Corporate Carbon Accounting: Balance Sheets and Flow Statements

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Abstract

Current corporate disclosures regarding carbon emissions lack commonly accepted accounting rules. The carbon accrual accounting system described here takes the rules of historical cost accounting for operating assets as a template for generating a Carbon Emissions (CE) balance sheet and flow statement. The asset side of the CE balance sheet reports the carbon emissions embodied in operating assets. The liability side conveys the firm's cumulative direct emissions into the atmosphere as well as the cumulative emissions embodied in goods acquired from suppliers less those sold to customers. Flow statements report the cradle-to-gate carbon footprint of goods sold during the current period. Taken together, balance sheets and flow statements generate key indicators of a company's past, current and future performance with regard to carbon emissions.

JEL classification: M41, M48, Q53, Q54.

1. Introduction

Recent years have witnessed numerous companies around the world issuing voluntary "net-zero pledges" regarding their greenhouse gas emissions.[2] According to a 2022 survey, more than two-thirds of the Fortune 500 firms have articulated the goal of reaching a net-zero position by 2050 (Gill, 2022). Beyond pledging to drive their corporate carbon footprints to zero in the future, companies increasingly advertise select products as being already "carbon-neutral".[3] While these announcements have been heralded as a potentially significant step in the global decarbonization effort, some analysts have argued that the lack of commonly accepted measurement and reporting standards for greenhouse gas emissions ultimately obscures the credibility of corporate claims as well as companies' commitments to a net-zero trajectory.[4]

This article argues that corporate reporting on carbon emissions can become more transparent and credible provided companies adopt carbon accrual accounting systems that mirror historical cost accounting for operating assets. Accrual accounting enables the separation of stock from flow variables. In direct analogy, an accrual accounting system for Carbon Emissions (from here on abbreviated as CE) enables a CE balance sheet and a CE flow statement.[5] The latter effectively becomes the equivalent of an income statement in financial reporting. We emphasize that, in contrast to financial reporting, the asset side of the CE balance sheet does not report conventional asset values, but instead records the emissions embodied in the firm's operating assets. The sources of these emissions, recorded on the liability side of the balance sheet, are either the firm's own direct (Scope 1) emissions or those incurred by companies along the firm's upstream supply chain.

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[2] For reasons explained below, the analysis in this paper will focus on carbon dioxide (CO_2) as the primary greenhouse gas.
[3] In response to the rapidly growing number of claims by companies that some of their products are "low carbon" or even "carbon neutral", the European Commission recently adopted a *Directive on Green Claims* that seeks to prevent frivolous and misleading claims regarding the carbon content of select products (European Commission, 2023a).
[4] See, for instance, Tollefson (2022), Fankhauser (2022) and Aldy et al. (2023).
[5] Appendix B provides a list of all acronyms used in this paper.

With concerns about climate change intensifying, corporate buyers and retail customers increasingly seek information about and take responsibility for the emissions that have gone into products and services purchased from suppliers.[6] In accordance with this broader corporate social responsibility perspective, the accounting system described in this paper postulates that measures of Product Carbon Footprints (PCFs), i.e., tons of carbon dioxide per unit of the product, encompass all emissions from a product's cradle(s) to the company's gates (Kaplan and Ramanna, 2021).[7] Assuming this perspective is increasingly adopted among the companies along a supply chain, the resulting cradle-to-gate PCFs measures will be determined in a recursive and informationally decentralized manner. Similar to the way product costs are calculated along a supply chain, the calculation of PCFs then relies on local knowledge of the direct emissions actually incurred at each stage of the supply chain (Kaplan, Ramanna and Reichelstein, 2022).

Regarding a company's overall corporate carbon footprint, the natural flow measure emerging in our responsibility accounting framework is Carbon Emissions in Goods Sold (CEGS). In direct analogy to Cost of Goods Sold (COGS) in income statements, CEGS yields the total tons of carbon dioxide obtained as the sum of all product PCFs multiplied by the current sales quantity of that product. CEGS thus becomes a measure of the contemporaneous damage that products sold by the firm have contributed to the global climate. The ratio of CEGS to COGS can therefore serve as a effective measure of the average carbon intensity of a company's sales products.[8]

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[6] In auctions for public construction projects, for example, European procurement agencies require so-called *Environmental Product Disclosures* that include a measure of the CO_2 embodied in the cement product that bidders submit for consideration; see HeidelbergCement AG (2021).

[7] The chemical company BASF refers to its PCF measures as cradle-to-gate product carbon footprints (BASF, 2021; Kurtz, 2022).

[8] The British Companies' Act of 2013 requires publicly listed firms to report a measure of carbon intensity in addition to their absolute Scope 1 and 2 emissions (Downar et al., 2013).

A company's net CE flow, the equivalent of income (profit) in the CE flow statement is, by construction, always equal to zero. This identity reflects that any carbon balances are passed on without a profit markup to the firm's customers. A company's net CE flow ("income") is thus calculated as emissions transferred to customers as parts of goods sold less CEGS, and, by construction, this difference is equal to zero.

Just as balance sheets and income statements convey essential information about a firm's financial position, CE statements yield several key indicators of a firm's past, current and future performance in the domain of carbon dioxide (CO_2) emissions. The liability side of the CE balance sheet tallies a firm's cumulative Direct Net Emissions (DNE), that is, cumulative direct emissions less any applicable carbon dioxide removals, accumulated after some reference date. Emissions accumulated after some reference date are a Key Performance Indicator (KPI) for technology firms like Google and Microsoft that have set the more ambitious goal of removing from the atmosphere their entire legacy emissions (Smith, 2020; Pichai, 2020). Companies seeking to highlight the trajectory of their recent direct emissions and removals can do so by disaggregating the cumulative values in those balance sheet accounts according to their recent annual increments.

The asset side of the CE balance sheet shows the emissions embodied in the firm's long-term operating assets, e.g., machinery and equipment, as well as those in short-term assets, e.g., inventories.[9] The significance of this carbon KPI is that the emissions recorded in operating assets will flow through to the firm's sales products in future periods. Therefore, the overall CO_2 balance on the asset side of the CE balance sheet generates a lower bound for the total emissions that the company will report in connection with its future product sales.[10]

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[9] In the public discussion about climate change, German companies and analysts frequently refer to "Klimabilanzen"(which translates to "climate balance sheets"). Yet, these references do not pertain to conventional balance sheets, but simply a list of a company's product related emissions (Omnicert, 2023).

[10] The tons of CO_2 recorded on the asset side of the CE balance sheet only provide a lower bound for emissions to be included in future product sales because these also include the firm's direct emissions to be realized in future periods.

In today's reporting environment, the most common corporate carbon flow measure is direct emissions, adjusted for any recognized CO_2 offsets in the current year. Any claim for a company to be on a path to net-zero according to the CEGS metric is generally more stringent than a corresponding claim when corporate carbon footprints only comprise direct net emissions. For such a firm to drive CEGS to zero, either both its direct emissions and the indirect emissions acquired from suppliers in its production inputs must go to zero, or one of these emission sources must become carbon negative. In comparison to DNE, the CEGS metric is also less vulnerable to opportunistic outsourcing of carbon intensive production processes. Specifically, a company can claim substantial reductions in its direct emissions simply by redrawing the boundaries of its business, e.g., divesting itself of in-house power generation.

The earlier study by Kaplan and Ramanna (2021) refers to the cradle-to-gate carbon footprint of a product as its E-liability. The carbon accrual accounting system described in this paper builds on the idea of calculating E-Liabilities in a decentralized and recursive fashion by introducing CE balances sheets and CE flow statements. The rationale for distinguishing between carbon emission stock and flow variables by means of an accrual accounting system is essentially the same as in financial accounting. To assign a proper share of the total direct and indirect emissions incurred in any given period to the emissions embodied in products sold, the accounting system relies on both intertemporal and cross-sectional accruals that effectively separate stock from flow variables. Taken together, CE balance sheets and flow statement integrate the measurement of individual PCFs into a reporting framework that enables a comprehensive assessment of a company's carbon emissions performance over time.

Because the carbon accrual accounting system described here builds directly on the principles underlying historical cost accounting, it should be relatively straightforward to adapt existing accounting enterprise software to keep the books for carbon accounting. Further, it should take only "reasonable" effort for external auditors to certify that CE statements were prepared in accordance with principles that mirror generally accepted accounting principles for operating assets. Auditor certification will be particularly important for regulatory compliance such as the determination of carbon import duties. The European Union has decided on the adoption of these import duties by the year 2026 under its Carbon Border Adjustment Mechanism.[11]

The remainder of this paper is organized as follows. Section 2 reviews the challenges companies face in reporting their carbon emissions in accordance with the Greenhouse Gas Protocol. Accrual accounting for CO_2 emissions and the resulting CE balance sheets and CE flow statements are introduced formally in Section 3. Section 4 takes the perspective of an analyst examining a company's CE statement seeking to assess any progress the company has made on its decarbonization path. We discuss several open issues regarding carbon accounting in Section 5. Conclusions are presented in Section 6.

