e.g., DEFRA, CO_2 emissiefactoren, ADEME/Base Empreinte) better satisfy CSRD-style disclosures. Simpler factor-only approaches (e.g., ICAO, EPA) can remain decision-useful for screening, but reporters should explicitly disclose omissions (e.g., non-CO_2 effects) and quantify their impact where feasible to meet CSRD expectations of transparency.

Standardization or, at a minimum, a clear understanding of methodological variations is essential to ensure consistency and comparability in emissions reporting. The analysis demonstrates that methodologies excluding non-CO_2 effects or applying generalized factors risk underestimating the true climate impact of air travel, potentially undermining regulatory compliance and sustainability efforts. Figure 1 visually reinforces the need for transparency in assumptions and data inputs across methodologies. As long-haul flights continue to dominate aviation-related emissions, aligning emissions estimates with regulatory frameworks like CSRD and integrating non-CO_2 effects will be pivotal in fostering sustainable aviation practices.

Three caveats qualify these findings. First, several tools are partially proprietary ("black-box"), so we relied on published documentation and observable input–output behaviour; this limits perfect replication and may transmit unobserved assumptions. Second, scope heterogeneity (TTW vs. WTW), allocation rules, and class handling were preserved to respect each method's intent; hence, part of the divergence is structural rather than parametric. Third, the MCA is a qualitative 0–3 rubric scored from documentation with rater reconciliation and sensitivity checks; results should be read as structured evidence, not deterministic rankings. These constraints do not overturn the central patterns but call for cautious interpretation and transparent disclosure when applying any single methodology in CSRD reporting contexts. The main implication is the need for greater standardization. Heterogeneous boundary choices and treatments of non-CO_2 effects undermine comparability and credibility, especially on long haul. A practical minimum rule set for ESRS would include explicit TTW/WTW declaration, documented non-CO_2 treatment (with RFI sensitivity), traceable/versioned factors and allocation rules, and reproducible calculations. Guidance should balance scientific rigour with operational feasibility to avoid undue data burden. Alignment with transport reporting norms (e.g., ISO 14083 structure) and consistent non-CO_2 treatment would improve transparency and reduce uncertainty for CSRD/ESRS disclosures. Until convergence, organisations should disclose omissions and provide sensitivities to WTW and non-CO_2 to maintain auditability and comparability.

Linking the factor-based MCA scores (Table 1) and the emissions curves (Figure 1) shows no universal monotonic dependence at short haul, but a clear tendency at long haul: frameworks that explicitly include non-CO_2 effects (via RFI) and/or WTW upstream factors—criteria that also lift MCA scores—systematically report higher CO_2e per passenger. Illustrative pairs are DEFRA (high MCA; RFI 1.7; WTW enabled) with the steep long-haul slope, versus ICAO and EPA (lower MCA; TTW-only; no RFI) with consistently lower long-haul values. CO_2 emissiefactoren and TU Chalmers (mid-to-high MCA, RFI $\approx$1.7) likewise sit above TTW-only lines for long distances, while TREMOD (RFI up to ~3.0) occupies the upper envelope when its settings are applied. A useful counterpoint is Base Empreinte: it scores well on documented non-CO_2 treatment, yet its default TTW setting (no WTW uplift) keeps its curve below other RFI+WTW methods; this underlines that which score components are present (non-CO_2, WTW) matters more for magnitude than overall score alone.

In short, higher MCA scores correlate with higher reported emissions chiefly when those scores are driven by boundary completeness (WTW) and explicit non-CO_2 treatment; factors like aircraft type, booking class, or airline specificity raise the score but do not systematically increase or decrease totals on their own. Practically, this means MCA "quality" reflects scope and transparency, not an intrinsic bias to inflate numbers: where reporters adopt TTW-only or omit non-CO_2, long-haul emissions appear lower; where WTW and RFI are documented and applied, long-haul emissions are higher and more complete. Consistent with this, the binary standards mapping (Table 2) tracks disclosures oriented to CSRD/ESRS and GHG Protocol: methods that explicitly position for regulated reporting tend to document WTW and non-CO_2 options, which in turn explains their higher long-haul CO_2e rather than any inherent methodological "penalty." Overall, we therefore do not observe a simple "higher-score $\rightarrow$ lower (or higher) emissions" rule; instead, the apparent association at long distances is mechanistic, arising from inclusion of WTW and non-CO_2 effects that both raise MCA scores and increase CO_2e, while short-haul dispersion remains small and largely decoupled from scoring.

