An Accounting Architecture for CO_2-Statements

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June 2025

*We thank participants of the working group on corporate carbon accounting and reporting for helpful suggestions and discussions. Special thanks to Thomas Becker, Sunil Dutta, Jon Glover, Jochen Kurtz, Julie Mulkerin Ortiz, Fernando Penalva, Stephen Penman, Thorsten Sellhorn, and Mike Szabo. Financial support for this study was provided by the German Research Foundation (DFG Project-ID 403041268, TRR 266).

Abstract

It remains a continuing challenge for companies worldwide to reliably assess the greenhouse gas emissions incurred in connection with their operations. Here we argue that financial accounting offers an architectural template for corporate carbon accounting systems consistent with current reporting frameworks for carbon emissions. The resulting CO_2-statements yield a measure of a company's current corporate carbon footprint, while stock variables on the CO_2-balance sheet convey summary information about an entity's past emissions performance and any recent changes therein. All accounting metrics emerge from a single ledger based on a transactional system of double-entry bookkeeping. Taken together, CO_2-statements enable a unified, comprehensive, and temporally consistent assessment of the direct and indirect emissions of a business entity and its sales products. The similarities to existing financial accounting systems are bound to facilitate the adoption of such statements from both an enterprise software and an assurance perspective.

Keywords: carbon accounting, corporate emissions, sustainability reporting

JEL Codes: M41, M48, Q54, Q56

1 Introduction

The Greenhouse Gas (GHG) Protocol is the globally recognized reference framework for reporting corporate carbon emissions. Classifying different emission inventories into direct and indirect, as well as upstream and downstream emissions, the GHG Protocol takes a comprehensive life-cycle approach to assessing a company's overall Scope 1–3 emissions[1–3]. While this framework has been adopted by organizations worldwide and included in disclosure mandates, multiple stakeholder groups have been clamoring for more comprehensive and more reliable information about the carbon footprint of corporations and their sales products[4–10]. In response, the GHG Protocol has recently launched a comprehensive revision of its guidance documents, scheduled for completion by 2027.

This perspective article argues that financial accounting offers a practical template for carbon accounting systems that are consistent with existing emissions reporting frameworks[11–15]. Similar to financial statements, the proposed system for carbon accounting results in CO_2–statements, comprising a CO_2-balance sheet and periodic statements showing the emissions an entity and its supplier network have contributed to the atmosphere in the current period. We argue that CO_2-statements provide analysts with a comprehensive and temporally consistent assessment of an entity's Scope 1, 2, and upstream Scope 3 emissions. The CO_2-balance sheet records stock variables that effectively summarize an entity's past emissions performance and any improvements thereof. In contrast, the net CO_2-contribution metric provides a measure of an entity's periodic corporate carbon footprint. All accounting metrics emerge from the same ledger based on a transactional system of double-entry bookkeeping, with the unit of measurement being one ton of CO_2 (or CO_2 equivalents)[16;17].

Several multinational companies have recently adopted internal product carbon accounting systems to determine the so-called cradle-to-gate product carbon footprints (PCFs) of their sales products[18–20]. Such footprint measures seek to capture the total direct carbon emissions that have been incurred at the different stages of production in a supply network. Earlier studies have pointed to both efficiency gains and reliability advantages if cradle-to-gate PCFs are assessed in a sequential and decentralized manner[21–25]. Accordingly, each firm in a supply network operates its own product carbon accounting system in order to determine the PCFs of its sales products and services on the basis of primary data for the PCFs of inputs received from its Tier 1 suppliers as well as its own direct (Scope 1) emissions.

In accordance with the GHG Protocol's guidance to report an entity's emissions on a life-cycle basis, cradle-to-gate PCFs can be supplemented with estimates of the emissions to be incurred in the use phase of a product. For mass-produced consumer goods, like automobiles, car manufacturers will be able to draw on precise statistical information regarding average product usage and the emission factors associated with usage in different locations. The resulting cradle-to-grave PCFs then combine assessments for the Scope 1, 2, and upstream Scope 3 emissions that have been incurred thus far with forecasts of the downstream Scope 3 emissions expected to materialize during the product's use phase, thereby enabling cradle-to-grave life cycle assessments[26].

Reliable PCF figures are increasingly demanded not only by consumers but also by corporate customers seeking to decarbonize their supply chains[18;27]. Even more urgent, standardized PCF calculations become indispensable in jurisdictions where subsidies and tax breaks for "green" technologies are tied to the assessed carbon footprint of a product[28;29]. In a similar vein, the Carbon Border Adjustment Mechanism to be implemented by the European Union in 2026 requires an assessment of the carbon dioxide emissions embodied in goods delivered to the gates of the European Union[30].

The cradle-to-gate PCFs of goods and services sold in the current time period become a key building block of the CO_2-contribution metric. Just as Cost of Goods Sold is a key component of the measure of financial income, Carbon Emissions in Goods Sold conveys the total emissions embodied in goods and services sold in the current period. Certain expense items not closely related to the production process, such as the emissions associated with business travel conducted in the current period, can be added as separate line items to the CO_2-contribution. Direct carbon removals undertaken by a company, or a contractor acting on its behalf, are a source of "revenue". We interpret the bottom-line net CO_2-contribution as the entity's current corporate carbon footprint, as it conveys the net tonnage of carbon dioxide an entity's operations have contributed to the atmosphere in the current accounting period.