2. Current Carbon Reporting Frameworks

The Greenhouse Gas (GHG) Protocol currently is the common reference framework for assessing corporate carbon footprints. As the name suggests, the GHG Protocol covers multiple atmospheric gases with global warming potential. Our discussion here focuses exclusively on CO_2 because of its dominant contribution to global warming, and because for many businesses it is effectively the only greenhouse gas emitted. Furthermore, the climate science community has developed widely accepted multipliers that convert greenhouse gas emissions other than CO2 to CO_2 equivalents.

The Protocol classifies direct emissions as those stemming from flue gases and tailpipe exhaust streams at a firm's own production facilities (Scope 1). Indirect emissions (Scope 2 and 3) are those emanating from operations in a company's upstream supply chain as well as those generated by the company's customers, their customers and so forth. Scope 2 is a carve-out from the broader category of indirect emissions, as Scope 2 emissions pertain exclusively to the

[11] The objective of the Carbon Border Adjustment Mechanism (CBAM) is the creation of a level playing field for imports to the European Union from countries that do not subject producers to the same price on carbon emissions that is applicable within the European Union (European Union, 2022).

generation of electricity and heat provided by external suppliers (World Resources Institute, 2004).

Many jurisdictions around the world, including the U.S. and Europe, require major CO_2 emitters to report their annual direct (Scope 1) to federal registries. For jurisdictions that have adopted carbon pricing regulations in the form of a carbon tax or a cap-and-trade system, emission charges are usually based on a company's direct emissions. Those jurisdictions have instituted detailed measurement and verification systems for determining a company's actual direct emissions in any given year and the resulting carbon charges (Downar et al., 2021).

The assessment of Scope 3 emissions, in contrast, appears to have been uneven in practice. A recent study by Hale (2021) found that in a sample of 417 companies, the vast majority disclosed their Scope 1 and 2 emissions, and about 20% included some Scope 3 figures. Technology firms like Google indicate that they limit their count of Scope 3 emissions to employee commuting and travel. A survey of the entire computer technology sector found that firms underreport their Scope 3 emissions by about half relative to the standards of the GHG Protocol (Klaassen and Stoll, 2021).[12]

It is widely acknowledged that assessing a company's Scope 3 emissions entails enormous data collection challenges. Most companies hire outside consultants that perform an analysis of the life-cycle emissions for the goods and services transacted by the company. However, outside consultants must generally rely on industry-wide average emission estimates rather than primary data reflecting the actual emissions incurred by the parties along a company's supply chain. Consequently, any reductions in actual emissions achieved by a firm's suppliers will at best be partially reflected in the company's reported carbon footprint metrics (Kaplan, Ramanna and Reichelstein, 2023).

[12] Glenk (2023), Griffin and Sun (2023) and Wagenhofer (2023) point out multiple obstacles to making the reporting of Scope 3 emissions comparable across firms and informative for a firm's stakeholders.

A further issue with comprehensive Scope 3 assessments is the impossibility of measuring the carbon emissions incurred through the future use of a sales product at the time the product leaves the seller's gates. To illustrate this difficulty, consider the sale of an aircraft to an airline. According to the GHG protocol, the manufacturer should take a life-cycle perspective in estimating the total lifetime emissions - from cradle to grave - generated by operating the aircraft. Such estimates, however, must remain speculative, as they require forecasts for both routes and miles flown in future years as well as the type of fuel the aircraft will be using, e.g., kerosene versus sustainable aviation fuels. These considerations explain in part why the 2022 exposure draft by the SEC envisions a safe harbor provision for corporate Scope 3 disclosures (Security and Exchange Commission, 2022).

The experience companies have in tailoring the design of costing systems to their own operations should allow them to assess the actual carbon emissions embodied in different sales products, provided they have reliable information on the carbon balances embodied in the inputs received from suppliers. At each link in the chain, firms can then rely on primary data regarding their own production activities, their own direct emissions and the indirect emissions represented by the carbon balances of their production inputs, the latter ideally calculated in a recursive manner by the firm's upstream suppliers (Kaplan, Ramanna and Reichelstein, 2022). Several multinational firms have recently developed internal accounting systems with the aim of calculating PCFs in a recursive manner, relying on actual local company-level emissions data at each link of the supply chain (BASF 2021, Kurtz, 2022; Meier, 2022).

The informational advantages of calculating PCFs in a decentralized and recursive manner are readily illustrated in the context of the above aircraft example. Suppose the airline receives a cradle-to-gate PCF measure from the manufacturer of the aircraft. This figure reflects the actual upstream emissions embodied in the constituent aircraft parts as well as the emissions accumulated in the aircraft's assembly. The airline, in turn, calculates the carbon footprint of particular flights by including the emissions associated with fuel combustion, other variable inputs and a periodic depreciation charge on the stock variable representing the initial PCF of the aircraft. Just as the cost of a flight is calculated by an internal costing system, a carbon accrual accounting system can determine the emissions required for a particular flight from the cradle of all requisite inputs to the airline's gate, i.e., the delivery of the flight. Aggregating the cradle-to-gate figures for all flights undertaken in a particular year, the airline obtains a measure of its Carbon Emissions in Goods Sold (CEGS) for that year.

Reliance on primary firm-level data for determining product carbon footprints in a recursive manner along a firm's supply chain has critical implications for firms' incentives to reduce CO_2 emissions. First, any reduction a firm obtains in its actual direct emissions will be fully reflected in the current PCF metrics. Secondly, firms will be in a position to exert pressure on their suppliers to reduce the PCF of inputs purchased by the firm. Microsoft Corporation, for instance, has indicated that the carbon emissions attributed to products and services included in the firm's Scope 3 count will become a criterion for supplier selection in the future (Comello et al., 2022).

In closing this section, we note that the sequential calculation of upstream Scope 3 emissions, as advocated here, in no way prevents companies from issuing separate estimates for the probable emissions associated with the future use of their products. By their very nature, these assessments must remain estimates, while upstream Scope 3 reports, in contrast, can be based on actual emissions incurred, provided more firms along the supply chain undertake their own in-house PCF measurements. Firms seeking to disclose cradle-to-grave carbon footprint measures in full accordance with the GHG Protocol standard may therefore find it useful to split these disclosures into cradle-to-gate actuals and gate-to-grave estimates.

3. Accrual Accounting for Carbon Emissions

This section describes the proposed bookkeeping for carbon emissions through a sequence of sample transactions that a business would undertake as part of its normal operational cycle. The illustration applies to both manufacturing and service businesses. Assuming the company has already initiated a carbon accrual accounting system in a previous period, there will be an opening CE balance sheet, illustrated in Table 1.[13]

CE in Assets (in 000 tons of CO_2)		CE in Liabilities (in 000 tons of CO_2)	
Buildings	z_1	x_1	Emissions Transferred In (ETI)
Machinery and Equipment	z_2	y_1	Direct Emissions (DE)
Raw Materials	z_3	*less*	
Work-in Process	z_4	(x_2)	Emissions Transferred Out (ETO)
Finished Goods	z_5	(y_2)	Direct Removals (DR)

$$\sum_{i=1}^{5} z_i = x_1 + y_1 - (x_2 + y_2)$$

Table 1: **CE Balance Sheet**

The unit of measurement for all accounts is one ton of CO_2.[14] In direct analogy to a financial balance sheets which maintain the identity:

$$Assets = Liabilities + Equity$$

at all points in time, the corresponding identity for a CE balance sheets is:

$$CE\ in\ Assets = \ CE\ in\ Liabilities.$$

Like the entries on a financial balance sheet, the entries on a CE balance sheet represent stock variables that accumulate carbon balances across time periods. However, the CE balance sheet does not record conventional asset or liability values. The accounts on the left-hand side record

[13] See Appendix B for a comprehensive list of all acronyms.

[14] As noted above, companies can account separately for greenhouse gases other than CO_2, or alternatively calculate CO_2 equivalents by applying suitable multipliers for other greenhouse gases.

the emissions embodied in the firm's operating assets. The company effectively assumes responsibility for these emissions (it 'owns' these emissions) as it acquires production inputs and carries out its operations. The sources of these emissions, recorded on the liability side, are either the firm's own direct (Scope 1) emissions or those incurred by the firm's upstream suppliers.

The balances for all accounts on the liability side increase monotonically over time, albeit some with a negative sign. In each period, the firm's direct (Scope 1) emissions and the carbon balances of goods and services acquired from suppliers in that period are added to the beginning balances of the Direct Emissions (DE) and Emissions Transferred In (ETI) accounts, respectively. Companies that seek to give the public a better understanding of the recent history of the company's direct emissions can do so by reporting the recent annual direct emission increments as separate line items on the CE balance sheet.