Table 1: Factors considered or applicable by methodology (MCA scores and ranking).

Factor (0–3)	**TIM**	**DEFRA**	**TU Chalmers**	**ADEME**	**TREMOD**	**CO2 emissiefactoren**	**Base Empreinte**	**ICEC**	**IATA CO2 Connect**	**EPA**
Aircraft capacity	3	2	0	1	0	0	1	3	3	0
Aircraft type	3	2	0	0	0	0	0	3	3	0
Airline-specifics	3	0	0	0	0	0	0	3	3	0
Booking class	3	3	2	0	0	3	0	3	3	0
Cargo allocation	2	2	1	1	1	1	1	2	3	1
Distance-based	3	3	3	3	3	3	3	3	0	3
Energy scope	3	3	3	3	3	3	0	0	0	0
non-CO_2	3	3	3	3	3	3	3	0	0	3
Passenger load	3	2	1	1	1	1	1	2	3	1
RFI (MCA score)	0*	3	3	0	3	3	3	0	0	0
Time-based	0	0	0	0	0	0	0	0	3	0
RFI (value, if fixed)†	—	1.7	1.7	—	2.4	1.7	1.8	—	—	—
Equal-weight MCA score	2.36	2.09	1.45	1.09	1.27	1.55	1.09	1.73	1.91	0.73
Rank (1=best)	1	2	6	8	7	5	8	4	3	9

Notes: (**Scoring rubric**) 0 = absent/unclear in public documentation; 1 = limited/implicit (e.g., global-average factor only, economy-only treatment, or generic passenger-km with no explicit class/cargo rules); 2 = partial/conditional (e.g., regional or distance-band averages, optional parameters, or indirect/derived treatment); 3 = explicit/comprehensive (e.g., flight-/airline-/aircraft-specific or class-specific implementation with referenced factor provenance and reproducible rules). (**Factor meanings**) *Airline-specifics*: use of airline-/flight-specific parameters (e.g., carrier-, route-, or aircraft-subtype inputs beyond global/regional averages). *Aircraft type*: explicit modelling by aircraft family/subtype affecting factors or seat density. *Aircraft capacity*: explicit seat maps/seat-density or capacity by class used in allocation. *Booking class*: published class multipliers or seat-share splits beyond "economy-only". *Cargo allocation*: published passenger–freight allocation method and application. *Distance-based*: use of GCD with stated corrections, distance bands, or route-level distances. *Energy scope*: TTW vs. WTW coverage and documentation (including factor provenance). *non-CO_2*: inclusion of high-altitude effects (e.g., NO_x, contrails) via RFI or other documented model. *RFI (MCA score)*: whether an RFI multiplier is *implemented and documented* for reporters to apply; it does not judge the chosen RFI magnitude. *Time-based*: explicit use of time/block-time or stage-length drivers in the calculator (publicly documented). (**Computation**) "Equal-weight MCA score" is the arithmetic mean across the 11 scored factor rows (0–3); the row "RFI (value, if fixed)" is descriptive and excluded from averages. Ranks use dense ranking (ties share a rank). *For TIM, contrail/NO_x/contrail-impact detail is documented but no single RFI multiplier is offered; we therefore score RFI implementation as 0 to avoid double-counting with *non-CO_2*. †Where a fixed RFI is published, its nominal value is shown for transparency only and is not part of the MCA score. All scores reflect the *reported* capabilities and documentation status of each methodology at the time of assessment.

Table 2: Standards considered or applicable by methodology (binary scoring and totals).

