Designing Carbon Mitigation Markets: Unlocking Willingness-to-Pay Across the Value Chain

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Abstract

The Greenhouse Gas Protocol (GHG Protocol) assigns overlapping emission responsibilities to multiple entities in an aviation value chain when an emission is created. However, current carbon market conventions limit carbon abatement purchases to two entities, typically an airline and another aviation supply chain stakeholder. The decoupling of carbon debit and credit accounting is a market design failure that excludes liable buyers, thereby increasing per entity costs and impeding the development of a voluntary Sustainable Aviation Fuel (SAF) market. We propose a dominant strategy incentive-compatible multi-category auction with a minimum revenue constraint that enables credit allocation to mirror the GHG Protocol's debit structure by removing the two-participant restriction. This results in a functioning carbon market that can activate previously excluded value chain participants by using a multi-party co-ownership structure, leading to cost-sharing of abatement costs and accelerating SAF market growth.

Keywords: carbon accounting, sustainable aviation fuel, auction design, mechanism design, GHG Protocol, environmental attribute certificates

1 Introduction

Many companies track their progress in reducing greenhouse gas emissions through reporting schemes, such as the Greenhouse Gas Protocol (GHG Protocol). To date, the GHG Protocol has been adopted by 97% of S&P 500 companies. The protocol allows reporting of a company's direct emissions through debits on a ledger. In addition, it tracks its indirect emissions in the upstream and downstream value chain. The same physical emission will be the responsibility of many entities, structured into different categories of responsibility [1]. Emission liabilities subsequently overlap across multiple entities in a value chain.

In an effort to mitigate their emissions footprint, companies can participate in mitigation action, including through carbon market-based mechanisms. In such markets, current conventions, as reflected in the World Economic Forum's SAFc accounting guidelines and in indicative guidance from the Science Based Targets initiative, restrict participation in

debits for carbon abatements to two purchasers, such as an airline (direct emission) and one stakeholder of the aviation supply chain (e.g., a business traveler or shipper).[1] This system does not allow other members of the value chain with responsibility for the same emission to participate in its mitigation [2, 3, 4].

The resulting accounting asymmetry between debits and credits leads to a market design failure because it isolates potential co-purchasers from participating in abatement markets. As a consequence, the per entity price of abatement measures increases and crowds out potential contributors along the value chain. The air transportation sector is an economic activity embedded in many value chains. Its carbon abatement costs per tonne of CO_2 remain on the order of $130 and higher [5]. Without splitting these costs among stakeholders, any single stakeholder may consider mitigation measures to be too costly. This institutional challenge can contribute to a dysfunctional voluntary market. The scaling of Sustainable Aviation Fuel (SAF), a promising short- to medium-term mitigation measure, subsequently continues to lag behind ambition [6]. In turn, expanding co-ownership of mitigation measures opens up the opportunity to expand the buyer pool and accelerate SAF adoption. Policy support could address such issues, but remains limited in scale and stability [7].

Co-ownership of emissions mitigation raises the question of whether such co-ownership dilutes the clear assignment of property rights. Abatement credits have the distinct property that they are non-rivalrous across categories. This means entities could share costs and claim credit without reducing the utility of existing participants. When an airline and business traveler jointly purchase SAF, each receives full abatement credit in their own category of responsibility; the joint "ownership" of mitigation options subsequently does not diminish the claim of the other entities. Adding a third participant, such as an airport or aircraft manufacturer, does not dilute the utility of each participant, as long as the third participant remains a distinctly different role within the value chain.

While these arguments establish the potential benefits of co-ownership, it is unclear how such a framework can be practically and institutionally implemented. Most importantly, a market framework is needed that aggregates the willingness-to-pay from different stakeholders for the same emissions mitigation measure. Such a framework must be complemented by a distinct definition of value chain ownership lenses to maintain clear property rights. Furthermore, free rider concerns among different stakeholders in the value chains need to be addressed. This paper assesses different options. Using auction mechanisms, it further shows theoretically that such a market can exist and function.

The paper proceeds as follows. First, we identify the current challenges in voluntary carbon markets, specifically SAF markets, resulting from arbitrarily constrained emissions debits and credits. We show that the GHG Protocol's accounting structure already supports multi-category debit allocation, but current market conventions fail to implement this multi-category allocation for credits. Second, we present a market framework in which the costs of mitigation measures are co-owned. Using methods from auction theory, we show that such markets can exist, considering properties such as dominant strategy incentive compatibility and cost recovery through a minimum aggregate revenue constraint.

[1] The GHG Protocol has not published definitive guidance, leaving this two-party convention as the de facto standard.

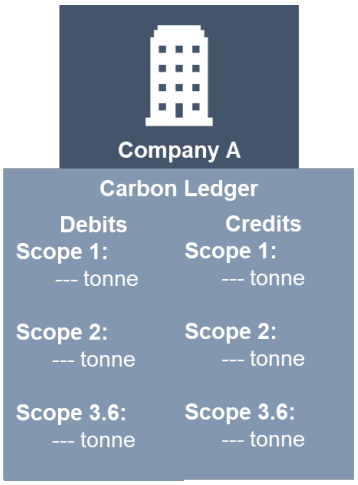


Figure 1: Conceptual depiction of a company's carbon emissions inventory including Scope 1, 2, and one Category of Scope 3. Current guidance recommends credits be disclosed separately; this view illustrates the structural parallels between credits and debits [11].