The account balances for Direct Removals (DR) and Emissions Transferred Out (ETO) also increase monotonically over time. As the name suggests, the periodic increment for Direct Removals reflects the tons of CO_2 that the company itself, or a contractor acting on its behalf, has removed from the atmosphere in a given time period. These tons effectively represent negative direct emissions, recorded with a negative sign in a contra-liability account on the right-hand side of the balance sheet.[15]

Emission transfers across companies are recorded in a manner analogous to receivables and payables of cash in financial accounting. Here, ETI effectively assumes the role of payables, while ETO assumes the role of receivables.[16] When the firm sells finished goods to customers, it records a receivable (shown as a reduced liability in the contra liability account ETO) for the

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[15] As discussed in more detail in Section 4 below, the accounting for CO_2 removals, and more for broadly for carbon offsets, is likely to be controversial. It therefore seems appropriate to record direct removals in a separate balance sheet account rather than net these negative emissions against direct emissions.

[16] The interpretation here is that the sale of a good entitles the seller to a receivable for x "CO_2 tokens" provided that is the assessed PCF of the good in question.

tons of emissions embodied in the goods sold. The buyer of the goods, in turn, records the same emissions quantity as a debit to its inventory and as a credit to its ETI account. Our convention of classifying Emissions Transferred Out and Direct Removals as contra liability accounts has the advantage that the left-hand side of the CE balance sheet exclusively carries the emissions embodied in the firm's operating assets. These embodied (stored) emissions will be become part of the firm's emissions in goods sold in future periods.

To illustrate the bookkeeping for the proposed system of carbon accrual accounting, the Transactions Tableau in Figure 2 presents the bookkeeping entries for seven sample transactions. The debits and credits for these transactions are shown in the rows labelled T_1-T_7. Changes to any asset and liability accounts are recorded in the columns of Table 2. Beginning balances, denoted by BB, are shown in the second row of the tableau. For reasons of parsimony, the two accounts Buildings and Property and Equipment in Table 1 have been combined into Plant, Property and Equipment (PPE) in Table 2. Thus, $z_1 + z_2 = BB_{PPE}$.

Table 2 shows *m* different Work-in-Process accounts ($WIP_1, WIP_2, \ldots, WIP_m$), and *n* different Finished Goods accounts ($FG_1, FG_2, \ldots, FG_n$). Reconciling these with the notation in Table 1, it follows that:

$$\sum_{i=1}^{m} BB_{WIP_i} = z_4,$$

and

$$\sum_{i=1}^{n} BB_{FG_i} = z_5.$$

Among the seven sample transactions represented in Table 2, transaction T_1 pertains to the purchase of raw materials. If the supplier of these materials has adopted its own carbon accounting system capable of assigning these materials individual PCF measures, the company can rely on these figures to debit its own MAT account(s). Otherwise, the company will need to estimate the emissions embodied in its materials based on secondary industry-level data.[17] Double-entry bookkeeping requires the carbon balance of the MAT account to be debited by u_1 tons of CO_2, with the corresponding credit recorded in the ETI account (Transaction 1).

When materials are transferred from inventory to production, the corresponding emission balances are transferred to the firm's Work-in-Process (*WIP*) accounts (Transaction 2). There is no change in liabilities associated the internal transfer of emissions across operating assets. In our illustration, the total number of tons of CO_2 transferred is:

$$\sum_{i=1}^{m} u_{2i} = u_2.$$

Similarly, no additional liability is incurred when depreciation charges reduce the book value of the PPE account (Transaction 3). The beginning balance of the PPE account, i.e., BB_{PPE}, represents current book value, that is, the emissions that were initially capitalized when the long-term assets were acquired, less depreciation charges accumulated in previous periods. Accordingly, the WIP_i accounts are debited with depreciation charges in the amounts of u_{3i} tons, with the corresponding credit going to the PPE account:

$$\sum_{i=1}^{m} u_{3i} = u_3.$$

Suppose next that as part of its annual operations the company directly emits u_4 tons of CO_2. These Scope 1 emissions need to be assigned first to the Work-in-Process accounts and ultimately to the company's sales products. The assignment rules for these direct emissions, as well as the indirect emissions transferred in transactions T_2 and T_3, can be based on internal allocation systems akin to cost accounting rules that assign overhead costs to different products. In the context of carbon accounting, a Product Carbon Footprint (PCF) measurement system can be conceptualized as a mapping:

[17] In direct communication, the chemical company BASF has indicated that as of late 2022 only a minority of the company's suppliers provide their own in-house PCFs for raw materials sold to BASF. For most of its raw materials, the company continues to rely on carbon footprint measures provided by external life-cycle analysis consultants (Kaplan, Ramanna and Reichelstein, 2022).

f: (DE, CE Inputs) → CE Outputs.

Here, the CE balance of inputs reflects the indirect emissions accumulated by the firm's suppliers, their suppliers and so forth. Inputs generally comprise consumable goods, like components that go into a product, and the periodic use of capital goods, in which case the corresponding carbon balance is prorated through annual depreciation charges. For multi-stage production processes, CE outputs first refer to work-in-process accounts and ultimately to finished goods. Appendix A illustrates how well-established product costing rules, such as activity-based costing, joint cost allocation and ISO rules, have been adapted to configure the internal carbon allocation systems for companies in the cement and chemicals industry.

The central role of a Product Carbon Footprint (PCF) measurement system, as represented by the mapping $f(\cdot)$ above, is to determine how "overhead emissions", including both direct (Scope 1) and indirect (Scope 2 and 3) emissions, are ultimately charged to different sales products. To that end, the allocation rules should reflect the specifics of the underlying production processes to capture the causal relation between emissions associated with specific production activities and the extent to which different products require these activities. The extensive literature on product costing suggests that the allocation bases ("drivers") underlying a company's internal PCF allocation rules can be chosen as proxy measures for resources consumed and their associated carbon emissions.[18] Similar to the discretion companies have in tailoring their inventory costing rules to the specifics of the companies' operations, the design of suitable PCF measurement systems should generally be industry- and company-specific.[19]

[18] See, for instance, Datar and Rajan (2019), Kaplan and Cooper (1998) and Kaplan and Anderson (2004).

[19] The case study by Landaverde et al. (2023) points to possible inconsistencies and under-counting of emissions when different industry groups advocate for different allocation rules in assigning intermediate products their PCF. Landaverde et al. (2023) illustrate this issue in connection with slag, a by-product of steel making. The specific rules adopted for calculating the PCF of slag determine whether this by-product qualifies as a low-carbon supplementary material for Portland cement (World Steel Association, 2014).

Table 2: TRANSACTIONS TABLEAU

	CE in Assets								=	CE in Liabilities			
Accounts	**PPE**	**MAT**	**WIP_1**	**...**	**WIP_m**	**FG_1**	**...**	**FG_n**		**ETI**	**ETO**	**DE**	**DR**
Beginning Balance	BB_{PPE}	BB_{PPE}	BB_{WIP_1}	...	BB_{WIP_m}	BB_{FG_1}	...	BB_{FG_n}		BB_{ETI}	BB_{ETO}	BB_{DE}	BB_{DR}
Transactions:													
T_1		u_1							=	u_1			
T_2		$-u_2$	u_{21}	...	u_{2m}				=				
T_3	$-u_3$		u_{31}	...	u_{3m}				=				
T_4			u_{41}	...	u_{4m}				=			u_4	
T_5			$-u_{51}$	...	$-u_{5m}$				=				$-u_5$
T_6			$-v_{61}$		$-v_{6m}$	w_{61}	...	w_{6n}	=				
T_7						$-u_{71}$		$-u_{7n}$			u_7		
Ending Balance	EB_{PPE}	EB_{PPE}	EB_{WIP_1}	...	EB_{WIP_m}	EB_{FG_1}	...	EB_{FG_n}		EB_{ETI}	EB_{ETO}	EB_{DE}	EB_{DR}

We postulate balancedness as one fundamental constraint on PCF measurement systems: the sum of direct emissions and indirect emissions embodied in production inputs must equal the emissions assigned to outputs. This balancing property was maintained for transactions T_2 and T_3, as total debits were in both cases equal to total credits. Balancedness will also be maintained in the assignment of the firm's Scope 1 emissions provided:

$$\sum_{i=1}^{m} u_{4i} = u_4.$$

Most multinational firms that have pledged to cease emitting greenhouse gases by 2050 have made their pledge on a net-zero basis. Thus, any gross emissions remaining at the target date must be compensated by carbon offsets.[20] While we defer a fuller discussion of the accounting for carbon offsets to Section 5 below, our sample transaction T_5 focuses on a setting where the company in question, or a contractor acting on its behalf, has removed u_5 tons of CO_2 from the atmosphere. The removal activity could be nature-based or engineered, e.g., direct air capture combined with geological sequestration (Wilcox, Kolosz, and Freeman, 2021). Suppose further that this removal is accompanied by an assurance that the u_5 tons of CO_2 will be "durably" removed from the atmosphere, that is, none these u_5 tons will be released back into the atmosphere for a long period of time, say for at least several hundred years.[21]

As argued above, the assignment of direct emissions to individual products (WIP accounts) should reflect the causal link between production activities and their associated CO_2 emissions. However, there will generally be no such causal link for direct removals. This naturally raises the questions whether generally accepted carbon accounting principles should leave companies with full discretion in assigning these removals. Specifically in connection with T_5, should the company be in a position to choose any vector ($u_{51},\ldots,u_{5m}$), provided its components add up to u_5? Giving firms such discretion will make carbon removals a tool for "managing" the reported PCF of select consumer products that are deemed to have a high demand elasticity with respect

[20] Recent years have witnessed a trading boom in the voluntary carbon markets, fueled by companies purchasing carbon offsets (Bloomberg Green, 2021).