The CO_2-balance sheet carries stock variables that are updated from one accounting period to the next. The left-hand side of this balance sheet records the emissions embodied in the entity's operating assets. These emissions have arrived at the entity's gates, or have been incurred within its gates, but have yet to be recognized as part of the current CO_2-contribution. The liability side of this balance sheet records the accumulated emissions embodied in goods and services received from the entity's suppliers as well as the entity's cumulative direct (Scope 1) emissions, less any accumulated direct removals. Each period's net CO_2-contribution is reconciled with the balance sheet through an account that carries the entity's accumulated past net CO_2-contributions. This feature is again in direct analogy to financial balance sheets, where owners' equity records an entity's past retained earnings.

The calculation of a company's net CO_2-flow, the third module of CO_2-statements, does not require product carbon accounting. This metric only includes the "raw" flows corresponding to a company's current direct emissions, net of current direct removals, plus the Scope 2 and upstream Scope 3 emissions associated with all incoming production inputs. As such, it comprises the emissions companies seek to report today under the GHG Protocol. However, in order for the incoming indirect emissions to be assessed on the basis of primary data about emissions actually incurred, the upstream suppliers have to maintain their own in-house product carbon accounting. If no company in a supply network were to calculate its own PCFs, all parties would need to estimate their indirect emissions (Scope 2 and upstream 3) on the basis of secondary data reflecting recent industry averages. This would result in a major duplication of estimation efforts and severely limit a company's incentives to reduce its direct and indirect emissions[31].

The main focus of this paper is on general principles for structuring CO_2-statements, rather than the specific accounting rules that ought to apply in their preparation. The central principle we advocate for is to separate stock from flow variables by means of balance sheets and periodic net contribution statements. Various organizations have in recent years proposed detailed carbon accounting rules[3;32–35]. The architecture of the CO_2-statements described here is sufficiently flexible so as to be compatible with any of these rules or some combination thereof. This flexibility pertains in particular to issues of product and entity boundaries as well as alternatives rules for allocating pools of overhead emissions. In the absence of mandated carbon accounting rules, adopters of the CO_2-statement approach can disclose separately the specific rules that have been followed in preparing their statements.

The CO_2-statements described here are in particular compatible with existing frameworks, such as the GHG Protocol or ISO 14064, and disclosure mandates, such as IFRS S2 and the EU's Corporate Sustainability Reporting Directive[36]. The many parallels between financial statements and CO_2-statements suggest that their adoption is neither overly complex nor costly. Recent software innovations show that existing financial systems can readily be expanded to run a ledger of carbon accounts[12;14;15]. Further, the underlying structure of double-entry bookkeeping and the relations that link the different components of CO_2-statements should facilitate the task of auditors in providing reasonable assurance that the statements were prepared in accordance with specific carbon accounting rules[31].

2 Preparing CO_2-Statements

The accounting ledger described in this paper is designed to capture all of an entity's current Scope 1, 2, and upstream Scope 3 emissions. To that end, Figure 1 illustrates the role of the proposed carbon accounting system in mapping the data inputs corresponding to different emission categories to accounting metrics in the form of a CO_2-statement and PCF metrics.

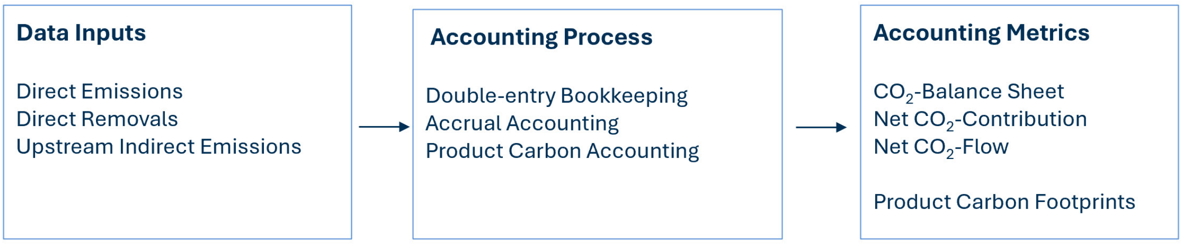

Figure 1. Illustration of corporate carbon accounting. This figure illustrates how the accounting process converts data inputs to accounting metrics.

Figure 2 shows an opening CO_2-balance sheet. As explained in further detail below, the account balances at the beginning of the current period, t, provide key summary statistics of an entity's past carbon emissions performance. In accordance with double-entry bookkeeping, every transaction that results in a debit of x tons of CO_2 (or CO_2 equivalents if multiple greenhouse gases are to be aggregated) to some account is matched with a corresponding credit of x tons to another account. Double-entry bookkeeping ensures that the CO_2-balance sheet adheres at all points in time to the identity:

$$CO_2 \text{ in Assets} = CO_2 \text{ Liabilities} + \text{Legacy } CO_2.$$

In contrast to financial accounting, the account balances on the left-hand side of the CO_2-balance sheet do not represent conventional assets that entail future value generation. Instead, the corresponding figures represent the emissions embodied in the firm's operating assets. For the account Materials, for instance, the beginning-of-the-period balance, MAT_t shows the tons of CO_2 that have been incurred in the production and delivery of the raw materials, product parts, and components in a firm's inventory. Similarly, for fixed assets like machinery, the value $M\&E_t$ shows the book value of the emissions embodied in machinery and equipment. These account balances reflect the original PCFs of the machinery assets at the time of acquisition, less any accumulated emissions that have been attributed to particular periods due to the use of the machinery in those periods. These attributions can be interpreted as carbon depreciation charges.

