

# Integrity gaps in certification and MRV across aviation mitigation policies

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## Abstract

The mitigation of aviation's climate impacts hinges on upstream emission reductions via sustainable aviation fuels and on out-of-sector solutions such as carbon offsetting and removals. Their credibility relies on climate claims that are substantiated by certification and monitoring, reporting and verification (MRV) architectures, yet no systematic comparison of how existing policies and standards operationalise certification requirements has been attempted. We assess MRV and certification provisions in ten policies and standards relevant to aviation, spanning sustainable aviation fuels and carbon credits. We use a novel 40-criterion evaluation framework developed through literature review, expert consultation and natural language processing. We find that the comprehensiveness of certification requirements is driven less by policy type (compliance versus voluntary) or technology family (fuels versus offsets and removals) than by how stand-alone and prescriptive the policy or standard is. The Paris Agreement Article 6.4 mechanism, which sets detailed rules for its methodologies, covers the broadest range of criteria but still exhibits selective blind spots. Instruments that delegate implementation of certification rules to third-party programmes with heterogeneous methodologies, such as CORSIA-eligible emission units and Paris Agreement Article 6.2, systematically show gaps in core integrity dimensions. Within CORSIA, certification requirements are substantially more stringent for alternative fuels than for eligible emission units, despite both being compliance options, resulting in uneven integrity standards for ostensibly equivalent mitigation. Overall, current policies and standards governing aviation mitigation claims are neither comprehensive nor internally consistent enough to guarantee integrity across and fungibility between different net-zero aviation pathways.

## Key policy insights

- Existing certification and MRV provisions across aviation policies and standards governing sustainable aviation fuels, offsets and carbon removal display differences in their comprehensiveness and strategic priorities.
- Diverging certification requirements lead to variable credibility of net-zero pathways in the sector and non-fungibility of supposedly equivalent mitigation options.
- Stand-alone and highly prescriptive certification frameworks, such as the Paris Agreement Article 6.4 mechanism and the EU Carbon Removal Certification Framework, tend to cover a much broader set of integrity criteria than instruments that delegate key rules to third-party programmes.
- Within CORSIA, certification requirements are substantially more stringent for alternative fuels than for eligible emission units, meaning airlines can meet the same compliance obligation with mitigation options that are held to markedly different integrity benchmarks.

## Introduction

Aviation accounts for approximately 4% of anthropogenic warming to date (Klöwer et al., 2021) and is among the fastest-growing contributors to climate change (International Air Transport Association, 2026), making its transition to net-zero emissions particularly challenging (Bergero et al., 2023; Sacchi et al., 2023). Owing to its complex climate impacts (Lee et al., 2021), high energy density requirements (Gnadt et al., 2019), long-lived capital stock, and limited availability of scalable, cost-effective alternatives to fossil jet fuel, aviation is among the few sectors strictly qualifying as ‘hard-to-abate’ (Dufour-Décieux et al., 2025) or ‘hard-to-electrify’ (Bachorz et al., 2025). Credible net-zero pathways for aviation depend on a narrow set of mitigation options whose effectiveness is inherently contested (Bardon & Massol, 2025; Peeters et al., 2016; Sacchi et al., 2023).

A defining feature of aviation’s mitigation portfolio is that the environmental benefits of all near-term options, which exclude electric or hydrogen-powered aircraft, are linked to upstream or out-of-sector emission reductions that are often not measurable at the point of use, when the jet fuel is combusted. Sustainable aviation fuels’ (SAFs) climate credentials depend almost entirely on upstream emissions accounting. Their carbon intensity reflects the embedded carbon in the feedstock, emissions due to land-use change, and processing and energy-related emissions across a supply chain spanning multiple countries and actors. Traditional carbon offsets generate climate value through counterfactual emission reductions in entirely different sectors or geographies. Carbon dioxide removal (CDR) is equally outside the boundaries of aviation and relies on precise

quantification and monitoring to establish like-for-like compensation of ongoing aviation emissions. In each case, emission reductions are not a directly measurable physical quantity, but a certified claim. This makes monitoring, reporting and verification (MRV) and the certification apparatus the central infrastructure underpinning any credible aviation climate strategy.

The stakes of inadequate certification are concrete. Trust in aviation mitigation options is low: passengers and aviation professional alike exhibit low willingness to pay a premium for aviation decarbonisation (Crouse et al., 2024; Guan et al., 2024; Mello, 2024; Schomakers et al., 2024), citing distrust in decarbonisation solutions as a motivation (Guan et al., 2024; Kallela, 2024; Silfvenius, 2024). The credibility deficit is not merely reputational, but it shifts financial burden onto airlines when passengers are unwilling to fund premiums. Because airlines operate at a thin profit margin (FullRatio, 2026), this may translate into competitive disadvantages for airlines that steward climate action.

Indeed, distrust towards aviation mitigation options is rooted in well-founded criticism. SAFs are widely regarded as the primary near-term decarbonisation pathway for aviation, given their compatibility with existing aircraft and fuel infrastructure (Bardon & Massol, 2025; International Air Transport Association, 2024a). However, the sustainable scalability of SAFs have been challenged (Bardon & Massol, 2025; Peeters et al., 2016; Sacchi et al., 2023; Scott, 2025), since SAFs have been known for years to have high lifecycle emissions, long carbon repayment times (Bell et al., 2025; Hill et al., 2006; Sacchi et al., 2023; Tilman et al., 2009; Wicke et al., 2012), and limited availability of sustainable feedstock (International Air Transport Association, 2025; O'Malley et al., 2021). Structural production shortfalls and aircraft compatibility constraints also undermine confidence in their near-term deployment (Martulli et al., 2025; Transport & Environment, 2025), leading to pressure to water down SAF mandates, such as RefuelEU Aviation (Regulation (EU) 2023/2305) (Lecca, 2026).

Against this backdrop, carbon offsetting has emerged as an important complementary mitigation measure (Becken & Mackey, 2017), with airlines being significant buyers of carbon credits (Stolz & Probst, 2024). Scrutiny of carbon offset programmes has revealed, however, systematic over-crediting (Probst et al., 2024; Romm et al., 2025; Trencher et al., 2024) and issues of permanence, additionality, and environmental integrity (Balmford et al., 2023; Gould, 2026). Moreover, most carbon credits are generated from emission avoidance or reduction projects or are carbon removals from temporary biogenic sinks. These credits are ill-poised to counterbalance ongoing fossil CO<sub>2</sub> emissions in a like-for-like fashion and compatibly with a global net-zero emission goal (Allen et al., 2025; Johnstone et al., 2025). While durable CDR could, in theory, address many of these

problems and play a significant role in aviation (Bachorz et al., 2025; Bergero et al., 2023; Brazzola et al., 2022, 2025; Paul et al., 2023; Sacchi et al., 2023), its certification apparatus is nascent and fragmented (Arcusa & Sprenkle-Hyppolite, 2022; Mercer & Burke, 2023; Schulte et al., 2024), and durable CDR integration into aviation policies is largely absent.