[21] Parts of the literature on carbon dioxide removals use the term "permanent" rather than "durable" to refer to carbon removals that prevent subsequent CO_2 releases for at least 1,000 years (Microsoft, 2021).

to CO_2 emissions. At the same time, such discretion may provide much needed incentives for firms to acquire carbon removals in the first place.[22] Concerns about selective "greenwashing" will be mitigated by requiring disclosures that disaggregate the reported PCFs into their constituent components, i.e., direct emissions, direct removals and carbon emissions embodied in upstream production inputs. We revisit the issue of accounting for carbon removals in Section 5 below.

Once work-in-process is completed, the carbon balances accumulated in the WIP accounts are transferred to the corresponding finished goods (FG_i) accounts on the asset side of the CE balance sheet (Transaction 6). The corresponding balancing requirement is:

$$\sum_{i=1}^{m} v_{6i} = \sum_{i=1}^{n} w_{6i}.$$

The carbon balances w_{6i}, for $1 \leq i \leq n$, are calculated as units of finished good i added to inventory multiplied with the product carbon footprint (PCF_i) of product i. PCF_i therefore becomes the cost accounting analogue of a product's (historical) unit cost.

As more companies along a supply's chain adopt their own internal PCF allocation system, the resulting carbon footprint measures of products moving along the supply chain will increasingly reflect an allocated share of each company's actual direct emissions, an allocated share of those actually incurred by its immediate suppliers, their suppliers' suppliers, and so forth up the entire supply chain. Importantly, this recursive calculation process will increasingly reflect firm-level data based on actual emissions incurred at each stage, while avoiding double counting of emissions.[23] The lack of double counting is readily illustrated in a hypothetical setting where

[22] As of 2022, a cost of $100 dollars per ton of CO_2 was commonly considered the "holy grail" of carbon removals (Ma, 2022). Compliance markets provide few if any incentives for companies to acquire removals. In particular, the European Union's Emission Trading System does not allow for carbon removals to offset the number of emission permits that need to be obtained for direct emissions.

[23] Avoiding double-counting of emissions will be crucial in connection with regulations that tie governmental subsidies to a product's assessed PCF. Under the Inflation Reduction Act (IRS, 2022), for instance, the magnitude of the production tax credit available for "clean" hydrogen is based on the product's assessed carbon content. As of mid-year 2023, the IRS had yet to specify which methods will be accepted for assessing the carbon content (footprint) of hydrogen.

every firm produces and sells only one product, though intermediate products may require multiple input components. Suppose further that the production processes require no capital goods and therefore there are no intertemporal allocations in the form of periodic depreciation or amortization charges. Companies along the supply network thus simply assemble components acquired from their suppliers, and in doing so incur direct emissions in the process. In such hypothetical settings, the resulting cradle-to-gate PCF measure of each sales product will exactly be equal to the sum of all direct emissions accumulated from the components going into that product.

The final transaction T_7 in Table 2 pertains to the sale of finished goods. If the carbon balance of the i-th product on the CE balance sheet is reduced by u_{7i}, the company sold s_i units of product i, where $PCF_i \cdot s_i = u_{7i}$. As these carbon balances go off the CE balance sheet, the company records an equal "revenue" (receivable) in its ETO account. The entries corresponding to T_7 in Table 2 are the basis of the company's periodic CE Flow Statement:

$$EB_{ETO} - BB_{ETO} - CEGS \equiv Net\ CE\ Flow = 0,$$

with

$$CEGS \equiv \sum_{i=1}^{n} PCF_i \cdot s_i = \sum\nolimits_{i=1}^{n} u_{7i}$$

denoting Carbon Emissions in Goods Sold. Since all carbon emissions are transferred "at cost" across businesses, the aggregate bottom line, i.e., the net CE flow measure, is always equal to zero. CE Flow Statements will nonetheless convey essential information about a firm's carbon emissions performance if CEGS is disaggregated into different product groups. Assuming the company seeks to disclose the carbon footprint of each one of its *n* sales products, Table 3 illustrates fully granular line item reporting.[24]

[24] Firms with a diverse portfolio of product groups are likely to aggregate homogeneous product groups into single line items on the CEGS statement.

Table 3: CE Flow Statement

u_7	=	Current Emissions Transferred Out
	Less	
u_{71}	=	$PCF_1 \cdot s_1$ (CE in Sales of Product *1*)
u_{72}	=	$PCF_2 \cdot s_2$ (CE in Sales of Product *2*)
.	=	.
.	=	.
.	=	.
u_{7n}	=	$PCF_n \cdot s_n$ (CE in Sales of Product *n*)
0	=	**Net CE Flow**

Carbon Emissions in Goods Sold (CEGS) emerges as the natural corporate carbon footprint metric for firms that take responsibility for the emissions embodied in production inputs acquired from their suppliers. CEGS provides an aggregate measure of a firm's entire "Upstream Scope 3" (including its Scope 1 and 2) emissions. In analogy to Cost of Goods Sold (COGS) in income statements, CEGS is a "cost measure" of the current damage that products sold by the firm have contributed to the global climate.[25] The ratio CEGS/COGS thus provides a measure of the current carbon intensity of a firm's sales products. To show a "profit" in the sense of having made a positive contribution to the world's climate, the CEGS metric would need to turn negative. This would require that across the links of a firm's supply chain direct

[25] The choice of allocation rules inherent in internal PCF measurement systems will leave companies with discretion in burdening individual products at the expense of others. In contrast to individual PCF metrics, however, the aggregate CEGS metric is largely invariant to the choice of the underlying PCF measurement system. Just as Cost of Goods Sold is invariant to the choice of a company's product costing system, provided there are no build-ups or depletions in inventory, balancedness ensures that alternative allocation rules result in the same aggregate CEGS figure.

emissions are, on average, more than offset by negative emissions associated with direct removals.

At the close of the operational cycle, the ending balances on the CE balance sheet are determined as the sum of the beginning balances in Table 1 and the sum of the entries in the columns of Table 2 for each balance account. For instance, $EB_{PPE} = z_1 + z_2 - u_3$ and $EB_{DE} = y_2 - u_4$.

4. Monitoring Carbon Reduction Pledges

Following the lead of national governments, a substantial number of multinational firms have in recent years articulated their own carbon reduction goals, frequently in the form of "net-zero by 2050" pledges (Gill 2022). However, absent a comprehensive measurement and reporting framework, these pledges will likely be met with continued skepticism (Hale, 2021; Tollefson 2022). Corporate carbon emission statements, comprising CE balance sheets and flow statements, provide a reporting framework that enables analysts and the public to monitor firms' progress on their proclaimed decarbonization paths.

A company's direct net emissions (DNE) in any given time period remains a common measure of its corporate carbon footprint. DNE emerges from the CE balance sheet as the difference $EB_{DE} + EB_{DR} - (BB_{DE} + BB_{DR})$. Companies can disclose further information about recent improvements in their direct emissions and removals by disaggregating EB_{DE} and EB_{DR} into the annual increments realized over the past *k* years.[26] Reporting annual DE and DR increments on the CE balance sheet will give analysts a better sense of the speed of emission improvements and the prospects for approaching a net-zero position within a certain time frame.

From a global climate change perspective, the DNE metric is of central importance because the sum of all direct net emissions in any given year, when added up across all economic entities, including firms, households, and other carbon emitting entities, yields the net addition of CO_2

[26] For both DE and DR, there would then be *k+1* accounts on the balance sheet, with the first account in each category reporting the cumulative quantities dating back more than *k* years.

to the atmosphere (Comello et al. 2023, Heal 2023). Yet, the DNE metric is incomplete at the level of individual companies because outsourcing carbon-intensive activities will allow a company to claim significant emission reductions without any real operational changes.

In contrast to the DE metric, CEGS is invariant to outsourcing emission-intensive activities, precisely because companies extend their responsibility to acquired upstream Scope 3 emissions. Further, a net-zero trajectory according to the CEGS metric generally also requires DNE to approach zero. Specifically, suppose a company is in a steady state in terms of its production and sales volume and does not engage in carbon removals. An emissions trajectory for which CEGS goes to zero then also requires both current direct emissions as well as the carbon balance in acquired assets, i.e., $EB_{PPE} + EB_{MAT}$, go to zero. For firms not in a steady state in terms of their production and sales volume, it is possible for CEGS to go to zero while direct emissions remain above some threshold level. This divergence would be accompanied by a build-up of the emissions recorded in FG or WIP, and therefore would be visible on the asset side of the CE balance sheet.