CO₂ in Assets			CO₂ Liabilities & Legacy
Buildings	BLD_t	ETI_t	Indirect CO_2 Emissions Transferred In
Machinery & Equipment	$M\&E_t$	DE_t	Direct CO_2 Emissions
Materials	MAT_t	(DR_t)	Direct CO_2 Removals
Work-in-Process	WIP_t	LEG_t	Legacy CO_2 Emissions
Finished Goods	FG_t		

Figure 2. CO_2-balance sheet. This figure illustrates an opening CO_2-balance sheet.

Ideally, the individual PCFs for materials and machinery have been provided by the firm's suppliers. Otherwise, the firm will, as is common practice nowadays, need to conduct its own life-cycle analysis with the support of external databases that reflect historical industry-wide averages for these materials. The importance of primary PCF data has led companies like the global chemical producer BASF to nudge their suppliers to provide PCFs, or "carbon tags", that reflect the suppliers' own product carbon accounting for the intermediate chemical products delivered to BASF[37].

On the liability side of the balance sheet, the account ETI_t shows the cumulative value of past Scope 2 and upstream Scope 3 emissions corresponding to goods and services that have arrived at the entity's gates since the inception of the carbon accounting system. The cumulative value of past direct (Scope 1) emissions is recorded in the account DE_t. Direct emissions may be counterbalanced by direct removal activities undertaken by the firm or one of its contractors. Representing a gain rather than a loss for the atmosphere, the account Direct Removals effectively becomes a contra-liability account to Direct Emissions. The balance of DR_t is thus effectively subtracted from DE_t. The difference between current direct emissions and direct removals will be referred to as a company's current net direct emissions. The underlying carbon accounting standards must, of course, specify quality criteria that direct removals must meet in order to be eligible for recognition, specifically criteria regarding additionality, durability, and reversibility[38–42].

Recent changes in the account balances on the liability side of the CO_2-balance sheet can be made explicit by a line-item decomposition that details the recent annual additions to a particular account, such as the additions to Direct Emissions in each of the past five years. The account balance LEG_t in Figure 2 represents the accumulated past net CO_2-contributions. Unless current direct removals exceed direct emissions, or the firm acquires inputs with negative carbon tags (e.g., biomass), the net CO_2-contribution metric will be a positive number, representing the net tonnage of carbon dioxide that has been emitted into the atmosphere as a consequence of the firm's current operations and input sourcing decisions.

In a further parallel to financial accounting, the carbon accounting standards in place will determine whether certain categories of current emissions are capitalized on the balance sheet or directly added to the current net contribution account. The GHG Protocol's Product Life Cycle Accounting and Reporting Standard, for instance, takes the position that only emissions attributable to products should be included in the calculation of product carbon footprints[32]. Business travel would be one applicable example in this context. However, to satisfy the guidance in the GHG Protocol's Corporate Accounting and Reporting Standard for including all incoming Scope 1, 2, and upstream Scope 3 emissions, carbon emissions in connection with business travel can be added directly to the current net contribution account. Similarly, the GHG Protocol's Product Life Cycle Accounting and Reporting Standard stipulates that the emissions embodied in fixed assets, like machinery and equipment, are not to be included in PCF calculations, as these types of emissions are not considered "attributable" to individual products. The CO_2-statement approach allows for the emissions embodied in the construction of a new plant to be first recognized on the balance sheet and then apportioned to subsequent time periods via depreciation charges.

T_1: Materials purchased: carbon tag of u_1 tons of CO_2

T_2: Materials transferred to WIP: carbon tag of $u_2 = \sum_i u_2^i$ tons of CO_2

T_3: Depreciation charges M& E: carbon tag of u_3 tons of CO_2

T_4: Machinery assets acquired: carbon tag of u_4 tons of CO_2

T_5: Direct emissions incurred: carbon tag of $u_5 = \sum_i u_5^i$ tons of CO_2

T_6: WIP transferred to FG: carbon tag of $u_6 = \sum_i u_6^i = \sum_i v_6^i$ tons of CO_2

T_7: CO_2 directly removed from the atmosphere: carbon tag of u_7 tons

T_8: Sale of Finished Goods: carbon tag of $u_8 = \sum_i u_8^i$ tons of CO_2

T_9: Business Travel: carbon tag of u_9 tons of CO_2

T_{10}: Net CO_2-contribution closed out to Legacy Emissions account

Figure 3. Sample Transactions. This figure illustrates the journal entries for ten sample transactions.

The mechanics of preparing of CO_2-statements can be illustrated through representative transactions and the corresponding bookkeeping entries. To that end, Figure 3 describes the journal entries for ten representative transactions. The tableau in Figure 4 displays a compressed version of the bookkeeping entries corresponding to these ten transactions. The net CO_2-contribution account, labeled "Contribution", is a flow variable, starting and ending each accounting cycle with a balance of zero. The final journal entry reconciles this flow variable to the balance sheet via the account Legacy CO_2 Emissions.

For the accounts on the left-hand side of the balance sheet, any debit increases the account balance, while credits decrease the account balance. The opposite applies to the accounts on the liability and legacy side. Further, credits will always equal debits provided $u_j = \sum_i u_{ji}$ if $j = 2$, $j = 5$, or $j = 8$, while $\sum_i v_{6i} = \sum_i w_{6i}$. We note that in connection with the ten transactions considered here, the ending balances of the accounts at date $t + 1$ are given by their balances at date t plus the sum of the entries in each column of the tableau shown in Figure 4.

It should also be noted that the emissions figure w_{6i} effectively determines the PCF of product i, that is, its *carbon intensity* expressed in tons of CO_2 per unit. Specifically, if q_i units of the i-th product were added to Finished Goods in the current period, then $PCF_i = \frac{w_{6i}}{q_i}$.