2 GHG Accounting Framework

The GHG Protocol was established as a carbon accounting framework to help companies, governments, and other entities track and reduce their emissions throughout their operations and value chains [1]. Entities will track their emissions similarly to financial accounting procedures. Furthermore, auditing and validation through external bodies such as the CDP (formerly known as Carbon Disclosure Project) are included [8]. This framework enables companies to disclose their carbon footprint and track progress towards potential net-zero claims. However, the GHG Protocol was developed to focus on eliminating source emissions first and secondarily by a company's direct action to switch to renewable energy products. The carbon accounting rules identified indirect supply chain emission responsibility without fully developing mitigation practices. Carbon disclosure practices have strategic value, as decarbonization initiatives have been shown to attract consumers and talent, enhance brand image, and reduce their cost of capital [9, 10]. In this framework, each entity maintains a carbon accounting ledger to track both emissions debits and abatement credits.[2] A conceptual depiction of the ledger is included in Figure 1.

The ledger is structured around different emission scopes, as defined by the GHG Protocol. Scope 1 covers direct emissions from owned or controlled sources. Scope 2 covers indirect emissions from purchased energy. Scope 3 encompasses 15 categories of value chain emissions, both upstream and downstream. These Scope 3 categories include business travel (Category 6) for corporations whose employees fly, use of sold products (Category 11) for aircraft manufacturers (airframers), and downstream leased assets (Category 13) for entities that

[2]Current GHG Protocol guidance recommends disclosing credits separately from the emissions inventory, resulting in distinct tracking systems in practice [11]. This paper adopts a unified ledger framework to highlight the symmetry between how debits and credits are allocated across categories. This unified framework allows a more direct comparison between debits and credit allocation, which could be obscured through separate tracking.

Entity	Scope	Category	Debit
Airline	1	—	50 tonnes
Business Traveler	3	6	50 tonnes
Airframers	3	11	50 tonnes
Lessor	3	13	50 tonnes

Table 1: Overlapping emission debits from a single flight emitting 50 tonnes CO_2. The same physical emission appears on multiple entities' carbon ledgers under different GHG Protocol categories.

lease aircraft to airlines [3]. In this system, the emissions scopes are interdependent. One organization's Scope 3 emissions are another's Scope 1 emissions. Given the numerous Scope 3 categories, a single Scope 1 emission is associated with multiple Scope 3 entries, likely across different companies' ledgers. For example, a commercial flight emitting 50 tonnes of CO_2 appears as the airline's Scope 1, a business traveler's Scope 3 Category 6, an airframer's Scope 3 Category 11, and a lessor's Scope 3 Category 13 [12]. The same physical emission is recorded as a debit on multiple ledgers by design [3] (see also Table 1 for an overview).

In a consistent accounting framework, the credit structure would mirror the debit structure on the same ledger. This implies that, in a consistent accounting approach, mitigating emissions within a supply chain would create overlapping credits across multiple categories and entities. An airline reducing its Scope 1 emissions through SAF use could enable corresponding Scope 3 credit claims by the business travelers, airframers, and lessors in their respective categories. In practice, the GHG Protocol provides less structure for credits. For example, the GHG Protocol states that if GHG reductions "take on a monetary value or receive credit in a GHG reduction", they should specify exclusive Scope 3 ownership of the reduction [3]. The GHG Protocol does not clarify how this reconciles with the overlapping ownership of Scope 3 debits [1]. As a result, market conventions drive how credits are allocated, leading to a decoupling of debits and credits due to limitations in recognizing Scope 3 shared benefits.

This creates a decoupling of carbon debit and credit accounting. While multiple entities record the same emission as a debit on their ledgers, credit allocation remains restricted to only two entities. This two-party debit convention gained widespread acceptance following the World Economic Forum's SAFc Framework. This framework established accounting guidelines enabling both the airline and a single Scope 3 beneficiary to claim credit from the same certificate [2]. Although it legitimized co-owned Scope 1 and Scope 3 claims, it excluded entities with overlapping responsibilities from contributing to abatement purchases.

Furthermore, the mechanisms for claiming credit on a carbon ledger interact with those through which the physical mitigation measures are supplied to markets. SAF reaches the market through two main procurement pathways:

- *In direct procurement*, an airline purchases physical SAF and combusts it in its aircraft, which is physically traceable. The airline receives the associated Environmental Attribute Certificate (EAC), which is a certificate of the emissions reduction (typically assessed on a lifecycle basis) relative to the use of fossil Jet-A fuel. The airline acts as an intermediary and may share the cost premium associated with SAF use with Scope 3 responsible entities. The airline can then allocate the Scope 3 environmental attributes

to those individual businesses once the physical SAF has been used. The International Air Transport Association (IATA) states that two end users with the same value chain role should not claim environmental attributes from the same emission abatement. However, they state that two users in the same value chain can claim distinct Scope 3 credits, allowing multiple Scope 3 purchasers to share a single allocation [13].