Firms seeking to convey information about changes in their recent CEGS figures can do so by providing line items for the recent annual ETO increments on their CE balance sheet. Further, both current DNE and total emissions recorded on the asset side of the CE balance sheet are informative in assessing whether a company is on a net-zero trajectory in terms of the CEGS metric. The emissions embodied in inventories and long-term assets on the CE balance sheet will flow through to future CEGS figures, and therefore provide a lower bound for future CEGS values. The informativeness of this lower bound will be industry-specific depending on the relative magnitude of direct vs. indirect emissions and the turnover rate for different operating assets.

In addition to long-term carbon reduction goals, such as "net-net zero by 2050", some companies have set interim reduction milestones. For instance, the cement and materials producer Heidelberg Materials has set the target of staying below 400 kg of CO_2 per ton of cementitious material by the year 2030.[27]. This target is to be achieved on average across the company's different cement recipes. In the notation of Table 2 above, the constraint of 400 kg of CO_2 per ton of cementitious material can be represented as:

$$\frac{CEGS}{\sum_{i=1}^{n} s_i} = \frac{\sum_{i=1}^{n} PCF_i \cdot s_i}{\sum_{i=1}^{n} s_i} \leq 400 \ \frac{kg\ CO2}{t\ cement},$$

where s_i refers to tons of cement of recipe *i* sold in 2030.

Well ahead of the 2050 target date, consumer-oriented companies like Shell, Nestle and Total have increasingly begun to market select products as "carbon neutral" (Bloomberg Green, 2021) The accounting framework described here enables firms to back up such claims with additional disclosures. Specifically, any claim that the carbon intensity of a particular product is already zero will be substantiated by decomposing PCF figures into their constituent parts: allocated direct emissions, allocated direct removals and allocated upstream Scope 3 emissions. Such disaggregated reporting would be aligned with the EU's recent Green Reporting Directive (European Union, 2023).[28]

Some technology firms, including Google and Microsoft, have articulated emission reduction goals that go beyond simply achieving a net-zero position in terms of their annual emissions by the year 2050. These companies aspire to become "climate neutral" in terms of removing, by a specific target date, their entire legacy emissions accumulated after their inception date. CE balance sheets allow for monitoring a firm's progress towards achieving such goals. Specifically, for firms that measure the legacy emissions in terms of their cumulative DNE, the account balances for $EB_{DE} + EB_{DR}$ would need to turn negative at the target date and stay negative thereafter. For companies that, in addition, include the cumulative indirect emissions acquired through their upstream supply networks in their legacy emissions, "climate neutrality" becomes

[27] See Cement News (2023). For Heidelberg Materials, achievement of this target would correspond to an almost 50% reduction in carbon intensity relative to 1990 levels.
[28] A 2023 court ruling in Germany affirmed the right of companies to advertise select consumer products as "CO_2 neutral", even if such claim are partially based on the purchase of carbon offsets. In its ruling the court emphasized that the defendant directed customers to a website that substantiated the company's zero carbon footprint claim (Zajonz, 2023).

a more stringent goal: the sum of the account balances $EB_{DE} + EB_{DR}$ +EB_{ETI} must then turn negative at the target date and remain negative thereafter.

From an incentive perspective, it will be essential that firms can take credit for any emission reductions achieved in the short run. The carbon accrual accounting system described in this paper provides high-powered incentives for continuous emission improvements. Every ton of CO_2 not emitted by the firm, and every ton of CO_2 not incurred by one of the firm's suppliers, will concurrently lower the firm's reported PCFs and the aggregate CEGS metric. Such first-order incentives are noticeably missing in the current implementation of the GHG Protocol, where PCF calculations rely on industry-wide averages provided by outside consultants.

4. Discussion

The carbon accounting rules introduced in the previous sections are suggested directly by the proven of financial and managerial accounting. This section discusses several issues that require further consideration as part of a comprehensive set of "generally accepted carbon accounting principles."

Intangibles. While the presentation in Section 3 has seemingly focused on physical goods, the carbon accounting framework presented here applies equally to service businesses, such as airlines or other transportation service companies.[29] Regardless of whether the firm's sales products are tangible, any emissions associated with intangible inputs such as employee travel and commuting as well as those associated with the use of electric power by work-at-home employees are to be included in the count of indirect emissions.[30] On the output side, a firm's direct and indirect emissions associated with R&D activities do not necessarily have to be

[29] In both the U.S. and Europe, the transportation sector has recently overtaken power generation and industrial production in terms of direct emissions (IEA, 2022).
[30] In 2020, technology firms like Google only included employee travel and commuting in the count of their Scope 3 emissions (Comello et al., 2022).

absorbed in the current CEGs, but could instead be capitalized on the CE balance sheet and amortized in future PCFs according to some predetermined amortization schedule.

Recycling. Full decarbonization will require the transition to a circular economy in which recycled products provide a substantial share of the raw materials used in industrial production. The carbon accrual accounting system described in this paper is centred around the postulate that carbon balances, accumulated at various stages of the supply chain, stay with a product until it is delivered to its end customer. Yet, this accrued carbon balance should be expunged when products reach the end of their useful life and go to the recycling stage. If raw materials derived from recycled products were to carry over any accumulated carbon balances, they would be subject to a potential sourcing bias in comparison to virgin raw materials. The carbon balance of any raw materials, whether they are virgin materials or obtained through recycling, should only reflect the emissions that the suppliers of these materials incurred for their delivery to customers.

Carbon Offsets have become a controversial topic in the recent discussion about a timely transition to a net-zero economy. As firms increasingly report corporate- and product carbon footprint measures that subtract offsets from gross emissions, two central questions emerge: what types of offsets are eligible for recognition on the company's books, and how should those eligible offsets be accounted for?

Transaction T_5 in Section 3 considers a removal offset where the company in question, or a contractor acting on its behalf, actively removed u_5 tons of CO_2 from the atmosphere and furthermore provided an assurance that the entire quantity of CO_2 would be "durably" sequestered.[31] Yet, the majority of carbon offsets currently traded in the voluntary carbon markets are so-called avoidance offsets. These are generated, for instance, through investments in renewable energy facilities. The reasoning underlying such offset accounting is

[31] Direct air capture of the CO_2, followed by its mineralization in volcanic rock, is a prime example of a permanent removal (Wilcox, Kolosz, and Freeman, 2021).

that the renewable energy facility induces other parties to consume less electricity from the grid, thereby avoiding the emissions associated with grid-based electricity.

The responsibility accounting framework described in this paper posits that a company investing in renewable energy will record lower indirect emissions in its PCFs to the extent that clean electricity actually replaces carbon-intensive electricity previously obtained from the grid. If the clean electricity is sold to third parties, however, the investor should not claim the reduction in the carbon footprint of the third party as an offset for itself. That would entail double counting, unless the third party were to record on its books the same amount of carbon-intensive electricity as it did before the investment in the renewable energy facility (Comello et al. 2022).

Avoidance offsets are generally based on counterfactual claims. The party recognizing the offset claims that its intervention caused fewer emissions, e.g., a forest was conserved rather than logged. These considerations have led multiple organizations like the Science-Based Target Initiative and companies like Microsoft and Stripe not to recognize avoidance offsets in the calculation of corporate carbon footprints (Microsoft, 2021; Joppa et al. 2021).

To date, few companies have been explicit regarding the threshold required for removals to be considered sufficiently durable to merit offset recognition (Joppa et al., 2021). In the absence of a generally accepted standard, companies can supplement their CE statements with disclosures regarding the duration profile of the portfolio of removals that have been recognized. For carbon removals that might plausibly not be durable and suffer a partial reversal within a ”short” period of time, companies might nonetheless recognize the removal activity, provided any reversal would also be included in the company’s subsequent direct emissions. For such an accounting approach to be credible, however, there would have to be confidence that past removal activities are regularly monitored and verified.[32]

[32] Kaplan, Ramanna and Roston (2023) suggest the introduction of “contingent liabilities” for carbon removals that might reverse within a “short” period of time.