For modular product parts and components that go into individual products, it will be straightforward to charge the individual Work-in-Process or Finished Goods accounts with the carbon tags of the parts and components that belong to the respective products. Yet, Scope 1 and 2 emissions frequently take the form of overhead emissions for which there will be multiple allocation rules that reflect the causal link between products and production activities resulting in carbon emissions. To illustrate this point in connection with transaction T_5, the entries u_{5i} should reflect the application of a causally meaningful allocation rule for assigning the pool of current direct emissions to the Work-in-Process accounts, and ultimately to the Finished Goods accounts. One universal constraint on such allocation rules is for them to be balanced, that is, $u_5 = \sum_i u_{5i}$.

Consequential allocation issues also arise in connection with Scope 2 emissions. For instance, energy service providers calculate the carbon intensity of electricity delivered to customers on the grid during specific hours of the year, following either a market- or location-based approach[2;33;34]. Importantly, these two approaches may result in dramatically different assessments of the Scope 2 emissions incurred by energy-intensive businesses, for instance, technology firms that operate cloud computing centers[4;29;43].

Panel A in Figure 5 displays a net CO_2-contribution statement in accordance with

	CO_2 in Assets									Contribution	=	CO_2 Liabilities			Legacy CO_2
Beginning Balance	BLD_t	$M\&E_t$	MAT_t	WIP_t^1	…	WIP_t^m	FG_t^1	…	FG_t^n	0	=	ETI_t	DE_t	DR_t	LEG_t
Transactions:															
T_1 Materials purchased			u_1		…			…			=	u_1			
T_2 Materials transferred			$-u_2$	u_2^1	…	u_2^m		…			=				
T_3 Depreciation M&E		$-u_3$			…			…		u_3	=				
T_4 Machinery acquired		u_4			…			…			=	u_4			
T_5 Direct Emissions				u_5^1	…	u_5^m		…			=		u_5		
T_6 WIP Transfer to FG				$-v_6^m$	…	$-v_6^m$	w_6^1	…	w_6^n		=				
T_7 Direct Removal					…			…		$-u_7$	=			$-u_7$	
T_8 Sales of FG					…		$-u_8^1$	…	$-u_8^1$	u_8	=				
T_9 Business Travel					…			…		u_9	=	u_9			
T_{10} Closing					…			…		$u_7 - u_3 - u_8 - u_9$	=				$u_7 - u_3 - u_8 - u_9$
Ending Balance	BLD_{t+1}	$M\&E_{t+1}$	MAT_{t+1}	WIP_{t+1}^1	…	WIP_{t+1}^m	FG_{t+1}^1	…	FG_{t+1}^n	0	=	ETI_{t+1}	DE_{t+1}	DR_{t+1}	LEG_{t+1}

Figure 4. Transaction Tableau. This tableau shows the bookkeeping for ten sample transactions.

what we term partial PCF costing. Accordingly, some overhead emissions are charged directly to the current net contribution rather than being routed through the inventory accounts. The top lines in Panel A represent the emissions embodied in current sales, that is, the sum of the $s_i \cdot PCF_i$. These emission figures add up to the aggregate Carbon Emissions in Goods Sold (CEGS), the carbon accounting equivalent of Cost of Goods Sold in the calculation of financial income. The charges for General & Administrative Emissions are added to CEGS. These correspond to depreciation charges and business travel in the above example. The bottom line net CO_2-contribution is then obtained by subtracting current direct removals.

We interpret the net CO_2-contribution as a measure of the firm's current corporate carbon footprint. Analogous to the measurement of financial income, this metric matches current "CO_2 expenses" with current "CO_2 revenues". As of today, the net contribution will be a positive number for the vast majority of businesses as the tonnage of carbon dioxide emitted into the atmosphere exceeds the tonnage removed from the atmosphere. All emissions contributed to the atmosphere in previous accounting periods are accumulated in the entity's account Legacy CO_2 Emissions. For a business to meet a "carbon-neutrality" or "net-zero" goal by a certain target date, say 2050, the net contribution would have to come down to zero by the target date and remain a non-positive figure thereafter. In conclusion, partial PCF costing enables a unified implementation of both the product life-cycle and the corporate standard of the GHG Protocol with regard to

Panel A: Partial PCF Costing

$PCF_1 \cdot s_1$	=	CO_2 in Current Sales of Product *1*
$PCF_2 \cdot s_2$	=	CO_2 in Current Sales of Product *2*
.	=	.
.	=	.
.	=	.
$PCF_n \cdot s_n$	=	CO_2 in Current Sales of Product *n*
$\sum PCF_i \cdot s_i$	=	**Carbon Emissions in Goods Sold (CEGS)**
Y	=	General & Administrative Emissions
Less		
X	=	Current Direct CO_2 Removals
$\sum PCF_i \cdot s_i + Y - X$	=	**Net CO_2-Contribution**

Panel B: Full PCF Costing

$PCF_1^+ \cdot s_1$	=	CO_2 in Current Sales of Product *1*
$PCF_2^+ \cdot s_2$	=	CO_2 in Current Sales of Product *2*
.	=	.
.	=	.
.	=	.
$PCF_n^+ \cdot s_n$	=	CO_2 in Current Sales of Product *n*
$\sum PCF_i^+ \cdot s_i$	=	**Carbon Emissions in Goods Sold (CEGS)**
$\sum PCF_i^+ \cdot s_i$	=	**Net CO_2-Contribution**

Figure 5. Net CO_2-Contribution. This figure displays CO_2-contribution statements for both partial and full PCF costing.

Scope 1, 2, and upstream Scope 3 emissions[1;32].