- *In book-and-claim procurement*, the EAC is decoupled from the physical fuel flow, allowing parties to purchase the certificate independently of where the fuel was used [14]. This means that the physical SAF may be combusted by a different carrier and in a different location. Such a mechanism addresses logistical constraints arising from uneven SAF availability across airports. EACs in this context are established based on the purchase of SAF and its introduction into the general aviation fuel system, which is legitimate given SAFs' drop-in nature and the assumption that CO_2 is a well-mixed greenhouse gas. In this framework, Scope 1 and Scope 3 claims can be sold separately by market makers other than the airline (e.g., a fuel producer) and without alignment of user groups. Yet, the general restrictions on co-ownership lenses typically apply under today's frameworks.

Through either method, the EAC must be tracked in a SAF registry, which helps account for entities' EAC claims and makes them auditable. While direct procurement channels can, in theory, be audited without such a registry through the physical chain of custody, a book-and-claim environment is fully dependent on accurate and specific documentation, such as the Proof of Sustainability statement. Registries track SAF volumes and their associated credits from generation (during production and use) to retirement. Retirement entails taking the EAC out of circulation once the named Scope 1 and Scope 3 beneficiaries retire the EAC, and the EAC is claimed against an annual emissions inventory. After retirement, the named entities can track their carbon credits on their carbon credit ledger, which remains auditable through the registry [14].

3 Carbon Market

Carbon markets serve an important role in offering carbon abatement. They link the physical process of mitigation on the supply side to the willingness-to-pay to buy such mitigation options on the demand side. Given the high cost of carbon mitigation in the aviation sector, abatement efforts over the past decade have focused almost exclusively on cross-sector offsets, such as cookstove distribution programs and forest preservation. Such programs offer relatively inexpensive credits, often below \$20 per tonne of CO_2 [15]. Furthermore, institutional frameworks for aviation carbon mitigation such as International Civil Aviation Organization's Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA) have implemented such mechanisms and markets [16]. However, offsets have been subject to significant criticism. Recent studies show that many offsets may not have delivered claimed emission reductions, due to concerns regarding lack of additionality (projects would have occurred regardless of intervention), inflated baselines (elevated baseline scenarios overestimate projects' impact), permanence (emission abatements may be reversed), and double counting (the same emission reduction credit being claimed by parties whose inventories should be mutually exclusive) [17, 18, 19]. As a result, there have been legal challenges, including litigation against Delta Air Lines over offset-based carbon neutrality claims [20].

In light of these shortcomings, carbon offsetting in the aviation sector has created the need for alternative crediting schemes, such as insets - that is, measures to reduce emissions within the aviation value chain. For insets, direct purchase of mitigation measures by operators can play a role, which may bypass more traditional carbon markets. However, as EACs and book-and-claim mechanisms are increasingly used, more liquid carbon markets for aviation carbon mitigation could emerge. Such markets could create willingness-to-pay to support scale-up, including more expensive mitigation measures such as SAF, and support the currently lagging scale-up efforts in this industry [7, 6].

As discussed above, current market conventions restrict SAF credit allocation to a two-party structure. When an EAC is retired in a registry, only two entities are recognized as contributors: the airline, which claims a Scope 1 credit, and a single Scope 3 purchaser in the value chain (e.g., user, airframer, airport) [14]. This two-party restriction in the SAF market generates two market failures:

1. The distribution of credit is incomplete, which results in an inconsistency in the carbon accounting. This is because, fundamentally, not every Scope 3 emission is connected to a Scope 1 emission if SAF is used and the two-party allocation model is applied. EACs could be allocated to additional categories, with each recipient receiving full credit without diluting other participants' utility. For example, an airline may reduce its Scope 1 emissions through SAF use on a flight - and a business traveler may participate in their carbon ledger. Yet no credit would be given to OEMs or airports, who would still bear the full carbon debt of the flight.
2. The single Scope 3 beneficiary convention excludes willing buyers from other categories who could participate without diminishing existing participants' utility, making them non-rivalrous. As such, the current restriction on participation increases per entity costs. When two of n responsible entities must fund 100% of abatement costs, they effectively pay for credit categories they cannot claim (and that do not receive credit - see point 1). If SAF costs \$400 per tonne of CO_2 abated and 4 classifications (one Scope 1 and three Scope 3) share responsibility, cost distribution would be \$100 per entity on average. Efficient distribution among the parties could be determined by their relative utility of the abatement. Current conventions force two participants to pay \$200 each, potentially exceeding their willingness-to-pay and constraining SAF market development.