To fix the credibility crisis affecting aviation decarbonisation options, MRV and certification architectures are needed to verify the veracity of climate claims by tracking the GHG impact of different mitigation options (Lebling et al., 2024); to provide assurance that emission reductions and removals are durable and additional, backed by science-based evidence and rigorous standards; and to prevent greenwashing and potential harm to local environments or communities (Mercer & Burke, 2023; Schulte et al., 2024).

A growing literature has assessed certification and crediting standards and methodologies for traditional offsets (Cabiyo & Field, 2025; Chagas et al., 2025; Huber et al., 2024; Kreibich, 2024; Romm et al., 2025; Ruiting et al., 2025; Swinfield & Scott, 2025) and CDR methods (Arcusa & Sprenkle-Hyppolite, 2022; Howes et al., 2023; Malins et al., 2023; Martirosian et al., 2025; McDonald et al., 2021; Meyer-Ohlendorf et al., 2023; Mitchell-Larson et al., 2022; Thorsdottir et al., 2024; Zakkour & Cook, 2024). Substantially less studies have dealt with the certification requirements for SAFs (International Air Transport Association, 2024b). No study has compared certification architectures across all three pillars of near-term aviation's mitigation portfolio — SAFs, traditional offsets, and CDR — within a single integrated framework, and no systematic assessment exists of how existing policies and standards position aviation relative to high-integrity certification benchmarks. This gap matters because aviation policy, such as the Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA) (ICAO, 2021), regularly treats SAFs and offsets as interchangeable or complementary without interrogating whether their underlying certification standards are truly equivalent.

We provide the first cross-cutting, criterion-level comparison of MRV and certification requirements across policies and standards that either directly govern aviation mitigation or could deliver credits to be used in aviation, drawing lessons for how to close the most consequential integrity gaps. We make three contributions. First, we develop a novel evaluation framework of 40 certification criteria derived from literature review, natural language processing pipeline analysis, and expert validation, which can also serve as reusable basis for future assessments. Second, we apply this framework to systematically compare relevant policies, voluntary carbon market initiatives and standards spanning CORSIA, ReFuelEU Aviation (Regulation (EU) 2023/2305 on ensuring a level playing field for sustainable air transport), the EU Emission Trading System (Directive 2003/87/EC), the EU Carbon Removal and Carbon Farming Certification Framework (EU CRCF, Regulation (EU)

2024/3012), the California Low Carbon Fuel Standard (LCFS), and Paris Agreement Article 6. Third, we translate the findings into concrete policy recommendations for strengthening aviation's certification architecture.

## **Methods**

Our analysis comprises of four steps: (1) construction of an evaluation framework; (2) selection and scoping of the corpus of policies, voluntary carbon market initiatives, and standards; (3) manual expert coding of certification requirements; and (4) aggregation and scoring.

First, we developed a comprehensive certification evaluation framework (Figure 1) spanning 10 categories (governance, adaptability, counterfactuals, quantification, boundaries, MRV, permanence, accounting integrity, sustainability, and social safeguards) and divided into 40 certification criteria and 62 indicators (Supplementary Table 1 and 2).



Figure 1 Evaluation framework based on 10 categories and 40 certification criteria.

To build the evaluation framework, we conducted a systematic literature review of peer-reviewed and grey literature on carbon certification, MRV, and aviation climate policy to identify the full range of criteria relevant to high-integrity mitigation certification (Supplementary Table 3). The initial framework was then refined through ten consultations with subject-matter MRV and certification experts (8 from academia, 2 from CDR and CCS-focused NGOs), who assessed the completeness, relevance, and internal consistency of the categories and criteria, and identified potential gaps. For each criterion, we then formalised a textual description based on the literature and on the discussions emerging

from the expert consultations (Supplementary Table 1). Finally, we deployed natural language processing (NLP) tools to verify whether the criteria identified through our top-down framework were consistently reflected across a broad corpus of certification-relevant normative texts — encompassing public policies, standards, and VCM initiatives related to SAFs, CDR, carbon capture and storage, and traditional carbon credits (Supplementary Table 4). The natural language pipeline combined a keyword-based classification approach with a large language model (LLM)-based approach, using the criteria definitions formalised in the preceding step to classify text segments and assign them to the corresponding criteria within our framework. Supplementary Methods 1.2 describes this approach in detail, and Supplementary Results 1 presents its outcomes.

We then selected ten policies and standards to be assessed via the framework (Table 1). In the following, we use “policies and standards” as the overarching term for the normative texts we analysed: “policies” include measures conducive to the reduction of emissions in the aviation sector or relating to technologies that can be used in the aviation sector; and “standards” include both international, regional, and voluntary carbon market initiatives that set consistent quality criteria for crediting activities. Our use of “standards” is not to be confused with documents produced by standardization bodies, such as ISO, CEN or BSI. We use “methodologies” to refer to the specific rules for MRV and certification of particular activities, such as the methodologies applied under certification programmes approved under a standard.

We chose the ten policies and standards based on two criteria: direct relevance to aviation mitigation activities and the centrality of certification to their design. Aviation relevance was assessed based on whether the policy or standard governs activities that airlines, fuel suppliers, or aviation policymakers can deploy to meet climate obligations. Dominant standards—such as the Paris Agreement Article 6.4 mechanism, the ICVCM Core Carbon Principles, and the EU Carbon Removal and Carbon Farming (CRCF) regulation set benchmark requirements for high-integrity credits and will likely influence the design of future certification programmes. We also included sector- and technology-specific policies, such as the California Low Carbon Fuel Standard (LCFS), which provide detailed quantification, permanence, and MRV provisions for carbon capture and storage, which is central for durable CDR. Finally, we included aviation climate policies (e.g., CORSIA) and sustainable aviation fuel mandates (e.g., ReFuelEU). The centrality of certification-relevant provisions in these policies and standards was assessed through the NLP analysis of policy text density around certification-related terms (Supplementary Figure 4). Our corpus of policies and standards deliberately excludes mitigation options where emission reductions occur downstream at the point of propulsion (e.g., hydrogen aircraft), as these do not

require the same upstream certification architecture. Moreover, no policies currently regulate these options.