The full PCF costing approach displayed in Panel B of Figure 5 postulates that direct removals and all emissions directly charged as current CO_2 contributions under partial PCF costing instead be routed through the inventory accounts and thus be included in the PCF measures. This is, of course, common practice in cost accounting in order to determine each product's full cost[44;45]. A central argument in favor of full costing is that even if periodic emissions are not directly attributable to individual products, they can nonetheless be assigned in a manner that captures the causal link between activities, the incurrence of emissions, and the activity needs of individual products. Such causal links are well established in cost accounting for assigning the depreciation charges associated with fixed assets to the products requiring these fixed assets. Further, current direct removals can be netted against direct emissions, and the resulting direct net emissions can be assigned to products according to the same rules that are applied for direct emissions. Even for distant Scope 3 categories, such as business travel, economic value drivers, such as the gross margins of different products, will frequently constitute a defensible approach to apportioning different emission categories among a firm's sales products.

In Panel B of Figure 5, PCF_i^+ denotes the full cost carbon intensity measure of the i-th product. The resulting net CO_2-contribution statement then reduces to the sum of the product carbon footprints of the individual product lines, that is, the sum of the $PCF_i^+ \cdot s_i$. The statement thus identifies the contribution each product line makes to the overall corporate carbon footprint. In order for a business to fulfill its net-zero pledge, some of the PCF_i^+ will need to turn negative, because either the firm or some of its suppliers undertake sufficiently sizable direct removals.

If all companies in a supply network adopt full PCF costing and report the corresponding carbon tags to their customers, the PCF accompanying a consumer product has a straightforward interpretation. It comprises an allocated share of the seller's actual direct net emissions, an allocated share of the actual direct net emissions of the seller's Tier-1 suppliers, an allocated share of the actual direct net emissions of the seller's Tier-2 suppliers, and so forth up to the initial nodes of the supply network[11].

Provided allocations are consistently balanced at every stage (i.e., they add up properly), the reported PCFs entail no double counting of emissions. This is readily seen in a hypothetical supply network where producers have no operating assets, neither in inventories nor in fixed assets. In such settings, all direct net emissions incurred in the network flow through to the end-products such that the sum of the $PCF_i^+ \cdot s_i$ is equal to the total net direct emissions incurred by the network. A frequently expressed concern about the GHG Protocol's reporting standards is the systematic double counting of emissions. This is, of course, unavoidable if corporate carbon footprints are to provide a periodic measure of a company's Scope 1, 2, and upstream Scope 3 emissions. By construction, each company's net CO_2-contribution then includes a share of its suppliers' Scope 1 emissions. In contrast, concerns about double-counting do not apply to the calculation of product carbon footprints, provided these are determined as cradle-to-gate PCFs on the basis of primary data reflecting the actual emissions incurred in the supply network. Every ton of CO_2 directly emitted by some party in the supply network is then accounted for once, and only once, in the resulting product carbon footprints.

The two contribution measures displayed in Figure 5 will coincide for businesses in service industries, for example, airlines. Since there are no substantial inventories for either Work in Process or Finished Goods in these industries, all Scope 1, 2, and upstream Scope 3 emissions attributed to the current period will then be reflected in the current net CO_2-contribution. This basic observation also has implications for broader concerns about "greenwashing" in manufacturing industries. Any attempt to "greenwash" individual products using biased allocation rules will effectively be counterbalanced and "washed out" in the aggregate, CO_2-contribution measure, unless there are significant changes in inventory.

It is worth recalling that in order to comply with the GHG Protocol's Corporate Accounting and Reporting Standard, companies are not required to assess individual PCFs[1]. Instead, companies could simply track the following emissions categories: current direct emissions less current direct removals, the indirect emissions embodied in goods, services and assets acquired by the company in the current period, as well as the CO_2 emissions projected to be incurred during the use phase of products sold in the current period. We refer to the upstream portion of this life-cycle emissions metric as the net CO_2-flow, with the corresponding statement shown in Figure 6.

Q	=	Current Direct CO_2 Emissions
Z	=	Indirect CO_2 Emissions Transferred In
Less		
X	=	Current Direct CO_2 Removals
$Q + Z - X$	=	**Net CO_2-Flow**

Figure 6. Net CO_2-Flow. This figure shows the statement of net CO_2-flows.

Relating the journal entries in the context of the above example to the net CO_2-flow metric, we observe that the variables introduced in Figure 6 amount to: $X = u_7$, $Q = u_5$, and $Z = u_1 + u_4 + u_9$.

Tracking only CO_2 flows in accordance with the GHG Protocol may appear simpler as the accounting architecture proposed here insofar as neither Scope 1 emissions nor incoming Scope 2 and upstream Scope 3 emissions must be apportioned between the balance sheet and the net contribution statement. Further, any differences between the two metrics are temporary insofar as they add up to the same total value over the entire life of the business. The corresponding algebra in Box 1 shows that the difference between the net CO_2-flow and the CO_2-contribution is always equal to the current change in the left-hand side of the CO_2-balance sheet.

From a system-wide perspective, however, the omission of PCF calculations at the company level would entail a critical drawback: Companies would no longer be able to assess their incoming indirect emissions on the basis of the carbon tags accompanying the receipt of production inputs. As a consequence, the assessed PCFs would no longer be able to serve as "information vehicles" for conveying the actual emissions accumulated in a product. Companies would then need to resort to estimating their indirect emissions by relying on external databases that reflect industry-wide averages, leading to a significant duplication of efforts along the supply chain, both in terms of estimating emissions and also receiving auditor assurance on these estimates[31].