These failures are not inherent to sustainable goods markets. They arise from an institutional framework that does not maintain consistency in the allocation of property rights on the debit and credit sides. The GHG Protocol recognizes that multiple entities bear responsibility for the same emission, yet the market restricts participation as if only two entities were liable. A market that aligns participation with liability would permit additional Scope 3 categories to contribute and distribute costs across responsible parties, and provide the transparency necessary to sustain trust.

4 An Alternative SAF Crediting Scheme

The previous section established that the GHG Protocol assigns overlapping emission responsibility across multiple Scope 3 entities; however, market conventions restrict the credit

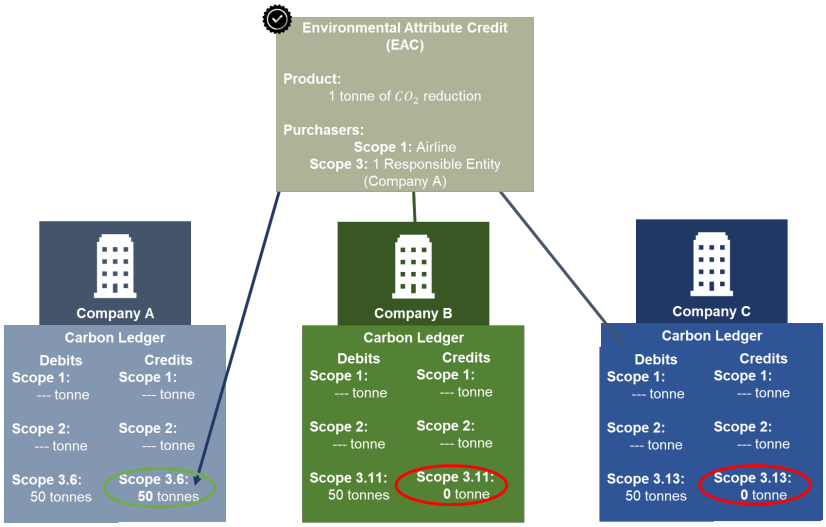


Figure 2: The two-participant restriction only allows a single Scope 3 entity to participate in the purchase of an EAC, isolating other entities with those same emissions on their ledger from helping abate those emissions.

allocation to only two participants. This section aims to identify the institutional requirements for reconciling this asymmetry.

The GHG Protocol's accounting of carbon debits today demonstrates the value chain's interdependence, where multiple Scope 3 entity debits propagate from a single Scope 1 emission. In developing a consistent carbon accounting structure, the credit market should reflect this structure. If multiple categories are responsible for a single emission, they can participate in its abatement - and subsequently co-own the full mitigation from their specific lenses.

A central theme of this dynamic is the EAC's property of being non-rivalrous across categories. Today, when an airline and a business traveler jointly purchase SAF, each receives full credit in each of their respective categories. The business traveler's credit is not diminished by the airline's allocation of the emission abatement credit, even though they are sharing the same physically backed mitigation action.

This concept can be extended to cover all Scope 3 subcategories. Such a system does not constitute double-counting as long as each Scope and Scope category is fully and uniquely responsible for the associated emissions debit. Implementing this concept requires defining co-ownership of emissions debits and credits. Co-ownership is when multiple entities, each with an established, distinct category of responsibility, hold a simultaneous claim to an emission abatement. Co-ownership means that, at the time of retirement, the entities will also be listed as owners in their respective categories in the registry. It gives each owner the obligation to report full emissions debits and the right to claim credit on their carbon ledger. The co-ownership does not grant transferability across categories, meaning that an entity owning a Scope 3 - Category 13 EAC can not account for it as a Category 6 credit. Implementing this method will require registries to track each category of responsibility at the time of the EAC's retirement. If no responsible entity exists for a given category or has not been identified as part of the shared EAC ownership, the potential credit for that category remains unallocated at retirement.

A practical challenge of this approach is the definition of emission scopes. Rigorous tracking and a clear understanding of the value chains is important for this purpose. The GHG Protocol, in its current form, may face limitations in that regard. For example, users of a flight may include business travelers (for the passengers in the cabin) and shippers (for cargo in the belly of the aircraft). These are currently considered in different Scope 3 categories (Categories 6 and 9). As both constitute users of the same flight, it does not seem appropriate to establish full emissions debits for both user groups, but rather to allocate partial emissions to each user group. On the contrary, an aircraft manufacturer and an aircraft engine manufacturer are both listed within Scope 3, Category 11 of the GHG Protocol. Yet, it can be argued that they are both fully responsible for a flight's emissions debit and should subsequently be allowed to co-own emissions credits for a flight. These examples highlight the need for tools and decision rules to establish value chain tracing and distinguish scope categories - which is beyond the scope of this paper.

The co-ownership system enables cost-sharing for mitigation options along the value chain. In such a market, aggregate willingness-to-pay for the mitigation action, such as a SAF, must meet the producer's cost-recovery constraint as depicted in Figure 3. For this purpose, a coordinating mechanism is needed, which can either lay in a decentralized market instrument or market makers. In this context, it is important to note that the SAF producer's cost-recovery constraint is in the aggregation sum of the categories' payments, rather than requiring the individual categories to pay a predetermined amount. This category-neutrality subsequently requires the market orchestrator to aggregate heterogeneous valuations through price discovery rather than assigning responsibility levels ex ante.