*Table 1 Overview of corpus of policies and standards included in the manual analysis, including the rationale for inclusion (i.e., the relevance for aviation mitigation pathways).*

<b>Policy</b>	<b>Acronym or abbreviation</b>	<b>Description</b>	<b>Relevance for aviation mitigation pathways</b>
<b>CORSIA Eligible Fuels</b>	CORSIA eligible fuels (CORSIA SAFs and CORSIA LCAFs)	Mechanism to reduce offsetting requirements under CORSIA if aircraft operators deploy CORSIA eligible fuels, which include SAFs and lower carbon aviation fuels (LCAFs).	With CORSIA being the leading CO <sub>2</sub> mitigation mechanism for the international aviation sector, the eligibility criteria of CORSIA eligible fuels drive the quality of SAFs and LCAFs in the sector.
<b>CORSIA Emission Units Eligibility Criteria</b>	CORSIA emission units	Offsetting scheme for CO <sub>2</sub> emissions from international aviation, dictating certification requirements of eligible programmes.	With CORSIA being the leading CO <sub>2</sub> mitigation mechanism for the international aviation sector, the eligibility criteria of CORSIA eligible emission units drive the quality of offsets in the sector.
<b>California Low Carbon Fuel Standard</b>	LCFS	Fuel policy aiming at progressively reducing the carbon intensity of transport and generating credits to reduce emissions. Our analysis focuses on emission reduction crediting activities, especially carbon capture and storage (CCS).	While the LCFS does not apply to aviation, its innovative approach could inspire the aviation sector to integrate carbon credits, especially those based on CCS and offering like-for-like equivalence, in a system that equally include negative emissions and emissions reductions in the calculation of jet fuel carbon intensities.
<b>Regulation (EU) 2019/266 and Regulation (EU) 2018/2067 pursuant to Directive 2003/87/EC</b>	EU ETS	Emission trading scheme imposing a cap on different sectoral emissions. Our analysis is constrained to the monitoring and reporting requirements for the issuance of allowances.	MRV is a fundamental part of the cap-and-trade schemes <sup>4</sup> . Provisions relative to MRV and accounting for aviation emissions influence aviation mitigation pathways in the EU.
<b>Carbon Removal and Carbon Farming Regulation (EU) 2024/3012 of the European Parliament and of the Council</b>	EU CRCF	Certification framework for permanent carbon removals, carbon farming and carbon storage in products.	European standard that certifies CDR projects in the European Union. Integration of CDR in aviation could possibly be based on the inclusion of these credits into CORSIA and other offsetting schemes.

<b>Regulation (EU) 2023/2305 on ensuring a level playing field for sustainable air transport</b>	ReFuelEU Aviation	Mandate increasing the use of SAFs up to 70% in 2050 in the EU, provided that SAFs meet eligibility criteria.	ReFuel EU eligibility criteria will largely influence the shape of SAF projects globally, as ReFuel EU currently is a main driver of SAF demand well beyond Europe.
<b>Paris Agreement Article 6.2</b>	Article 6.2	Mechanism to enable countries to bilaterally cooperate to reduce national emissions. Sets minimum requirements and fungibility for these transactions with further details left to bilateral agreements.	Article 6.2 projects can be used for Other International Mitigation Purposes, which includes the use of Internationally Transferred Mitigation Outcomes for the purposes of complying with voluntary or mandatory requirements of CORSIA <sup>1</sup> .
<b>Paris Agreement Article 6.4</b>	Article 6.4	Paris Agreement Crediting Mechanism (PACM) allowing multilateral trading of emission reductions with criteria applying to all countries and reduction/removal activities.	Emission reductions under the PACM may be allowed by ICAO into CORSIA <sup>2,3</sup> , which could drive CORSIA projects towards the quality standard imposed by PACM.
<b>Integrity Council for the Voluntary Carbon Market Core Carbon Principles</b>	ICVCM	Voluntary carbon market standard that grants CCP label to private sector certification programmes adhering to its requirements.	Determining high-quality carbon credits. CCP labelled crediting programmes are likely interoperable with CORSIA as the ICVCM requirements build on CORSIA eligible units but apply additional requirements.

We compiled a corpus of 54 regulatory texts and supporting documents relative to these ten policies and standards, including regulations, delegated acts, formal decisions, technical annexes, guidance documents, and FAQs where relevant (Supplementary Table 5). Where MRV and certification rules are constrained to specific sections, only the relevant chapters or sub-regulations were retained. The document corpus was frozen in February 2026.

Finally, we manually coded and evaluated the requirements of each policy or standard using expert judgment (Ovádek et al., 2024). For each policy or standard, an expert coder assigned text excerpts to indicators and evaluated whether requirements were absent (score: 0), partially present (0.5, indicating disclosure or partial alignment), or present (1, indicating substantive requirements). Ambiguous cases were resolved through structured discussion among the author team. Indicator scores were weighted by whether they represented primary requirements (weight 1) or conditional sub-requirements (weight 0.5), then aggregated to criterion and category levels.

## Results

### Comprehensiveness of certification policies and standards

No single policy or standard fully covers all 40 certification criteria. Even the most comprehensive policies and standards explicitly address only a subset of indicators, suggesting that all certification architectures involve trade-offs. However, coverage varies enormously: Article 6.4 addresses approximately 78% of indicators, while Article 6.2 covers just below a third (Figure 2). This reflects the fact that the policies and standards in our sample were developed for different purposes, some to be all-encompassing (e.g, Article 6.4), some to be constrained to some certification and MRV aspects but diving deep on these aspects (e.g., LCFS and EU ETS), some to be high integrity (e.g. ICVCM), some to be lighter on the administrative side (e.g., CRCF) such to lead to quicker adoption of the climate solutions they certify.

Standalone certification standards — those that define their own certification methodologies rather than delegating to third-party programmes — exhibit broader coverage of certification criteria. Article 6.4 and the EU CRCF fall into this category and score among the top policies and standards overall. This reflects two reinforcing factors. First, these standards are designed to cover a wide range of activity types across multiple sectors, so their criteria must span dimensions that are irrelevant for narrower instruments. Second, as standalone standards they must be prescriptive enough to guide methodology development, other than policies and standards that simply set a minimum set of requirements but then assess the implementation of these minimum requirements by certification programmes on a case-by-case basis. ICVCM represents a partial exception: while it functions as a gateway standard—analogueous to CORSIA emissions units— that approves external programmes, its comprehensiveness reflects incorporation of institutional learning from voluntary carbon market failures and a multi-stakeholder development process that attempted to systematically incorporate perceived best-practice requirements (Kessler et al., 2024).