Reliable PCF figures that reflect the actual emissions incurred by a producer's supply network are being increasingly demanded by customers, regulators, and the general public. Importantly, a company's ability to report reliable and audited PCF figures to its customers is critical in providing first-order incentives for reducing both its direct and indirect emissions. Any reduction in actual emissions translates fully and immediately to a reduction in the reported PCFs of goods and services delivered to customers.

3 CO_2-Statement Analysis

An effective corporate decarbonization strategy requires a systematic analysis of all carbon emission sources[46]. CO_2-statements provide readers with information on the origins and destinations of emissions, as well as the causal and temporal relations between economic activities and emissions. Emissions embodied in a new fleet of electric vehicles, for example, will be included in the net CO_2-flow statement in the period of purchase. As these vehicles are utilized in subsequent periods, the corresponding carbon depreciation charges are either attributed to products (goods transported) or directly charged in the CO_2-contribution statement. Any remaining CO_2 balances embodied in the vehicle assets will remain on the balance sheet.

In industries that deliver carbon-intensive primary products, such as steel, cement, aluminum, and chemicals, Scope 1 emissions constitute the dominant share of the overall corporate carbon footprints. The pathway to decarbonization for these industries thus hinges on improvements in their annual direct emissions less direct removals. Provided companies disclose not only the cumulative values in the accounts DE_t and DR_t on the balance sheet, but also line-item information showing the recent annual increments, CO_2-statements will reveal the recent trajectory and the rate of change for these critical carbon performance metrics.

As companies take responsibility for the indirect emissions incurred by their suppliers, decarbonization efforts must be gauged and evaluated by improvements in the CO_2-contribution metric. In order for that metric to show convergence to a net-zero goal, direct removals must ultimately outweigh the remaining direct net emissions incurred by the company in question or by its suppliers[6]. A company's recent trajectory of net CO_2-contributions can either be gauged from past contribution statements or from the Legacy Emissions account, LEG_t, on the balance sheet, provided this account provides a line-item decomposition showing the recent annual increments.

CO_2-balance sheets can serve as an effective tool for managing companies' compliance with so-called carbon budgets. Popularized by the Science Based Targets initiative (SBTi), some companies and industries have set upper bounds for the cumulative emissions they pledge not to exceed in the future in order to be compliant with global efforts to stay below certain warming thresholds[47–49], such as the 1.5°C threshold. Compliance with an industry-specific carbon budget can then be gauged directly from a company's net direct emissions account, that is, $DE_t - DR_t$, assuming the carbon budget is stated in terms of Scope 1 emissions. Alternatively, if the carbon budget is stated in terms of a company's Scope 1, 2, and upstream Scope 3 emissions, the relevant target becomes the balance of the Legacy CO_2 Emissions account.

Some companies in the technology sector, including Google and Microsoft, have gone beyond the common "net-zero by 2050" goals by pledging to undo their entire legacy emissions by some future date[50–52]. If legacy emissions are equated with the company's past cumulative Scope 1, 2, and upstream Scope 3 emissions, then the relevant target becomes a value of zero for the balance of the Legacy Emissions account. Attaining this far more ambitious goal will require not only rapid decarbonization of a company's supply network, but direct removals will, in addition, have to significantly outweigh current direct emissions in the years leading up to the target date.

The availability of reliable PCF figures for a company's entire product portfolio will allow management to assess the contribution each product makes to the overall corporate carbon footprint and, in addition, to relate this contribution to the profitability of individual products. Similarly, CO_2-statements lend themselves to analyzing the carbon intensity of a business in the aggregate, such as the ratio of Carbon Emissions in Goods Sold to Cost of Goods Sold, the ratio of the net CO_2-contribution to an entity's net profit, or the ratio of CO_2 in Assets to total operating assets[53]. For companies experiencing significant growth or contraction in their operations, such aggregate carbon intensity metrics will be more informative than absolute emission figures in assessing progress on a company's decarbonization pathway. Aggregate intensity metrics will also facilitate a meaningful comparison of the carbon performance of different firms in the same industry[54].

While the CO_2-statements presented here have maintained a historical cost perspective, they nonetheless lend themselves to extrapolating from the past to the future. Specifically, it is worth recalling that the tons of carbon dioxide recorded on the asset side of the balance sheet will be included in future statements of the entity's net CO_2-contribution. Akin to issuing earnings forecasts, analysts will be in a position to combine the information conveyed by the relevant accounts on the asset side with the history of recent direct net emissions to forecast a company's near-term trajectory of CO_2-contributions.

4 Concluding Remarks

In Germany, policymakers and managers often refer to the "Klimabilanz" (i.e., "climate balance sheet") of an organization. To the best of our knowledge, no company or governmental office has thus far issued a proper Klimabilanz, arguably because there has been no commonly acknowledged framework for the information variables to be recorded on such balance sheets. The main thesis of this article is that an accounting architecture grounded in double-entry bookkeeping can enable corporate CO_2-statements that mirror financial statements in several key dimensions. As businesses in a supply network increasingly adopt their own systems for product carbon accounting in accordance with common standards, the resulting CO_2-statements give analysts a temporally consistent and comprehensive assessment of the Scope 1, 2, and upstream Scope 3 emissions actually incurred by the business and its supplier network.

Going forward, early adopters of the carbon accounting architecture described in this paper can rely on recent enterprise software solutions to enable automation of the bookkeeping process and maintain connectivity between the financial and the CO_2 accounts[12;14;15]. In the absence of regulators mandating detailed carbon accounting rules, companies should qualitatively disclose the rules that were applied in preparing their CO_2-statements. To maintain comparability and accountability, such disclosures are particularly needed in connection with the choice of product boundaries and the rules for allocating pools of overhead emissions. For certain industries, such as chemicals and automotive, it might suffice to disclose that the CO2-statements were prepared in accordance with industry-specific guidelines, for instance, Catena-X[34] and Together for Sustainability[33].