Standard (0/1)	**TIM**	**DEFRA**	**TU Chalmers**	**ADEME**	**TREMOD**	**CO2 emissiefactoren**	**Base Empreinte**	**ICEC**	**IATA CO2 Connect**	**EPA**
CORSIA	1	0	0	0	0	0	0	1	1	0
ISO 14083	1	0	0	0	0	0	0	0	0	0
IATA RP 1726	1	0	0	0	0	0	0	0	1	0
DGAC (France)	0	0	0	1	0	0	1	0	0	1
Umweltbundesamt (DE)	0	0	0	0	1	0	0	0	0	0
CAA (UK)	0	1	0	0	0	0	0	0	0	0
GHG Protocol	1	1	1	1	1	1	1	0	0	0
CSRD / ESRS	1	1	1	1	1	1	1	0	0	1
Total (sum)	5	3	2	3	3	2	3	1	2	2
Rank (1=highest)	1	2	3	2	2	3	2	4	3	3

Notes: (**Scoring**) Binary values indicate explicit, documented applicability/alignment in public sources for each methodology: 1 = claimed or formally referenced; 0 = no explicit claim found. The **Total (sum)** counts the number of standards with explicit applicability per methodology; **Rank** uses dense ranking (ties share a rank). (**Interpretation**) A 0 does not imply incompatibility; it indicates the methodology does not state alignment in its documentation as assessed. This table does not judge legal compliance; it summarizes documentation claims. (**Standard scope**) *CORSIA*: ICAO's MRV/offsetting scheme; counted as 1 if the method states CORSIA use or conformity. *ISO 14083*: reporting of GHG emissions for transport operations; 1 if documentation maps to 14083 structure (FU, boundary, data quality) or states alignment. *IATA RP 1726*: airline/passenger CO_2 calculation recommended practice; 1 if cited as basis or conformance target. *DGAC (France)*: recognition/use in French national guidance (e.g., ADEME/Base Empreinte); 1 if formally referenced by DGAC or embedded in national practice. *Umweltbundesamt (DE)*: TREMOD basis; 1 if method is UBA's own (e.g., TREMOD) or explicitly adopts UBA guidance. *CAA (UK)*: UK authority context; 1 if the method is the UK's reference set (e.g., DEFRA) or states CAA alignment. *GHG Protocol*: corporate accounting framework; 1 if documentation explicitly positions the method for Scope 3 Category 6 reporting or provides a mapping. *CSRD/ESRS*: EU disclosure framework; 1 if documentation claims suitability/mapping for ESRS reporting (e.g., boundary clarity, factor provenance, audit trail). (**Versioning**) Claims reflect documentation status at the time of assessment; methods and standards evolve. Where ambiguity existed, we defaulted to 0 to avoid over-claiming.

5. Conclusion

This study compared commonly used aviation GHG calculation methodologies using a structured documentation review, controlled computations on standardized flight profiles, and a factor-based MCA scored from public sources. We find modest dispersion for short haul but large divergence for long haul, driven primarily by (i) inclusion or omission of non-CO_2 effects (often via an RFI) and (ii) boundary choice (TTW vs. WTW). Frameworks that implement explicit non-CO_2 treatment and WTW options (e.g., TIM, DEFRA, CO_2 emissiefactoren, ADEME/Base Empreinte) tend to report higher CO_2e than TTW-only calculators (e.g., ICAO, EPA), reflecting a more complete scope rather than methodological inflation. Methods that incorporate class, cargo allocation, aircraft type, or airline specificity improve representativeness and auditability but do not, on their own, systematically raise or lower totals.

Linking emissions to scoring shows no universal monotonic relationship: higher MCA scores correspond to higher reported emissions mainly when the score is elevated by boundary completeness (WTW) and explicit non-CO_2 treatment; other score components chiefly enhance transparency. The binary standards mapping corroborates this positioning: methods that explicitly align to CSRD/ESRS and the GHG Protocol are also those that document WTW and non-CO_2 options, which explains their higher long-haul CO_2e values.