The inclusion of multiple entities introduces the risk of free-riding in the system. This is possible when entities receive credit without making a financial contribution to the mitigation. The market mechanism must ensure that only entities that financially contribute to the purchase of emission abatement receive credit. Some categories may therefore go unallocated because they do not contribute to the cost, even when other entities have abated the underlying emissions. Maintaining the integrity of the credit structure requires contribution as a condition for allocation. As such, it remains to be shown how a functioning market can be established.

5 A Market for SAF with Non-Rival Abatement Credits

To establish when and under which conditions a market can emerge, we now model an auction-based market in which a SAF producer auctions the EACs generated by its fuel production to address these requirements. We conceptualize an auction involving a single SAF producer and several entities (e.g. corporations) seeking to abate their Scope 3 aviation-related carbon emissions through the purchase of SAF. Auctions are well-suited in these nascent markets because they enable price discovery across heterogeneous participant categories without requiring market designers to specify valuations ex ante. The SAF producer sets a minimum aggregate revenue constraint reflecting production costs plus a reasonable rate of return, and offers EAC allocations across multiple categories of responsibility to leverage the non-rivalrous investment capacity of the different categories. Furthermore, the market setup must ensure that only financially contributing entities receive credit, preventing allocation of credit to free-riders. Additionally, it must be transparent to maintain trust in a market where participants are unable to observe other entities' valuations. The following section develops an

auction mechanism that satisfies these requirements while maintaining theoretical guarantees on truthful bidding.

5.1 Market Variables and Participants' Valuations

On the supply side, the SAF producer is characterized by a marginal cost of production $C \in \mathbb{R}_+$ and a production capacity $Q_{\max} \in \mathbb{R}_+$, the maximum amount of SAF they can produce. SAF production costs, like conventional jet fuel, can vary heavily based on the cost of their feedstocks and their conversion process [16]. Today, these producers also have yet to achieve similar economies of scale as conventional jet fuel refineries reinforcing the competitive disadvantage for SAF [6]. These parameters are assumed to be publicly disclosed data.

On the demand side, $N \coloneqq \{1, \ldots, n\}$ is the set of n corporations participating in the market, and $M \coloneqq \{1, \ldots, m\}$ denotes the set of Scope 3 categories. Corporations seek to decarbonize through the purchase of EACs. Each corporation $i \in N$ enters the market with a reported quantity $q_{i,j} \in \mathbb{R}_+$ of aviation-related carbon emissions in category $j \in M$, and corresponding marginal value $v_{i,j} \in \mathbb{R}_+$ for abating emissions in this category. Finally, each corporation $i \in N$ has a global spending limit $B_i \in \mathbb{R}_+$ for the purchase of abatement credits.

The main factor entering a corporation's valuation of abatement is their willingness to maintain their social license to operate. Indeed, business models that depend on aviation are threatened by flight shaming around corporate and private travel [21]. As a result, corporations often make commitments to decarbonization and their valuation of abatement can thus be directly linked to the reputational damage they would incur if they failed to uphold these commitments, or if their emissions were deemed excessive by the public opinion.

These pressures generate heterogeneous valuations across emission categories. Company-wide net-zero commitments, now standard among firms such as Apple, Microsoft, and Amazon, create a baseline willingness-to-pay for credits across available categories [9]. Aviation-specific scrutiny then amplifies valuations for certain categories, particularly Category 6 (Business Travel), beyond this baseline [21]. These factors drive an entity to value abatement credits and then participate in this market.

5.2 The Auction Design Problem

We now define the auction structure for the multi-category auction. We assume that the corporations' valuations for abatement are private knowledge. To facilitate efficient price discovery, we therefore structure the market as an auction run by the SAF producer. For the remainder of this paper we also make two simplifying assumptions: (i) there is a single unit of SAF up for sale (and $Q_{\max} \geq 1$) scalable to the production of the SAF producer, and (ii) each corporation i may purchase abatement credits in at most one category j, with $q_{i,j} \geq 1$. A more general auction would allow corporations to demand varying quantities of abatement over multiple categories and aggregate these preferences to determine the optimal SAF production level, the allocation of credits, and the associated payments. Our assumptions are made both for analytical tractability and to obtain a simpler auction format that could be more readily deployed in the short term.