Section 3 touched upon the accounting for carbon removals that are deemed eligible for recognition on the company's CE balance sheet. Since it will generally be impossible to causally attribute CO_2 removals to individual products, there would be justification for giving companies discretion in allocating the tons of CO2 removed among the sales products. Concerns about "greenwashing" can be ameliorated by a requirement to disclose the constituent components of the reported PCFs: direct emissions, direct removals and indirect emissions. An alternative accounting treatment would require a proportional adjustment of the direct emissions attributed to the company's operational facilities. The proportional adjustment factor would be given by the overall ratio of current direct net emissions to direct emissions[33]. We conjecture, however, that the incentives to acquire costly carbon removals in the first place appear considerably stronger if companies have discretion in applying the carbon credits to targeted product groups with a higher carbon elasticity of demand. Similarly, companies might be more reluctant to acquire carbon removals if these were to be subtracted merely as a lump-sum amount from CEGS (calculated on the basis of gross direct emissions) in an annual carbon flow statement.[34]

Initialization. If adopted consistently within a supply network, the accrual accounting system proposed in this paper will assess the carbon footprint of a product as an allocated share of the actual direct emissions (net of any removals) incurred by companies in the network that have contributed parts and services to the product in question. At the same time, companies can unilaterally implement their own PCF allocation rules without their suppliers and suppliers' suppliers having done so. For parts and services supplied by firms that do not provide their own

[33] In the notation of Table 2, the proportional adjustment factor would be given by $\frac{u_4 - u_5}{u_4}$. Further, if u_{4j} denotes the gross direct emissions attributed to facility *j* and $u_4 = \sum_j u_{4j}$, then:

$$u_{4j} \cdot \frac{u_4 - u_5}{u_4}$$

tons of CO_2 would be attributed in adjusted direct emissions to facility *j*.

[34] Regarding global atmospheric damage, it does not matter whether direct removals have occurred in a location separate from direct (gross) emissions. Since for single-product firms, there is no allocation issue, it would suggest itself to calculate the one PCF figure based on current direct net emissions, rather current direct (gross) emissions.

PCF calculations based on primary data and in-house PCF allocation rules, corporate buyers can still rely on PCF estimates based on secondary data reflecting industry-wide averages.[35]

Firms preparing a CE statement for the first time, say in the year 202x, could set the beginning values on the initial CE balance sheet to zero. By so doing, the reported PCF and CEGS figures would effectively be undervalued in the early years, since any emissions embodied in operating assets acquired prior to 202x would be excluded. As mentioned in the previous section, some companies have set the goal of eliminating their entire legacy emissions incurred after some reference date. Those companies may want to initialize the CE balance sheet in the year 202x with their own estimates for the accounts Direct Emissions, Direct Removals, Emissions Transferred In, and CE in Assets.[36] These figures would be understood to be estimates of the emissions incurred between the initial reference date and the year in which the carbon accounting process commences, i.e., the year 202x.

5. Concluding Remarks

Businesses across a wide range of industries, spanning traditional manufacturing, services and technology, have begun to accept responsibility not only for their own CO_2 emissions, but also those embodied in goods and services procured from their suppliers. As these businesses seek to provide credible reporting on any progress made towards a net-zero emissions economy, the issue of commonly accepted carbon accounting standards becomes central. This paper has argued that the time-tested principles of historical cost accounting for operating assets can serve as a template for comprehensive and credible corporate carbon reporting.

The essential building blocks of the carbon accrual accounting systems advocated here are cradle-to-gate carbon footprints of individual products that companies determine in a decentralized and sequential manner. In the aggregate, these building blocks yield the metric

[35] As described in further detail in Appendix A, the chemical company BASF implemented its own PCF measurement system without most of its suppliers having done so (BASF, 2021).
[36] The account ETO could effectively serve as a "plug variable" in equating CE in Assets and CE in Liabilities on the initial balance sheet.

Carbon Emissions in Goods Sold (CEGS). It represents a measure of the contemporary damage that the delivery of a company's products and services have done to the world's climate. CE balance sheets track a firm's carbon performance over time. In particular, cumulative direct emissions, cumulative direct removals as well as the carbon emissions embedded in operating assets are key indicators of a firm's past and future carbon emissions.

The cost of adopting the carbon accrual accounting system described in this paper should prove relatively modest. Since the entire accounting framework is grounded in the rules of historical cost accounting for operating assets, existing financial accounting software should only require limited modifications. Further, auditors should face no conceptual barriers in certifying that a carbon emission statement has been prepared in accordance with accounting principles consistent with those used in preparing financial statements.

Appendix A

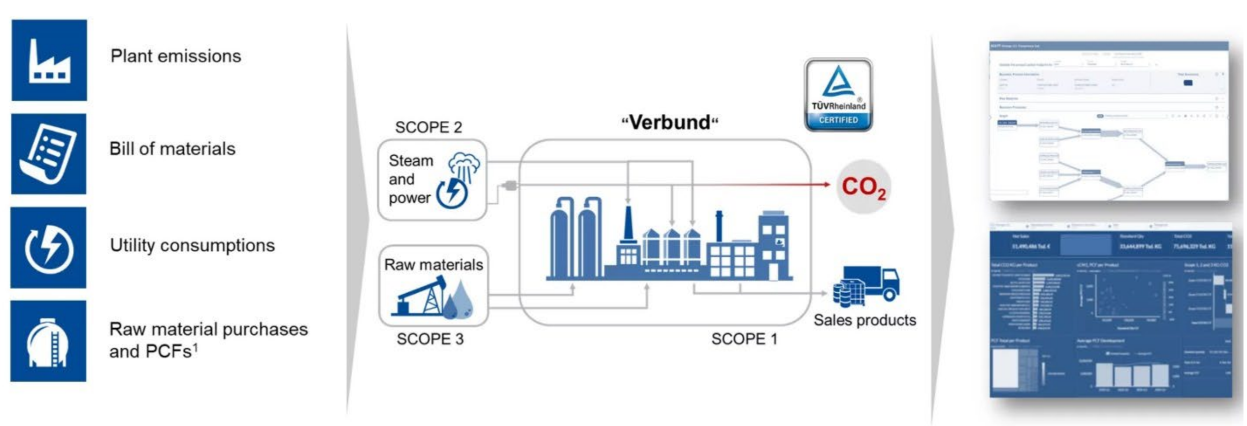
This appendix elaborates on the material in Section 3, arguing that the general principles underlying firms' cost accounting systems can guide the design of an internal PCF allocation system. Conceptually, a cost accounting system can be represented as a mapping from cost line items, comprising cash flows and accruals, to the firm's different sales products and/or services goods (Datar and Rajan, 2019). Cost line items are generally classified as either direct or overhead. As the name suggests, direct costs are immediately attributable to a product and therefore do not require an allocation rule. For instance, the payment made to a supplier for a part that goes exclusively into one sales product is charged directly, i.e., dollar for dollar, to the sales product. In contrast, overhead costs represent expenditures for resources that serve multiple products and therefore require allocation among these products. These allocations are calculated according to an *allocation base* (driver) such as a physical measure (e.g., volume, weight, square footage), time, or an economic measure, e.g., the market prices of the sales products (Kaplan and Anderson, 2004; Datar and Rajan, 2019). For external reporting purposes, companies have considerable discretion in structuring their internal cost accounting systems. Specifically, the inherent jointness of overhead costs makes it impossible in most industries to identify a product's "true cost."

In the context of carbon accounting, the carbon balance of a part (component) that belongs exclusively to one product should also be fully absorbed by that product, akin to the treatment of a direct cost item. As mentioned in connection with transaction T_1 in Section 3, the carbon footprint measure of a part (component) is ideally reported by the part's supplier based on its own carbon footprint measurement system. Otherwise, the buyer of the part must form its own proxy-measure based on secondary, industry-wide data.

A company's Scope 1 and Scope 2 emissions will generally be overhead items that require meaningful allocations among the company's different products. To that end, companies already collect the requisite data on direct process and tailpipe emissions (Scope 1) incurred at specific production steps. Similarly, most companies continuously trace the usage of electricity and heat energy to particular production steps and activities, allowing them to attribute the Scope 2 emissions associated with electricity and heat obtained from external vendors to those production activities. Scope 3 emissions embodied in machinery and equipment can also be attributed to the production activities where the assets are located. For these types of production inputs, the corresponding emission charges require an intertemporal allocation, i.e., a depreciation charge, that reflects the useful life of the asset in question. The emissions accumulated in different production activities are ultimately assigned to the firm's products. This assignment can be the outcome of a multi-step procedure that reflects each product's usage of different production activities.

As one of Europe's largest CO_2 emitters, the chemical company BASF faces increasing demands from customers to calculate carbon footprint measures for its more than 40,000 chemical sales products (Kurtz, 2022). As mentioned in Section 3, the company's product carbon allocation system has been automated through its online tool SCOTT (Strategic CO_2 Transparency Tool). Figure 1 illustrates the flow of intermediate products and their accompanying carbon balances through the firm's network of production sites.

Figure 1: Product carbon footprint accounting at a chemical company (BASF, 2022).