For CSRD/ESRS-style disclosures, a minimum-viable approach emerges: (1) explicit declaration of TTW vs. WTW, (2) documented handling of non-CO_2 effects with RFI sensitivity, (3) traceable and versioned factors, allocation rules, and assumptions, and (4) reproducible calculations and audit trails. Simpler TTW-only tools remain useful for screening, provided omissions are disclosed and, where feasible, sensitivities to WTW and non-CO_2 are reported to maintain comparability and auditability (European Commission, 2023).

Limitations include partial "black-box" implementations (constraining replication), scope heterogeneity that we preserved to respect method intent (implying some structural divergence), and qualitative MCA scoring despite rater reconciliation and sensitivity checks. These do not overturn the central patterns but warrant cautious interpretation when selecting a methodology for corporate reporting.

Future work should (i) test harmonized calculation rules (common boundary declarations, standardized class/cargo allocations, and agreed non-CO_2 treatments) on large flight-level datasets with observed fuel burn; (ii) maintain open, versioned factor libraries with machine-readable provenance to track updates in WTW factors, load/class splits, and non-CO_2 multipliers; and (iii) benchmark organization-level results under CSRD/ESRS using uncertainty and sensitivity analyses (e.g., alternative RFIs, distance corrections, factor vintages). Progress on these fronts would improve transparency, reduce reporting uncertainty, and support credible, comparable aviation disclosures.

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Declaration of interests

☐The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Comparative Analysis of GHG Calculation Methodologies in Aviation

Yury Erofeev[a,b*], Stefan Majer[c], Prof. Dr. Daniela Thrän[a,d]

[a] *Faculty of Economics and Management Science, Leipzig University, Grimmaische Straße 12, Leipzig, 04109, Germany*

[b] *SQUAKE GmbH, Brunnenstraße 19, Berlin, 10119, Germany*

[c] *DBFZ Deutsches Biomasseforschungszentrum gGmbH, Torgauer Str. 116, Leipzig, 04347, Germany*

[d] *Department of Bioenergy, Helmholtz Center for Environmental Research - UFZ, Permoserstr. 15, Leipzig, 04318, Germany*

Corresponding author: yury.erofeev@squake.earth

Abstract

The aviation sector faces mounting pressure to deliver transparent, comparable greenhouse-gas (GHG) disclosures under European Sustainability Reporting Standards (ESRS). We provide a comparison of aviation GHG methodologies spanning simple factor tools and flight-specific, lifecycle-inclusive approaches. Our approach combines a structured documentation review (retaining calculators that publish or allow derivation of emission intensity per passenger-kilometre), controlled computations for standardized short-, medium-, and long-haul profiles under each method's native assumptions (energy scope, class/cargo allocation, distance modelling, non-CO2 handling), and a documentation-based multi-criteria analysis (0–3 rubric) on boundary clarity, non-CO2 treatment, data granularity, documentation/auditability, and reporting alignment; we also record standards applicability with a binary (0/1) screen and test sensitivity to weights and thresholds. Results show modest dispersion at short haul but pronounced divergence at long haul, driven chiefly by inclusion of radiative forcing indices (RFIs) and well-to-wake (WTW) factors; methods applying RFI+WTW report systematically higher CO2e than tank-to-wake calculators. High-scoring, well-documented frameworks and European factor sets emphasizing WTW and transparent assumptions are best positioned for ESRS-style disclosures, while some tools remain useful for screening if omissions are made explicit. We find no universal monotonic link between score and emissions; the long-haul association is mechanistic (scope completeness and non-CO2 inclusion). We propose a minimum-viable ESRS-ready approach: explicit energy scope declaration, documented non-CO2 treatment with RFI sensitivity, versioned/traceable factors and allocation rules, and reproducible calculations. Limitations include partial "black-box" implementations, scope heterogeneity, and residual judgment in scoring.

Keywords: Aviation emissions; Greenhouse gas accounting; Scope 3 emissions; Business travel; Non-CO2 climate effects; Sustainability reporting