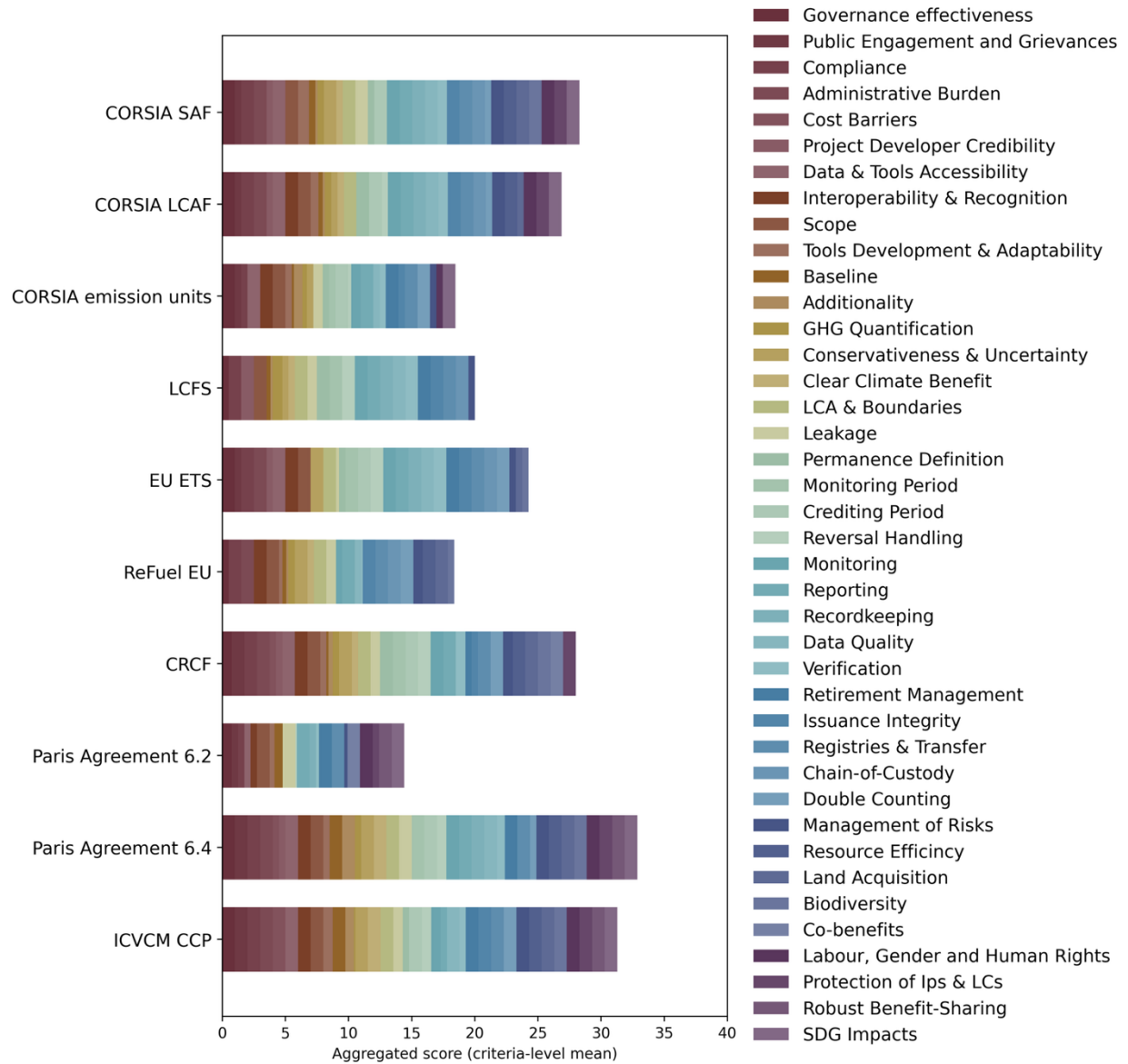


Figure 2 Aggregated scores of criteria-level mean of ternary presence (1= present, 0.5 = somewhat presence, 0 = absent) of 62 indicators (shown in Supplementary Table x and Figure 4) for the ten policies and standards analysed manually. The 40 criteria are further assigned to 10 categories, which correspond to their color as per Figure 1.

Policies and standards that set high-level gateway criteria, relying on underlying programmes for operational detail, systematically underperform. Article 6.2, which in our analysis shows the fewest number of criteria covered, exemplifies this dynamic: its provisions are deliberately brief and generic to accommodate a diverse range of underlying activities and different needs of participating parties. This creates structural gaps in quantification, sustainability, and system boundaries. Requirements are, however, expected to be detailed in bilateral country agreements. CORSIA emission units follow the same logic, maintaining few and vague requirements, such to allow its implementation

body (the International Civil Aviation Organisation) to decide which crediting programmes to include on a case-by-case basis. While enabling flexibility that could help, respectively, accelerating the adoption of climate solutions under bilateral agreements or the approval of credits into CORSIA, the design of these policies structurally obscures the quality of certified activities. This allows high degrees of heterogeneity in the eligible activities.

## **Heterogeneity of certification policies and standards**

Figure 3 shows that policies and standards do not merely differ in overall coverage, but also their priorities and blindspots. Figure 4 further details the presence of 62 indicators across policies and standards, highlighting their qualitative differences. Supplementary Results 2 fully discuss the certification requirements and the identified best-in-class practices of different policies and standards, which we selectively highlight below.