Under these assumptions, we simplify notation by letting v_i denote the valuation of corporation $i \in N$ for abatement in the Scope 3 category in which it seeks to purchase credits. These valuations arise from a corporation's valuation of its social license to operate. Moreover,

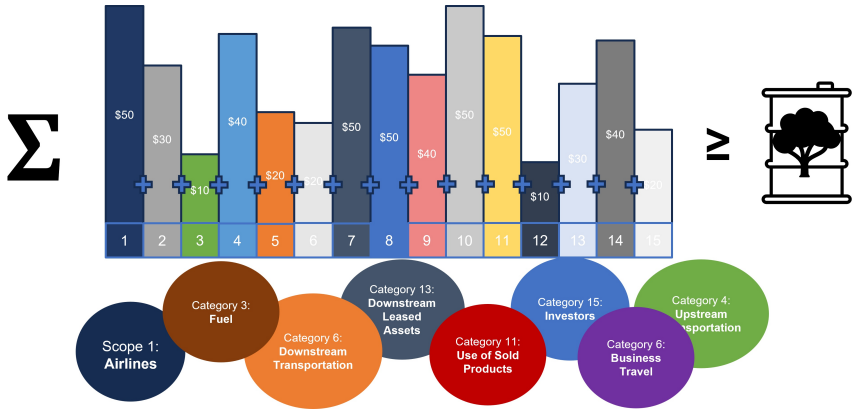


Figure 3: Depiction of auction categories breakdown with aggregate sum meeting the production cost of SAF.

the set of corporations N is now partitioned into m pairwise disjoint subsets $P_1, \ldots, P_m$, where P_j denotes the subset of corporations purchasing credits in category $j \in M$. By the revelation principle, we may, without loss of generality, restrict attention to strategyproof, direct revelation mechanisms in which corporations are asked to report their valuation for abatement. The aim for strategyproof or dominant strategy incentive compatibility is to help develop transparency in this market. Incentivizing corporations to bid truthfully can reinforce the effectiveness of this market to deploy reliable carbon credits. For each corporation $i \in N$, let $b_i \in \mathbb{R}_+$ denote the reported value, which may differ from the true value v_i. Such a mechanism therefore specifies, for each $i \in N$:

- an *allocation function* $x_i : \mathbb{R}_+^n \to [0,1]^n$ mapping bids b to corporation i's credit $x_i(b)$;
- a *payment function* $p_i : \mathbb{R}_+^n \to \mathbb{R}_+$ mapping bids b to corporation i's payment $p_i(b)$.

We allow for fractional credits: although a single unit of SAF is auctioned, a corporation may be credited for a fraction of that unit. This reflects the practical reality that corporations may only require a specified amount of credits. If credits were instead treated as indivisible, a fractional allocation $x_i(b) \in [0,1]$ can be interpreted as a randomized mechanism in which corporation i receives a unit of credit with probability $x_i(b)$. We assume quasilinear utilities, so that the utility $u_i(b)$ of corporation i from participating in the auction is given by

$$u_i(b) \coloneqq v_i \cdot x_i(b) - p_i(b).$$

With these notations, we can now formally state the auction's desiderata.

1. *Strategyproof*: it is a dominant strategy for corporations to report their true valuation. For each $i \in N$ and $b \in \mathbb{R}_+^n$,

$$v_i \cdot x_i(v_i, b_{-i}) - p_i(v_i, b_{-i}) \geq v_i \cdot x_i(b) - p_i(b). \tag{1}$$

   This property guarantees robustness to strategic manipulation, as corporations do not benefit from misreporting their valuations, which in turn promotes transparency and trust in the auction. This is critical, as past carbon credit markets have struggled with credibility and public trust [17, 18, 19].

2. *Individually rational*: corporations weakly prefer to participate. For each $i \in N$ and $b \in \mathbb{R}^n_+$,
$$v_i \cdot x_i(b) - p_i(b) \geq 0. \tag{2}$$
This guarantees voluntary participation, as corporations are never charged more than their valuation for any allocated credit. In a voluntary market, entities must view participation as an opportunity to decarbonize, not a financial burden.
3. *Budget-balanced*: the collected revenue covers the production cost C (see Fig. 3). For each $b \in \mathbb{R}^n_+$,
$$\sum_{i \in N} p_i(b) \geq C \cdot \max_{j \in M} \Big\{ \sum\nolimits_{i \in P_j} x_i(b) \Big\}. \tag{3}$$
This is a baseline requirement for the SAF producer, as production would not occur at a loss. The budget balance ensures the aggregate revenue constraint is met and that transactions support the development of the SAF market rather than delivering goods at below-cost prices.
Note that when no corporation receives credits ($x \equiv 0$), the right-hand side of (3) vanishes. This accommodates the possibility of insufficient market demand, in which case SAF is simply not produced.
4. *Ledger-balanced*: each Scope 3 category is allocated at most one unit of credit in aggregate. For each $b \in \mathbb{R}^n_+$ and $j \in M$,
$$\sum_{i \in P_j} x_i(b) \leq 1. \tag{4}$$
This is the key property addressing the discrepancies in carbon accounting discussed above. It ensures that no Scope 3 category is credited beyond the quantity of SAF actually produced, while crucially imposing no constraints *across* categories. By aligning the debit and credit sides of emissions accounting, it restores balance in corporate carbon ledgers.