In response to widespread calls from various stakeholder groups, the GHG Protocol has recently initiated a comprehensive revision of its guidance documents, aiming to unify the different requirements and recommendations developed over the years. Similarly, the European Union has begun work on a so-called omnibus package aimed at simplifying and unifying existing sustainability reporting directives. Provided all direct and indirect upstream emissions are accounted for, the resulting CO_2-statements described here enable unified reporting in accordance with the current guidelines of the GHG Protocol. In addition, these statements satisfy existing reporting mandates such as the Corporate Sustainability Reporting Directive introduced by the European Union (ESRS E1).

We state two formal claims relating the CO_2-contribution to the net CO_2-flow. To that end, we adopt the following notation:

- A_t: CO_2 in Assets at date t, that is, the left-hand side of the CO_2-balance sheet,
- CON_t: Net CO_2-contribution at date t,
- NCF_t: Net CO_2-flow at date t,
- $\Delta x_t \equiv x_{t+1} - x_t$ for any sequence $\{x_t\}$.

Net CO_2-flow, as defined in Figure 6, can then be expressed as $NCF_t = \Delta ETI_t + \Delta DE_t - DR_t$.

Claim 1. *$NCF_t = CON_t + \Delta A_t$.*

This claim follows from the identity: $LEG_{t+1} = LEG_t - CON_t$ and the fundamental balance sheet identity $A_t = ETI_t + DE_t - DR_t + LEG_t$. The latter implies:

$$\Delta A_t = \Delta ETI_t + \Delta DE_t - \Delta DR_t + \Delta LEG_t.$$

Direct substitution on the right-hand side of this equation yields:

$$\Delta A_t = NCF_t - CON_t.$$

The second claim submits that any differences between the income and the flow measure will average out across the lifetime of an entity.

Claim 2. *Suppose that $A_0 = 0$ and $A_T = 0$. Then $\sum_{t=1}^{T} CON_t = \sum_{t=1}^{T} NCF_t$.*

This claim is a direct consequence of Claim 1 after observing that $\sum_{t=1}^{T} \Delta A_t = A_T - A_0 = 0$.

Box 1. Net CO_2-contribution versus net CO_2-flow. This box formalizes the relations between these two metrics.

References

[1] GHG Protocol. A Corporate Accounting and Reporting Standard (2004).

[2] GHG Protocol. Scope 2 Guidance (2015).

[3] GHG Protocol. Corporate Value Chain (Scope 3) Accounting and Reporting Standard (2011).

[4] Bjørn, A., Lloyd, S., Brander, M. & Matthews, D. Renewable energy certificates threaten the integrity of corporate science-based targets. *Nature Climate Change* **12**, 539–546 (2022).

[5] Klaaßen, L. & Stoll, C. Harmonizing corporate carbon footprints. *Nature Communications* **12**, 6149 (2021).

[6] Fankhauser, S. *et al.* The meaning of net zero and how to get it right. *Nature Climate Change* **12**, 15–21 (2022).

[7] Hsu, A. *et al.* A research roadmap for quantifying non-state and subnational climate mitigation action. *Nature Climate Change* **9**, 11–17 (2019).

[8] Hale, T. *et al.* Assessing the rapidly-emerging landscape of net zero targets. *Climate Policy* **22**, 18–29 (2022).

[9] Luers, A. *et al.* Make greenhouse-gas accounting reliable - build interoperable systems. *Nature* **607**, 653–656 (2022).

[10] Jiang, X., Kim, S. & Lu, S. Limited accountability and awareness of corporate emissions target outcomes. *Nature Climate Change* **15** (2025).

[11] Reichelstein, S. Corporate carbon accounting: balance sheets and flow statements. *Review of Accounting Studies* **29**, 2125–2156 (2024).

[12] Asam, D., Ernstberger, J. & Friedl, G. How Carbon Accounting Supports Corporate Decarbonization. *Foundations and Trends in Accounting* **19**, 46–77 (2025).

[13] Glenk, G. Corporate Carbon Accounting: Current Practices and Opportunities for Research. *Foundations and Trends in Accounting* **19**, 96–126 (2025).

[14] Distler, B., Ernstberger, J., Keiling, M., Müller, F. & Szabo, M. Incorporating Carbon Emissions into Decision-Making - The Case of Transactional Connectivity (2024). URL `https://dx.doi.org/10.2139/ssrn.4784259`.

[15] Sessar, C. Never more relevant? Luca Pacioli's Work and the "Green Ledger" may revolutionize non-financial reporting. Center for corporate reporting (2023). URL `http://bit.ly/40994HG`.

[16] Reichelstein, S. Innovations in Corporate Carbon Accounting. *Foundations and Trends in Accounting* **19**, 9–45 (2025).

[17] Jia, J., Rossi, B., Chaudhury, A. & Taylor, E. A reporting framework for general purpose life cycle assessment to align entity-level GHG accounting with general purpose financial statements Keywords (2024). URL `https://dx.doi.org/10.2139/ssrn.4395987`.

[18] Saling, P., Pistillo, A. & Kurtz, J. Automated Product Carbon Footprint Calculation in the Chemical Industry to Steer Decarbonization Along the Value Chain. *Foundations and Trends in Accounting* **19**, 127–157 (2025).