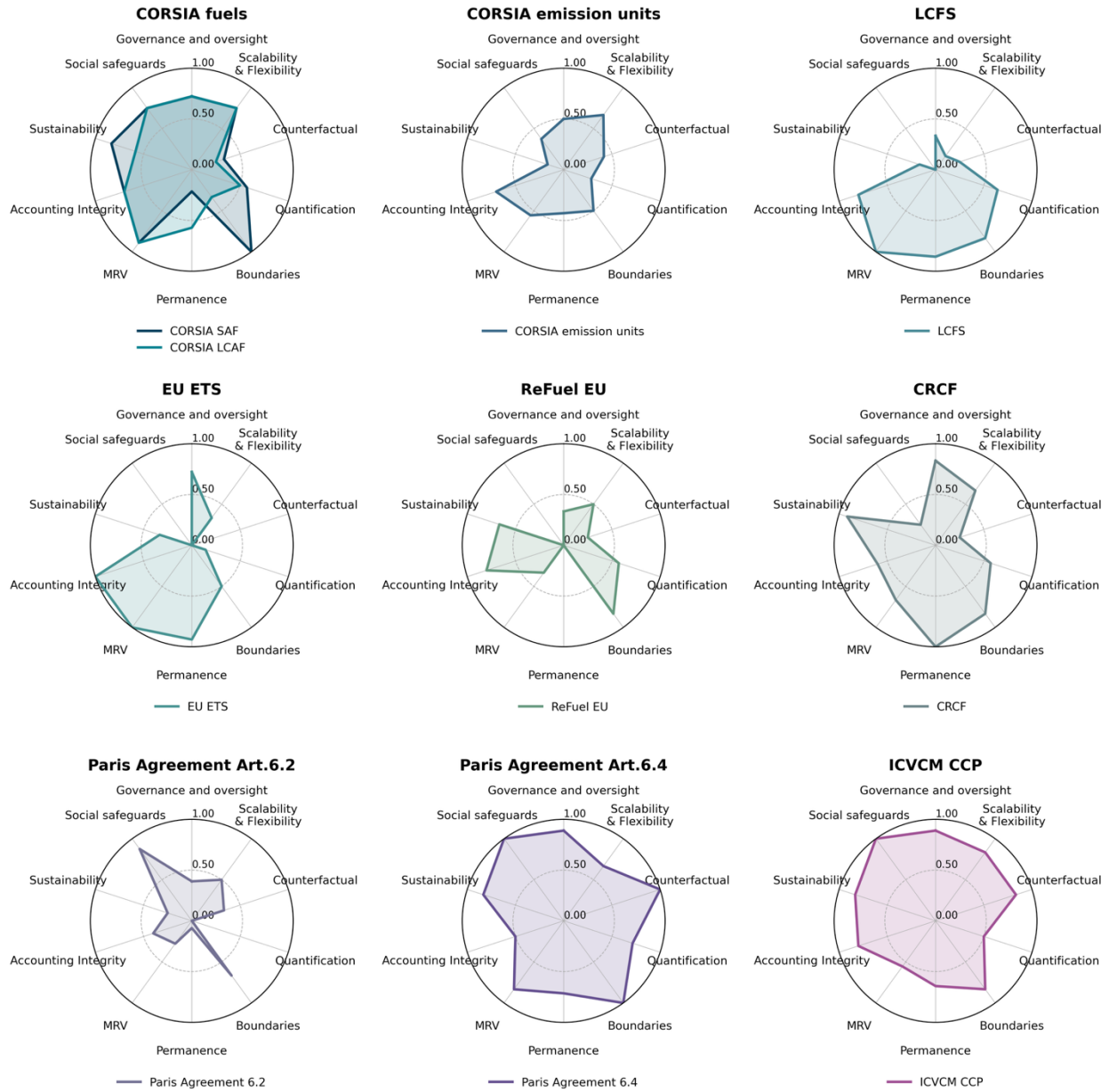


Figure 3 Distribution of aggregate score per category of each policy. The score is calculated as the mean of the normalized score per indicator, taking into account the number of indicators per each category (as these strongly vary). 0 corresponds to the total absence of indicator presence, while 1 corresponds to a policy or standard where all indicators of a category are present.