5.3 Towards a Welfare-Optimal Auction

There are many possible auctions—and thus many possible market outcomes—satisfying the formal requirements (1)–(4), making the auction design problem underspecified. It is therefore natural to restrict attention to Pareto-optimal outcomes and, among them, to select the outcome that maximizes social welfare, defined as the total utility of the SAF producer and the participating corporations. This criterion treats all participants symmetrically and does not favor any particular agent. Under the model of Section 5.2, the social welfare for a vector of bids $b \in \mathbb{R}^n_+$ is given by
$$\left(\sum_{i \in N} p_i(b) - C \right) + \sum_{i \in N} \big(v_i \cdot x_i(b) - p_i(b) \big),$$
where the first term is the utility of the SAF producer, and the summand in the second term is the utility of corporation $i \in N$. The payments cancel out and C is constant, hence maximizing social welfare reduces to maximizing the quantity
$$W(b) \coloneqq \sum_{i \in N} v_i \cdot x_i(b).$$

We now introduce some notations that will be helpful in describing the structure of our proposed auction. Given a vector of bids b, let $t_j(b)$ and $s_j(b)$ denote, for each category $j \in M$, the highest and second-highest bids, respectively:

$$t_j(b) = \max\{b_i \mid i \in P_j\} \quad \text{and} \quad s_j(b) = \max\{b_\ell \mid i \in P_j, \ell \in P_j \setminus \{i\}\},$$

with the convention that the maximum of an empty set is 0. Consequently, if $P_j = \emptyset$, then $t_j(b) = s_j(b) = 0$; if P_j is the singleton $\{i\}$, then $t_j(b) = b_i$ and $s_j(b) = 0$. Moreover, we order the categories in descending order of $t_j(b)$ and let (j) denote the index of the jth highest category, so that $t_{(1)}(b) \geq t_{(2)}(b) \geq \cdots \geq t_{(m)}(b)$ and adopt the convention that $t_{(m+1)}(b) = 0$. With these notations in hand, the following definition describes our proposed auction.

Definition 1. Given bid vector $b \in \mathbb{R}^n_+$, the SAF auction first determines the maximal number of categories to which credits can be allocated while maintaining budget balance:

$$k^\star(b) \coloneqq \max\left\{ k \in M \;\middle|\; \sum_{j=1}^{k} \max\{s_{(j)}(b), t_{(k+1)}(b)\} \geq C \right\}.$$

Then, the auction's allocation to corporation $i \in P_j$ is given by

$$x_i(b) = \begin{cases} 1/|\{\ell \in P_j \mid b_\ell = t_j(b)\}| & \text{if } b_i = t_j(b) \text{ and } 1 \leq j \leq k^* \\ 0 & \text{otherwise} \end{cases},$$

with corresponding payment $p_i(b) = x_i(b) \cdot \max\{s_j(b), t_{(k^\star+1)}(b)\}$.

To build intuition for the auction's structure, it is instructive to consider two special cases.

1. *One corporation per category.* In this case, the computation of $k^\star(b)$ reduces to

   $$k^\star(b) \coloneqq \max\{k \in M \mid k \cdot t_{(k+1)}(b) \geq C\}.$$

   The auction then allocates credits to the top $k^\star(b)$ categories (ranked by descending bids) and charges each of them $t_{(k^\star+1)}(b)$, namely the bid of the first excluded category. Thus, the auction leverages competition *across* categories: exclusion of lower-ranked categories disciplines bids and generates revenue from the included ones. The value $k^\star(b)$ is chosen to maximize the number of included categories while ensuring that the resulting per-category payments collectively cover the production cost C. This mechanism can be viewed as a variant of the standard multi-unit auction [22, §12.1.3 p.178].
2. *A single category.* When there is only one category, the auction reduces to a second-price auction with a production constraint. Full credit is allocated to the highest bidder, provided that the second-highest bid—the maximal payment that can be extracted from the winner—exceeds C. In this case, competition *within* the category ensures truthful bidding and revenue generation. If there are ties for the highest bid, the credit is split equally among the tied corporations.

In the general case, the proposed auction can be interpreted as interpolating between these two extremes, leveraging competition both *within* and *across* categories. An equivalent description of the allocation rule is given by the following iterative procedure:

1. Begin by tentatively including all categories. The resulting revenue is the sum of the second-highest bids across categories, $\sum_{j=1}^{k} s_{(j)}(b)$.
2. If this revenue fails to satisfy budget balance, exclude the least competitive category—namely, the category with the smallest highest bid—and treat its highest bid as a binding "reserve price" for the remaining categories.
3. Repeat Step 2 until the remaining categories generate total payments sufficient to cover the production cost C. If no such subset exists, the auction does not raise enough revenue: the SAF is not produced, and no credits are allocated.

The following proposition summarizes the properties of our auction.

Proposition 1. *The SAF auction of Definition 1 is strategyproof (1), individually rational (2), budget-balanced (3), and ledger-balanced (4).*

A proof of this proposition is provided in Appendix A.

6 Conclusion

The GHG Protocol asymmetrically accounts for carbon debits and credits across the current voluntary sustainable aviation value chain. While multiple Scope 3 categories share responsibility for a single emission, current market conventions restrict abatement credit allocation to only two participants. This inflates per entity costs, excludes willing buyers from other categories, and hampers the development of a SAF market. This is a key hurdle to the emergence of a voluntary carbon mitigation market, especially for "middle of the value chain" activities such as aviation, where abatement costs are high.