[1] preferably primary data calculated by the respective supplier, if not available secondary data will be used

Globally, BASF operates approximately 700 plants, procures about 20,000 different raw materials and about 10 TWh of energy annually from external vendors. The manufacture of chemicals frequently involves joint production processes, that is, work-in-process batches comprise multiple products moving in tandem through a particular production step. BASF discloses that it relies on ISO-compliant allocation bases to assign the carbon emissions associated with joint production processes to individual products (BASF, 2021). Applicable examples include physical- and revenue-based allocation bases (drivers). These allocation methods are commonly featured in cost accounting textbooks. The use of a particular allocation base for costing purposes, though, does not necessarily mean that the same allocation base is used for carbon accounting purposes. The emissions assigned to products include a periodic depreciation charge for the carbon balances of plant, property and equipment. SCOTT enables management at BASF to decompose a product's overall carbon footprint into its Scope 1-2-3 components, and to trace the accumulated emissions back to production steps that were major emission contributors (Kurtz, 2022).

For most of its raw materials, BASF currently relies on carbon footprint measures provided by external LCA consultants (Kaplan, Ramanna and Reichelstein, 2022). By licensing the SCOTT tool to independent software companies, BASF seeks to standardize the calculation of product carbon footprints among its suppliers in the chemical industry.[37] Similarly, the company has been explicit that it expects both transparency and improvements in the carbon footprints of inputs sourced from outside vendors (BASF, 2021). A comprehensive adoption of internal carbon allocation systems along the supply chain would ensure that cradle-to-gate product carbon footprints are increasingly based on actual company-level emissions data.

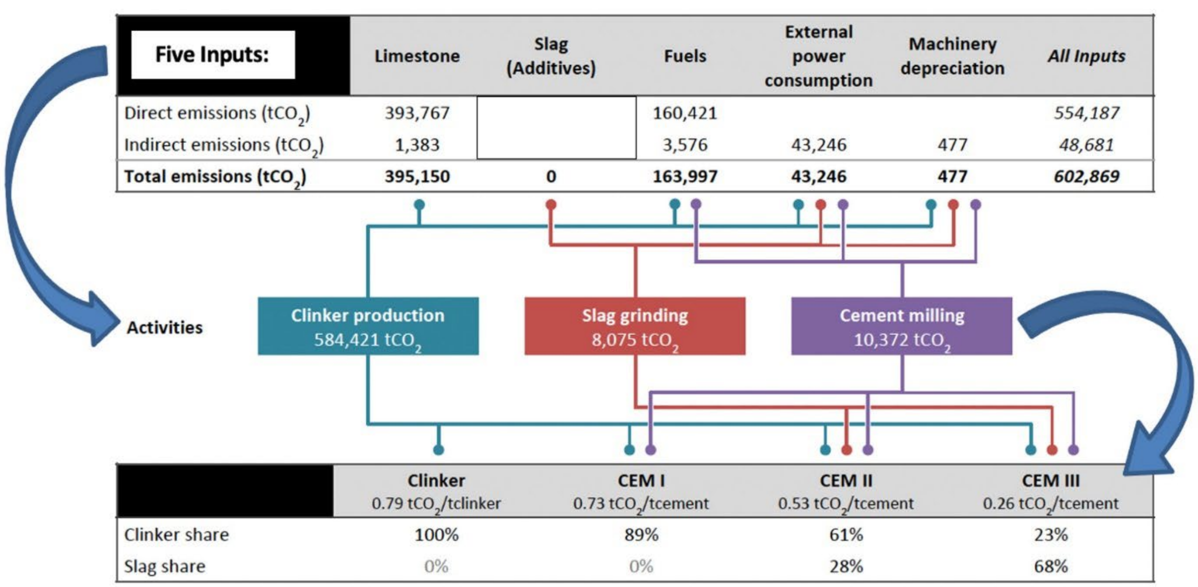
Several recent studies have argued that the principles of activity-based costing can serve as a template for the design of PCF allocation systems in the cement industry (Meier, 2022). The main ingredient in traditional cement is clinker, which is obtained by heating crushed limestone

[37] Licensing this tool allows the company to make its internal carbon accounting system "interoperable" with the company's suppliers (Luers et al., 2022).

in a kiln, a process that releases large quantities of CO_2. Cement producers have increasingly sought to replace clinker with low-carbon additives such as slag or calcined clay. The following description draws on a recent study of PCF accounting for cement products at Heidelberg Materials, formerly Heidelberg Cement (Landaverde et. al, 2023).

The top two rows in Figure 2 show the annual direct (Scope 1) and indirect emissions (Scope 2 and 3) incurred at one of the company's plants. Except for external power consumption, the indirect emission figures were based on third-party estimates that Heidelberg Materials made available for the study. The relatively minor depreciation charge in Figure 2 reflects that the company confined this category to emissions embedded in the steel required to build the cement plant. Further, this carbon balance was divided equally by the number of years the plant is assumed to be operational. Because slag, originating from the manufacture of steel, has traditionally been considered a waste product, the study followed the guidelines of the Energy Accounting and Reporting Standard of the Cement Industry by assigning slag a carbon balance of zero (WBCSD, 2011).

Table 2: Activity-Based Emission Allocations for Cement Products



Source: Landaverde et al. (2022)

The plant in question delivers four products comprising three cement recipes, labeled CEM I-III, and clinker which is subsequently transferred to other cement plants for further processing.

The carbon allocation system proceeds in two steps. First, all direct and indirect emissions are assigned to three manufacturing activities: clinker production, slag grinding and milling, where clinker and slag were mixed and milled into cement powder. In this first step, the emissions associated with the processing of limestone are charged exclusively to clinker production. The company relied on its own records to allocate the emissions embodied in fuels among the two activities clinker production and cement milling.

In the second step, the emissions accumulated in each of the three activities are assigned to the four products. The emissions from clinker production are prorated among clinker and the three cement products in proportion to each product's clinker percentage, ranging from 89% for CEM 1 to 23% for CEM III. Slag grinding emissions are distributed to CEM II and CEM III based on their slag percentages, 28% and 68%, respectively. Finally, milling emissions are spread uniformly across the three cement products since milling time and energy consumption were regarded as independent of the ingredient mix.

The resulting PCF figures, i.e., tons of CO_2 per ton of cementitious material, in Figure 2 demonstrate the potential for reducing the reported carbon content of CEM II and III by substituting slag for clinker in the cement recipe. At the same time, these cementitious materials involve a tradeoff for the manufacturer because, when mixed with water and gravel, CEM II and III require longer waiting times for concrete to harden.

With slag becoming increasingly attractive as a substitute for clinker in the manufacture of cement, the steel industry association has argued that slag is no longer a waste product. Correspondingly, the joint production process that yields steel and slag in fixed proportions should no longer assign zero carbon emissions to slag (Meier, 2022). While the World Steel Association prefers to allocate emissions in proportion to the relative mass of steel and slag produced, the Global Cement and Concrete Association prefers an allocation based on the relative value of steel and slag (World Steel Association, 2014). Such discrepancies entail the potential for significant under-counting of emissions if the two industries were to adopt different allocation methods in calculating the product carbon footprints of steel and cement, respectively. Similar issues arise when multiple natural resources are jointly extracted in a mining operation and the extracted resources are sold to different industries (Canon et al. 2020). Of course, under-counting of emissions will not be an issue in a system where carbon-to-gate product carbon footprints are determined sequentially such that the buyer accepts the carbon balance of the acquired input, e.g., slag, which has been determined according to the supplier's own PCF allocation rules.

In closing, we note that companies regularly revise their cost accounting rules with the goal of obtaining better predictions for the overhead costs that will be incurred when there are changes in either the production technology or the mix of the firm's sales products. Aside from this forecasting purpose, cost accounting also provides a tool for ex-post cost control by enabling managers to attribute cost overruns to specific production steps and/or products. In the context of carbon accounting, properly designed PCF measurement systems may prove similarly useful from an emissions control perspective.

Appendix B: List of Acronyms

BB: Beginning Balance

CE: Carbon Emissions

CEGS: Carbon Emissions in Goods Sold

COGS: Cost of Goods Sold

CO_2: Carbon Dioxide

DE: Direct Emissions

DNE: Direct Net Emissions

DR: Direct Removals

EB: Ending Balance

ETI: Emissions Transferred In

ETO: Emissions Transferred Out

FG: Finished Goods

GHG: Greenhouse Gases

KPI: Key Performance Indicator

MAT: Raw Materials

PCF: Product Carbon Footprint

PPE: Plant, Property and Equipment

References

Aldy, J., Bolton, P., Kacperczyk, M. and Z. Halem (2023) "Behind Schedule: The Corporate Effort to Fulfill Climate Obligations" *Journal of Applied Corporate Finance*. 1-9. https://doi.10.1111/jacf.12560/

BASF (2021) "Product Carbon Footprint Partnerships." https://www.basf.com/global/en/who-we-are/sustainability/we-drive-sustainable-solutions/quantifying-sustainability/product-carbon-footprint/partnerships.html

BASF (2022) "Product Carbon Footprint Methodology" https://www.basf.com/global/en/who-we-are/sustainability/we-drive-sustainable-solutions/quantifying-sustainability/product-carbon-footprint/partnerships.html

Bloomberg Green (2021) "Wall Street's Favorite Climate Solution is Mired in Disagreements." https://www.bloomberg.com/news/features/2021-06-02/carbon-offsets-new-100-billion-market-faces-disputes-over-trading-rules

Bloomberg NEF (2022) "Carbon Offset Prices Could Increase Fifty-fold by 2050". https://about.bnef.com/blog/carbon-offset-prices-could-increasefifty-fold-by-2050/.