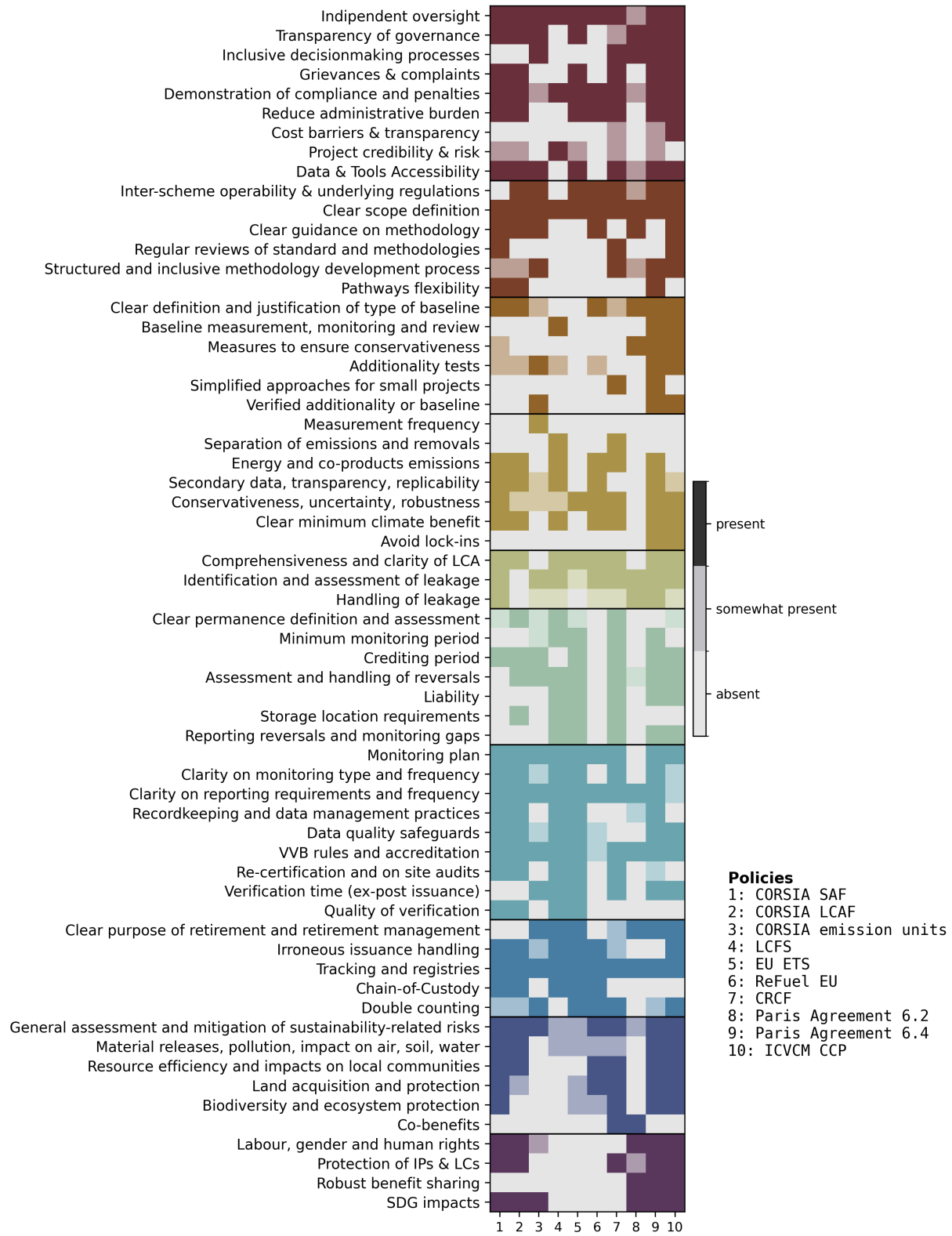


Figure 4 Indicator-level presence scores of each policy

## **CORSIA**

Within the CORSIA scheme, eligible fuels outperform eligible emission units across virtually every certification dimension. CORSIA emission units impose deliberately vague gateway requirements, as to accommodate diverse programmes on a case-by-case basis. This results in broad coverage of certification dimensions, but low scores due to insufficient detail on each dimension. On the other hand, CORSIA eligible fuels perform strongly on system boundaries, reflecting the explicit inclusion of the full supply chain within lifecycle assessment boundaries, and a differentiated treatment of land-use change emissions. CORSIA EFs further perform well on MRV to accurately track SAF and LCAF volumes as well as their emission reductions: CORSIA eligible fuels need to comply with MRV fundamentals such as monitoring plans, annual reporting, recordkeeping, and verification by independent, accredited bodies. Finally, CORSIA SAFs impose various sustainability requirements: they have safeguards against food–energy trade-offs, water stress, and soil degradation; they mandate disclosure of related impacts; and they impose strict land-related rules regarding biomass sourcing, prohibiting conversion from land with high carbon stock and high biodiversity. A central weakness is counterfactuals: CORSIA eligible fuels adopt a fixed 89 gCO<sub>2</sub>/MJ baseline, which in many regions exceeds the actual carbon intensity of conventional jet fuel (Gössling et al., 2026; Jing et al., 2022). Because airlines can be exempted from their offsetting obligations under CORSIA if their fuels demonstrate a 10% reduction in carbon intensity over this baseline, this high benchmark can enable minimal decarbonisation effort to qualify for CORSIA offsetting exemptions and create conditions for strategic tankering. This undermines the effectiveness of CORSIA.

## **California LCFS**

The LCFS leads on MRV and permanence, consistent with its mandate to equate CCS-based crediting with regulated emission reductions from road transport. Its CCS Protocol requires operators to demonstrate 100-year geological storage via computational modelling and monitoring liability, contribute to a risk-rated buffer account, and retain liability for reversals for 50 years post-closure, with credits invalidated proportionally to detected leakage. Verification standards are rigorous: accredited, independently rotating verification bodies, mandatory site visits, and long-term recordkeeping. On accounting integrity, regulated entities annually retire credits from a dedicated account; the Executive Officer can audit, invalidate, or adjust credits, and external credit imports are prohibited. The LCFS fully lacks provisions related to social safeguards, sustainability criteria beyond their immediate regulatory mandate, counterfactuals and additionality. These are however structurally appropriate for a fuel standard instrument but become significant liabilities if its provisions were to inspire the certification of CCS-based

credits in the aviation sector. The LCFS also pioneers financial incentives for novel technologies including DACCS, though scalability provisions remain limited.

## **EU policies and standards**

The three EU policies and standards in our analysis form an interlocking regulatory architecture, each delegating to shared foundational texts. The CCS Directive (Directive 2009/31/EC) underpins permanence rules under both the EU ETS and EU CRCF, which partially owe to it their high scores in permanence. For example, the CCS Directive requires that storage sites be demonstrated suitable to accept the total expected CO<sub>2</sub> volume with low reversal risk, and that the operator retains liability for monitoring and reversal management for a minimum of 20 years until responsibility is formally transferred to the competent authority, if low risk of reversals has been observed. Together with the LCFS, the EU CCS Directive is among the few policies and standards requiring immediate material leakage notification to competent authorities. While mentioning buffer pools, it lacks however detail on how these should be calculated or applied. RED III (Directive EU 2023/2413) governs biomass sustainability across all three EU policies and standards and SAF tracking under both ReFuelEU and the ETS. However, the fragmentation across these three instruments creates integration gaps, most critically on biomass sustainability, where the RED III assumption of carbon-neutral combustion at the point of use is scientifically contested (Fallasch et al., 2025; Martirosian et al., 2025; Nordahl et al., 2024).

Similarly to the LCFS, the EU ETS performs strongly on MRV and accounting integrity, which are key dimensions to ensure that the substitution of emission reductions in one sector with emission reductions in another sector are truly equivalent from a climate perspective. On MRV, the EU ETS demands calculation- or measurement-based monitoring strategies — the latter resolving emissions to hourly basis — and mandates regular plan review and update, consistent with the CCS Directive. EU ETS verifiers must be nationally accredited, fully independent, and apply risk-based verification plans with testing of control activities. On accounting integrity, it establishes a Union Registry and log system that track transactions and compliance with EU ETS accounting rules. Due to its compliance-oriented character, many aspects, traditionally important for certifications, are neglected, such as sustainability, social safeguards, and counterfactuals.

ReFuelEU imposes the most stringent accounting integrity rules among the policies and standards assessed. Its strict mass-balance system tracks SAF deployment and its associated emissions reductions and does not allow any book-and-claim elements, unlike CORSIA eligible fuels. Tracking of SAFs also happens via a Union-wide database, which is established by RED III and which has optional links to national databases. Erroneous issuance is dealt with by cancelling from the Union database SAF quantities and verified

emissions that are subsequently found to not comply with the sustainability requirements. To avoid double counting, as CORSIA, ReFuelEU prohibits claiming SAF batches under other greenhouse gas scheme, selling them to a third party, or otherwise using to generate overlapping emissions reduction claims. ReFuelEU's sustainability criteria are governed by RED III, which differs from CORSIA's sustainability framework; in practice, SAF batches are typically certified under one set of criteria, constraining which scheme they can be claimed under. However, where a batch is certified under multiple sustainability frameworks, operators must declare a single scheme and confirm no overlapping claims. EU ETS rules allow SAF supplied under ReFuelEU to be considered for allowance allocation, subject to defined emission factors and reporting obligations. Aircraft operators must also disclose participation in financial support schemes and ensure that the same SAF batch has not received overlapping public support. Similarly, under the RED III, delegated acts require methodologies that prevent avoided emissions from being credited where CO<sub>2</sub> capture has already been credited under other legal provisions. On the other hand, ReFuelEU is less explicit or completely lacking requirements on governance, counterfactuals, permanence (although under EU regulation the requirements of the EU CCS Directive apply), and social safeguards. On counterfactuals, as for CORSIA eligible fuels, ReFuelEU relies on fixed benchmarks (89gCO<sub>2</sub>/MJ); however, it applies higher climate benefits thresholds over this benchmark (70%) and additional rules to avoid strategic tankering, overall making it a stronger mitigation policy.