[19] BMW. BMW group vehicle carbon footprint reports (2024). URL `http://bit.ly/4lcS7nJ`.

[20] Landaverde Lorenzo, T., Liebmann, P., Meier, R., Sutherland, M. & Reichelstein, S. Heidelberg Materials: Assessing Product Carbon Footprints (2023).

[21] Kaplan, R. & Ramanna, K. Accounting for Climate Change. *Harvard Business Review* (2021).

[22] Kurtz, J. Product Carbon Footprints - zur Vergleichbarkeit der Produkte die wir kaufen? *Controlling* **34**, 44–50 (2022).

[23] Kaplan, R., Ramanna, K. & Reichelstein, S. Getting a Clearer View of Your Company's Carbon Footprint. *Harvard Business Review* (2023).

[24] Comello, S., Reichelstein, J. & Reichelstein, S. Corporate carbon reporting: Improving transparency and accountability. *One Earth* **6**, 803–810 (2023).

[25] Ramanna, K. A proto-standard for carbon accounting and auditing using the E-liability method (2024). URL `https://dx.doi.org/10.2139/ssrn.4957358`.

[26] Lu, S., Serafeim, G. & Toffel, M. W. Driving Decarbonization at BMW (2022).

[27] Microsoft. Our Sustainability Journey (2023). URL `https://bit.ly/488G6ua`.

[28] Glenk, G., Holler, P. & Reichelstein, S. Policy Support for Electrolytic Hydrogen: Implications of Alternative Carbon Accounting Rules (2025).

[29] Pineau, E. & Guillaume, G. France's new EV cash incentive rules toughen market for Chinese-made cars (2023). URL `http://bit.ly/4n93RcM`.

[30] Böhringer, C., Fischer, C., Rosendahl, K. E. & Rutherford, T. F. Potential impacts and challenges of border carbon adjustments. *Nature Climate Change* **12**, 22–29 (2022).

[31] Becker, T. Automotive Supply Chain Decarbonization as a Driver for Carbon Accounting and Vice Versa. *Foundations and Trends in Accounting* **19**, 78–95 (2025).

[32] GHG Protocol. Product Life Cycle Accounting and Reporting Standard (2011).

[33] Together for Sustainability. The Product Carbon Footprint Guideline for the Chemical Industry (2024). URL `http://bit.ly/4laKIFs`.

[34] Catena-X. Catena-X Product Carbon Footprint Rulebook (2023). URL `https://bit.ly/3MJUXBR`.

[35] ISO. ISO 14064-1:2018 (2018). URL `https://www.iso.org/standard/66453.html`.

[36] European Commission. The Commission Adopts the European Sustainability Reporting Standards (2023). URL `http://bit.ly/44ndEob`.

[37] Kurtz, J. & Pistillo, A. Carbon Emissions—Perspective from the Chemical Industry with focus on Product Carbon Footprints (2024).

[38] Allen, M. *et al.* The Oxford Principles for Net Zero Aligned Carbon Offsetting (2024).

[39] Microsoft. Criteria for high-quality carbon dioxide removal (2021). URL `https://bit.ly/3k4Sfvj`.

[40] Frontier. An advance market commitment to accelerate carbon removal (2024). URL https://frontierclimate.com/.

[41] Wilcox, J., Kolosz, B. & Freeman, J. Carbon Dioxide Removal Primer (2021). URL https://cdrprimer.org/.

[42] Brander, M., Ascui, F., Scott, V. & Tett, S. Carbon accounting for negative emissions technologies. *Climate Policy* **21**, 699–717 (2021).

[43] O'Brien, I. Data center emissions probably 662% higher than big tech claims. Can it keep up the ruse? (2024). URL http://bit.ly/3ZFCqgN.

[44] Friedl, G., Hofmann, C. & Pedell, B. *Kostenrechnung - Eine entscheidungsorientierte Einführung* (Springer, München, 2017), 3 edn.

[45] Horngren, C., Datar, S. & Rajan, M. *Cost Accounting - A Managerial Emphasis* (Pearson, Boston, 2015), 15 edn.

[46] Klaaßen, L. & Steffen, B. Meta-analysis on necessary investment shifts to reach net zero pathways in Europe. *Nature Climate Change* **13**, 58–66 (2023).

[47] Friedlingstein, P. *et al.* Global Carbon Budget 2023. *Earth System Science Data* **15**, 5301–5369 (2023).

[48] Bjørn, A., Lloyd, S. & Matthews, D. From the Paris Agreement to corporate climate commitments: Evaluation of seven methods for setting 'science-based' emission targets. *Environmental Research Letters* **16**, 054019 (2021).

[49] Krabbe, O. *et al.* Aligning corporate greenhouse-gas emissions targets with climate goals. *Nature Climate Change* **5**, 1057–1060 (2015).

[50] Joppa, L. *et al.* Microsoft's million-tonne CO2-removal purchase - lessons for net zero. *Nature* **597**, 629–632 (2021).

[51] Gill, K. Understanding the real hurdles to jump before reaching net-zero emission goals (2022). URL https://bit.ly/3L9dpSH.

[52] Microsoft. Microsoft carbon removal - Lessons from an early corporate purchase (2021). URL http://bit.ly/44c9QF7.

[53] Greenstone, M., Leuz, C. & Breuer, P. Mandatory disclosure would reveal corporate carbon damages. *Science* **381**, 837–840 (2023).

[54] Jia, J., Ranger, N. & Chaudhury, A. Designing for Comparability: A foundational principle of analysis missing in climate reporting systems. (2023). URL https://dx.doi.org/10.2139/ssrn.4258460.