This paper outlines a framework for revised carbon accounting rules for carbon credits and introduces a broad concept of multi-category emission co-ownership to maintain consistency between debits and credits in carbon accounting schemes. Such an accounting paradigm would not only change the institutional framework of carbon accounting but would also allow new business models for carbon mitigation to evolve. More importantly, co-ownership of carbon credits would spread the cost of abatement across the value chain, while also requiring new business approaches to effectively aggregate willingness-to-pay across the aviation value chain.

In such a framework, a system of market makers and registries needs to evolve that can track mitigation measures and aggregate willingness-to-pay across multiple Scope 3 beneficiaries. The proposed multi-category auction with minimum aggregate revenue constraint aligns the SAF market structure with the accounting structure. The mechanism activates additional liable entities, ensures cost recovery with a minimum aggregate revenue constraint, and eliminates strategic manipulation incentives through dominant-strategy incentive compatibility. It shows, for the first time, that such an institutional accounting structure can lead to the emergence of a functioning carbon accounting market.

This structure extends beyond aviation to any sustainable goods market in which multiple entities share responsibility for the same emissions. The key insight is that GHG Protocol guidance on avoiding "double-counting" has artificially increased the cost of sustainable goods, without fully establishing trust. Recognizing that credits can be non-rivalrous across categories but rivalrous within categories creates an opportunity to activate previously unused willingness-to-pay.

However, there are still limitations to the deployment of this auction. The market relies on current GHG Protocol Scope 3 definitions, which may require refinement to capture aviation-specific value chains more precisely. The minimum aggregate revenue constraint permits unequal contributions across categories, potentially leading to drastic differences in payments. Extending the mechanism to allow bidders to participate in multiple categories simultaneously while maintaining DSIC is still an open theoretical problem. Finally, verifying legitimate category claims will require additional methods as the buyer pool expands.

Even with these limitations, this paper demonstrates that multi-category credit allocation can resolve the decoupling between debit and credit accounting under the GHG Protocol and is implementable. Deploying this multi-category credit allocation with a well-designed mechanism would unlock efficiency gains and help accelerate voluntary sustainable goods markets.

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A Appendix

We provide a proof sketch for Proposition 1 below. Full details will be provided in an expanded version of the paper.

Proof of Proposition 1. That the auction is individually rational, budget-balanced, and ledger-balanced can be readily verified from the provided expressions for the allocation x_i and payment p_i in Definition 1.

The only nontrivial property is strategyproofness. For this, we use Myerson's characterization of strategyproofness for single parameter domains [23, Lemma 2]. This characterization guarantees that the auction is strategyproof provided that for each corporation $i \in N$, (i) the allocation x_i is non-decreasing in i's bid, and (ii) the payment p_i is given by

$$p_i(b_i, b_{-i}) = \int_0^{b_i} s \frac{dx_i}{ds}(s, b_{-i}) ds.$$

In cases such as ours where the allocation jumps from 0 to a non-zero value, the above formula is equivalent to requiring that an allocated bidder pays their threshold bid.

For our auction, when a bidder is allocated, the minimum bid they could have submitted and still be allocated is constrained from below by both $s_{(j)}(b)$—the bid needs to be the highest bid in its category—and by $t_{(k^\star+1)}(b)$—otherwise, category j becomes less competitive than category $(k^\star+1)$ and category j is no longer one of the winning categories. Consequently, bidder i's threshold bid is $\max\{s_{(j)}(b), t_{(k^\star+1)}(b)\}$ which is precisely their payment under Definition 1.

It thus remains to show that the allocation rule x_i is monotone in b_i. For this, we start at the lowest bid 0 and analyze how $x_i(b_i, b_{-i})$ varies as we increase b_i. Note that $x_i(b_i, b_{-i})$ is constant equal to 0 as long as $b_i < t_{(j)}(0, b_{-i})$. Indeed, bidder i is not the highest bidder in their category in this case.

We thus focus on the case $b_i > t_{(j)}(0, b_{-i})$, at which point bidder i becomes the highest bidder in their category. We distinguish two cases:

- $j \leq k^\star(0, b_{-i})$. In this case category j is one of the winning categories, even when bidder i's bid is 0. Bidder i becoming the highest bidder only increases category j's top bid, and guarantees that category j remains allocated by the auction. Thus bidder i's allocation becomes 1 for all values for $b_i > t_{(j)}(0, b_{-i})$.
- $j > k^\star(0, b_{-i})$. In this case, category j is an excluded category when i's bid is 0. Category j will become one the winning category once i's bid becomes large enough. This happens at the latest when i's bid beats the highest bid in one of the winning categories. At this point, bidder i's allocation becomes 1. By the same argument as in the previous case, further increasing their bid can only help securing bidder i's allocation.

Hence, we see that the allocation rule is non-decreasing in both cases, concluding the proof of strategyproofness. □