The CRCF excels on permanence through its layered definitions across activity types and its reliance on the CCS Directive. Permanent carbon removals are defined as storage lasting several centuries, temporary removals from carbon farming as lasting at least five years, and carbon storage in products as lasting at least 35 years. Provisions on monitoring of and liability for geological CO<sub>2</sub> standards are based on the CCS Directive. On the other hand, one of the available approaches to establish biochar permanence, based on estimating the permanent fraction of biochar, as well as the lack of post-application permanence monitoring, are highly contested (Fallasch et al., 2025). The CRCF is also weaker on counterfactuals, where it takes a controversial approach by setting a zero-baseline for permanent removals and by not having additionality tests (Boettcher et al., 2025; Fallasch et al., 2025; Martirosian et al., 2025). Similarly, on quantification, its approach to uncertainty via conservatism values does not correspond to best practices based on sensitivity analyses, Monte Carlo simulations, and quantifications of different types of uncertainty.

## **Article 6 and the ICVCM Core Carbon Principles**

Article 6.4 and ICVCM achieve the broadest overall coverage, excelling on governance, scalability, counterfactuals, boundaries, quantification, social safeguards and sustainability. Their comprehensiveness comes at a cost: both impose substantial administrative burden, which complicates enforcement and compliance oversight.

Article 6.4 leads on governance through its independent multinational supervisory body, structured public participation, grievance procedures, and mandatory data transparency. On counterfactuals, Article 6.4 establishes best practice through a structured, three-pathway baseline approach — performance-based baselines anchored to best available technologies, ambitious benchmarks set at the level of the best-performing comparable activities, and historical baselines subject to mandatory downward adjustment — with conservativeness requirements calibrated to the baseline type chosen, periodic updates increasing ambition over time, and carbon leakage monitoring tailored to leakage risk. Similarly, three options are allowed to demonstrate additionality: investment analysis, barrier analysis (both accompanied by common-practice analysis), or a performance-based approach allowing standardised demonstration without case-by-case review. On sustainability, Article 6.4 requires: activity-level environmental and social management plans covering health, safety, environmental, and social risks; operational safeguards against pollutant; stringent land-related protections extending to environmentally and culturally sensitive areas, displacement of indigenous peoples and local communities; exclusion of ecologically harmful practices such as monoculture forestry; and safeguards against adverse impacts on water, energy, soil, and ecosystem services across the full lifecycle. On social safeguards, Article 6.4 mandates safe working conditions, prohibits forced and child labour and human trafficking, and protects vulnerable and marginalised groups by guaranteeing non-discrimination and equal pay, promoting gender equality, and mandating Free, Prior and Informed Consent wherever indigenous people are affected. Beyond avoiding negative social impacts, it requires activities to actively generate employment and inclusive economic growth, conduct census and socioeconomic baseline surveys of affected populations, ensure appropriate benefit-sharing, and assess SDG impacts. Article 6.4 exhibits weakness on accounting integrity, as it relies on registries and corresponding adjustments applied by the host Parties but lacks mechanisms to handle erroneous issuance and double issuance. Provisions on permanence are relatively generic at the overarching level, reflecting a deliberate design choice to set high-level rules through a dedicated standard on non-permanence and reversals, while allowing the concrete implementation—such as monitoring duration, risk thresholds, and remediation measures—to be tailored to specific crediting activities in the upcoming methodologies.

Article 6.2 covers few categories, with the only strong-performing dimension being social safeguards—as expected from its development via multilateral negotiations that highlight the importance of safeguarding local communities and indigenous people. While Article 6.2 and 6.4 are conceived under the same policy architecture, they operate as distinct mechanisms. Their divergent scores in this analysis reflect these fundamentally different regulatory designs. Article 6.2 governs bilateral cooperative approaches between Parties with deliberately minimal prescriptive requirements, leaving design details to bilateral agreements. Notably, certification rules under a specific bilateral agreement can be adopted by more prescriptive crediting schemes, such as Article 6.4 or the ICVCM. Notably, it includes one criterion absent from all other instruments: a requirement to measure adaptation co-benefits and report how mitigation outcomes are shared between participating Parties. This reflects its bilateral benefit-sharing function.

Finally, the ICVCM's distinguishing feature is the fact that it covers all dimensions to a minimum extent (minimum aggregated presence score of 0.5), reflecting a lack of fundamental blindspots. Besides leading on social safeguards, where it shares many features with Article 6.4, it is first in class for its scalability architecture: it mandates institutionalised methodology development and review cycles, with defined expert feedback periods, scientific advisory input, and mechanisms to suspend or revise methodologies leading to overestimations of credited carbon. This creates a learning loop absent in most other standards. It leads on quantification through principles-based methodology approval rather than prescribing measurement methods, ensuring robustness, conservativeness, and uncertainty requirements are translated into activity-specific rules. Its weakest spot is sustainability due to limited minimum criteria on land-use change, alien species, and co-benefit recognition.

## Discussion and conclusions

Our findings suggest that there is no single existing policy or standard that comes without blind spots and that stands as the single best option for certifying mitigation solutions in the aviation sector. Instead, certification of aviation mitigation options would need to draw selectively on best practices across multiple policies and standards to ensure real, verifiable, and high-integrity emission reductions and offsets. Each policy or standard reflects deliberate design choices about which integrity dimensions to prioritise given its regulatory context and primary purpose. Therefore, the certification gaps we identify are not all equal: some are appropriate and conducive to the policy or standard's goal, others are genuine risks.