Cannon, C., et al. (2020) "The Next Frontier in Carbon Accounting: A Unified Approach for Unlocking Systemic Change." *Rocky Mountain Institute*. https://rmi.org/insight/the-next-frontier-of-carbon-accounting

Cement News (2023) "SBTi Validates Heidelberg Materials' 2030 CO_2 Reduction Targets" https://www.cemnet.com/News/story/174407/sbti-validates-heidelberg-materials-2030-co2-reduction-targets.html

Comello, S., Reichelstein, J. and S. Reichelstein (2023) "Corporate Carbon Reporting: Improving Transparency and Accountability" *One Earth.* https://doi.org/10.1016/j.oneear.2023.06.002

Comello, S., Reichelstein, J. and Reichelstein, S. (2022). "Corporate Carbon Reduction Pledges: An Effective Tool to Mitigate Climate Change?" In *Frontiers in Social Innovation*, Neil Malhotra, ed. (Harvard Business Press). https://doi.org/10.2139/ssrn.3875343

Datar, S., and M. Rajan (2019) "*Horngren's Cost Accounting: A Managerial Emphasis.*" https://www.pearson.com/en-us/subject-catalog/p/horngrens-cost-accounting/P200000005927/9780136713845

Downar, B. , Enstberger, J., Reichelstein, S. and A. Zaklan (2021) "The Impact of Carbon Disclosure Mandates on Emissions and Financial Operating Performance." *Review of Accounting Studies*, *26(3)*, 1137-1175. https://doi.org/10.1007/s11142-021-09611-x

European Commission (2023a) ”Directive on Green Claims.” https://environment.ec.europa.eu/publications/proposal-directive-green-claims_en

European Union (2023b) “Carbon Border Adjustment Mechanism” EU Green Deal. https://taxation-customs.ec.europa.eu/green-taxation-0/carbon-border-adjustment-mechanism_en

Gill, K. (2022) “Understanding the Real Hurdles to Jump Before Reaching Net-zero Emission Goals” *Fortune Magazine*. June 2022. https://fortune.com/2022/06/15/climate-change-carbon-emissions-net-zero-goals/

Glenk, G. (2023) “Toward Decision-Useful Carbon Information“. Working Paper, Mannheim Institute for Sustaianble Energy Studies. https://madoc.bib.uni-mannheim.de/64471/1/230510-Carbon%20Information.pdf

Griffin, P. and E. Sun (2023) “The Conundrum of Scope 3 Emissions for Corporate Reporting” *Accountability in a Sustainable World Quarterly,* Issue 2. 61-72. https://online.fliphtml5.com/jdbmp/ptht/

Fankhauser, S. et al. (2022) “The Meaning of Net Zero and How To Get it Right.” *Nature Climate Change 12(1)*. 15-21. https://doi.org/10.1038/s41558-021-01245-w

Hale, T. et al. (2021) “Assessing the Rapidly Emerging Landscape of Net Zero Targets.” *Climate Policy*, *22(1)*, 18-29. https://doi.org/10.1080/14693062.2021.2013155

Heal, G. (2022) “The Economics of Carbon Accounting and Carbon Offsets.” *NBER Working Paper* 30649. https://www.nber.org/system/files/working_papers/w30649/w30649.pdf

HeidelbergCement AG (2021) “Umwelt-Produktdeklaration. CEM III/B 42,5 N LH/SR. EPD-HCG-20210008-CAA1-DE.“ https://www.heidelbergmaterials.com/de/nachhaltigkeitsbericht

Internal Revenue Service (2022). “Inflation Reduction Act of 2022”. https://www.irs.gov/inflation-reduction-act-of-2022

Joppa, L. et al. (2021) “Microsoft’s Million-Tonne CO_2-Removal Purchase – Lessons for Net Zero.” *Nature*, *597(7878)*, 629-632. https://doi.org/10.1038/d41586-021-02606

Kaplan, R. and R. Cooper (1998) “Cost and Effect: Using Integrated Cost Systems to Drive Profitability and Performance.” *Harvard Business School Press*.

Kaplan, R. and S. Anderson (2004) “Time-Driven Activity-Based Costing”. *Harvard Business Review. https://hbr.org/2004/11/time-driven-activity-based-costing.*

Kaplan, R., and K. Ramanna (2021) “Accounting for Climate Change,” *Harvard Business Review.* 99(6), 120-131. https://www.johnwbyrd.net/wp-content/uploads/2022/04/Accounting-for-Climate-Change.pdf

Kaplan, R., Ramanna, K. and S. Reichelstein (2022) “Measuring Product Carbon Footprints from Cradle to Gate.” https://madoc.bib.uni-mannheim.de/63375

Kaplan, R., Ramanna, K. and S. Reichelstein (2023) “Getting A Clearer View of Your Company’s Carbon Footprint.” *Harvard Business Review (online) https://hbr.org/2023/04/getting-a-clearer-view-of-your-companys-carbon-footprint*

Kaplan, R., Ramanna, K. and M. Roston (2023) “Accounting for Offsets-Establishing the Foundation for Carbon-Trading Markets” Working-Paper 23-050. *Harvard Business School* file:///C:/Users/sterei/Downloads/Karthik%20Ramanna%20-%20Accounting%20for%20carbon%20offsets%20KRR%20Feb%2013%20(1).pdf

Klaassen, L. and C. Stoll (2021) “Harmonizing Corporate Carbon Footprints.” *Nature Communications*, *12(1)*, 1-13. https://doi.org/10.1038/s41467-021-26349-x

Kurtz, J. (2022) “Product Carbon Footprints: Zur Vergleichbarkeit der Produkte die Wir Kaufen?” *Controlling* 34, no. 4 (2022): 44–50. http://dx.doi.org/10.15358/0935-0381-2022-4-44

Landaverde T., Liebmann, P., Meier, R., Reichelstein, S. and Sutherland, M. (2023) “Heidelberg Materials: Assessing Product Carbon Footprints”. *Stanford GSB*, Case Study SM 365. https://www.gsb.stanford.edu/faculty-research/case-studies/heidelberg-materials-assessing-product-carbon-footprints

Luers, A. et al. (2022) “Make Greenhouse-Gas Accounting Reliable-Build Interoperable Systems.” *Nature*, *607(7920)*, 653-656. https://doi.org/10.1038/d41586-022-02033-y

Ma, M. (2022) “Why $100 per ton is the Carbon Removal Industry’s Holy Grail” *Protocol.* https://www.protocol.com/bulletins/carbon-removal-cost-per-ton

Microsoft (2021) “Microsoft Carbon Removal: Lessons from an Early Corporate Carbon Purchase.” https://query.prod.cms.rt.microsoft.com/cms/api/am/binary/RE4MDlc

Meier, R. (2022) “Global Warming Potential of Cement Products.” Mannheim Institute for Sustainable Energy Studies, University of Mannheim, *Working Paper*

OmniCert (2023) “Carbon Footprint und Klimabilanz” https://www.omnicert.de/carbon-footprint-und-klimabilanz

Tollefson, J. (2022) “Climate Pledges from Top Companies Crumble under Scrutiny.” *Nature*. https://doi.org/10.1038/d41586-022-00366-2

World Resources Institute (2004) "*The Greenhouse Gas Protocol: A Corporate Accounting and Reporting Standard*, Revised Edition."
https://ghgprotocol.org/sites/default/files/standards/ghg-protocol-revised.pdf

Security and Exchange Commission (2022) "SEC Proposes Rules to Enhance and Standardize Climate-Related Disclosures for Investors." https://Sec.gov/news/press-release/2022-46

Wagenhofer, A. (2023) "Sustainability Reporting: A Financial Reporting Perspective" *Accounting in Europe,* https://doi.org/10.1080/17449480.2023.2218398

WBCSD (2011). "CO2 and Energy Accounting and Reporting Standard for the Cement Industry: The Cement CO2 and Energy Protocol". https://cement-co2-protocol.org/en/Content/Resources/Downloads/WBCSD_CO2_Protocol_En.pdf.

Wilcox, J., Kolosz, B. and J. Freeman (eds.) (2021) "Carbon Dioxide Removal Primer." https://cdrprimer.org

World Steel Association. (2014). *Methodology for slag LCI calculation.* https://worldsteel.org/steel-topics/life-cycle-thinking/methodology-for-slag-lci-calculation/

Zajonz, D. (2023) "Wann ist "Klimaneutral" wirklich Klimaneutral?" https://www.tagesschau.de/wirtschaft/verbraucher/klimaneutral-werbung-olg-duesseldorf-100.html