Article 6.4 and the ICVCM represent the current frontier of certification architecture, embodying decades of institutional learning from failures and scandals associated with the voluntary carbon market and Clean Development Mechanisms (Cames et al., 2016; Probst et al., 2024; Romm et al., 2025; Swinfield & Scott, 2025). Emerging evidence shows that ICVCM-approved programmes are outperforming average carbon credits on quality metrics (BeZero, 2026). This suggests that the higher comprehensiveness scores of these standards translate, at least in part, into real-world integrity gains. However, comprehensive and robust standards e.g., well-designed additionality tests, need to be paired with enforcement, oversight and accountability mechanisms with sufficient teeth to avoid being gamed (Cames et al., 2016; Lezak et al., 2026). Furthermore, comprehensiveness should not be conflated with fitness for purpose. Certain certification criteria may be legitimately omitted when they are not relevant to a policy or standard's specific deployment context. Additionality, for instance, is essential in voluntary carbon markets to prevent the crediting of emission reductions that would have occurred regardless of the intervention (Cames et al., 2016; Probst et al., 2024; Schneider, 2009; West et al., 2020, 2023). It becomes considerably less central, however, when emitting and crediting activities are governed under the same compliance framework — as in cap-and-trade regimes (e.g., the EU ETS) or low-carbon fuel standards (e.g., the LCFS).

While some variation across policies is appropriate and legitimised by regulatory purpose, other identified certification gaps are not, and risk enabling lower-integrity mitigation in the aviation sector. The most acute concern is CORSIA's eligibility framework for emission units, which was designed to be broadly inclusive rather than to guarantee the integrity of individual crediting programmes. Its high-level gateway criteria delegate almost all substantive requirements to underlying crediting programmes, whose integrity has been widely questioned in the literature (Probst et al., 2024; Romm et al., 2025; Trencher et al., 2024). Vague requirements of this kind create structural conditions for a race to the

bottom. This risk is compounded by CORSIA's compliance architecture, in which SAF and LCAF deployment exempts airlines from offsetting obligations. This establishes a de facto equivalence between the two mitigation pathways, which is unmatched in the rigour of their certification requirements. Airlines therefore face a perverse incentive to favour low-cost, low-integrity offsets over SAFs, which are subject to detailed, ICAO-defined lifecycle assessment methodologies covering system boundaries, land-use change, feedstock sustainability, and quantification conservativeness. The dominant compliance pathway is thus liable to run through the least credible mitigation option. Article 6.4 units could in principle raise the integrity floor of CORSIA offsetting, given their substantially more comprehensive certification requirements and potential approval for use under the scheme (Carbon Pulse, 2025; Daws, 2024). However, without substantial strengthening of CORSIA's eligibility rules and buyer incentives, host countries will rationally reserve their highest-integrity mitigation for Article 6.4 trades with NDC-constrained partners, leaving aviation as an outlet for lower-integrity projects that cannot or should not qualify under the Paris framework.

A second significant risk concerns inconsistencies in biomass and leakage accounting across the EU's aviation climate apparatus, encompassing ReFuelEU, the EU ETS, and the CRCF. The zero carbon rating anchored in RED III reflects the assumption that biomass feedstocks are already accounted for within national emission inventories aligned with nationally determined contributions (Martirosian et al., 2025). This assumption breaks down when feedstocks for SAFs or biomass-based CDR are sourced from outside the EU or from countries with weak forest carbon accounting (Norton et al., 2019; Searchinger et al., 2009, 2018). The ETS then risks treating imported biomass as zero- or negative-carbon while the associated upstream emissions and carbon debt are uncaptured in any inventory, effectively inflating the imposed emission cap. A further risk stems from the prospective integration of biomass-based permanent CDR into the ETS (European Parliament, 2026). If certified under the CRCF — which lacks leakage safeguards — the higher prices available within the ETS could create a structural incentive to divert biomass away from land-use and agricultural applications that would otherwise store carbon in forests and soils and to displace mitigation away from agri-food systems (Fajardy & Mac Dowell, 2017; Tanzer & Ramírez, 2019). As these foregone mitigation opportunities fall outside ETS pricing, LULUCF and agricultural emissions rise while the cap tightens on the basis of biomass-linked removals.

Several limitations bear noting. First, our analysis assesses the presence of certification requirements, not their implementation quality. High-integrity requirements can be poorly implemented, while simpler policies and standards can be rigorously enforced. The credibility of a certification system therefore ultimately depends as much on compliance

infrastructure as on the requirements themselves. Second, our framework does not weight certification dimensions by their relative importance to the policy or standard regulatory purpose or to climate effectiveness, treating for example a framework that certifies a 10% carbon intensity reduction symmetrically with one that certifies a 90% reduction. Future work should develop normative weighting approaches anchored to climate pathway alignment and to regulatory purpose. Finally, the policy and standard landscape is evolving rapidly (Rodway-Dyer et al., 2024; Smith et al., 2024). Our corpus, frozen in December 2025, excludes important upcoming policy and international standardisation efforts, such as the development of activity-specific methodologies under the EU CRCF and Article 6.4 and the BSI flex standards for DACCS and BECCS.

Aviation's decarbonisation challenge is reliant on a robust certification infrastructure for climate claims. Our analysis shows that the policies and standards currently governing those claims are neither comprehensive enough nor sufficiently consistent to guarantee the integrity that credible aviation climate policy requires. Closing that gap is a precondition for the credibility of the sector's net-zero commitments. Several concrete reforms follow from our findings. First, CORSIA's eligibility criteria for emission units must be substantially strengthened. The current gateway model — which accepts credits from programmes with widely varying integrity levels — should be replaced with criterion-level minimum requirements aligned with the ICVCM Core Carbon Principles or Article 6.4. Second, the EU's aviation climate apparatus should close its biomass sustainability gap by revising the RED III carbon neutrality assumption for aviation-relevant feedstocks, particularly those sourced outside the EU, and by requiring full supply-chain emissions accounting in both ReFuelEU and EU ETS MRV frameworks. Third, enforcement infrastructure must match written requirements. High-integrity standards are not self-enforcing: standards such as Article 6.4 and the ICVCM should be accompanied by independent compliance monitoring, sanctions for overestimated credits, and auditable public registries. Without enforcement teeth, comprehensiveness on paper does not translate into integrity in practice.

#### **Declaration of interest statement**

No potential conflict of interest was reported by the authors.

#### **Declaration of Generative AI use**

Generative AI tools (Claude, Perplexity) have been deployed to support with coding tasks (troubleshooting and debugging), and refine and polish the language of the manuscript. The authors take full responsibility for the content of the article.

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