Corporate Carbon Accounting: Balance Sheets and Flow Statements

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Abstract

Current corporate disclosures regarding carbon emissions lack generally accepted accounting rules. The carbon accounting system described here takes the rules of historical cost accounting for operating assets as a template for generating Carbon Emissions (CE) statements comprising a balance sheets and a 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 company's annual corporate carbon footprint calculated as the cradle-to-gate carbon footprint of goods sold during the current period. Taken together, balance sheets and flow statements generate key performance indicators of a company's past, current and future performance in the domain of carbon emissions.

JEL classification: M41, M48, Q53, Q54.

1. Introduction

Recent years have witnessed numerous companies around the world issue voluntary "net-zero pledges" regarding their Greenhouse Gas (GHG) 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 effort to decarbonize the global economy, 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 the adoption of a carbon accrual accounting system that mirrors historical cost accounting for operating assets can provide analysts and society at large with comprehensive information about a company's emissions performance over time. In financial accounting, accruals enable the separation of stock from flow variables. In direct analogy, a Carbon Emissions (from here on abbreviated as CE) statement entails a CE balance sheet and a CE flow statement. The latter effectively becomes the equivalent of an income statement in financial reporting. CE statements enable companies to provide systematic and time-consistent reports about their past, current and future carbon emissions. In particular, CE balance sheets allow analysts to gauge whether companies are on track to meet their own voluntary carbon reduction pledges.

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[22] As explained below, the analysis in this paper focuses on carbon dioxide (CO_2) equivalents which account for GHGs other than CO_2 with an appropriate multiplier.

[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). In the U.S., companies like Delta Airlines face litigation over sweeping carbon neutrality claims (Greenfield, 2023).

[4] See, for instance, Tollefson (2022), Fankhauser (2022) and Aldy et al. (2023).

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, including long-term assets as well as inventories. 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.

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.[5] In accordance with this broader corporate social responsibility perspective, the accounting system described in this paper postulates that 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.[6] Provided this approach is increasingly adopted by companies along a supply chain, the resulting cradle-to-gate PCFs measures will be determined in a recursive and informationally decentralized manner. In direct analogy to how product costs are determined along a supply chain, the calculation of PCFs can then rely on local knowledge of the direct emissions *actually incurred* at each stage of the supply chain (Kaplan and Ramanna, 2021).[7]

The accrual accounting system introduced here distinguishes between carbon emission stock and flow variables. The rationale for doing so 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

[5] 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).
[6] The chemical company BASF refers to its PCF measures as cradle-to-gate product carbon footprints (BASF, 2021; Kurtz, 2022). BASF also discloses that its methodology for calculating PCFs is consistent with the guidelines provided by Together for Sustainability (2023), a consortium of companies in the chemical industry.
[7] The E-liability approach of Kaplan and Ramanna (2021) advocates for goods transacted along a supply chain to be accompanied by a measure of the accumulated carbon emissions. The corporate accounting system described in this paper integrates the resulting cradle-to-gate PCFs into CE statements comprising both a balance sheet and a flow statement.

to the emissions embodied in products sold, the accounting system relies on both intertemporal and cross-sectional accruals such that the annual CE flow statement reconciles with the CE balance sheet. Taken together, CE statements enable a comprehensive and time-consistent assessment of a company's carbon emissions performance.[8]

Regarding a company's current corporate carbon footprint, the natural flow measure emerging in our responsibility accounting framework is Carbon Emissions in Goods Sold (CEGS). Like Cost of Goods Sold (COGS) in income statements, CEGS yields the total tons of carbon dioxide obtained as the sum of the individual PCFs multiplied by the current sales quantity of that product. CEGS thus becomes a measure of the current damage that products sold by the firm have contributed to the global climate. This damage represents a loss that decreases owners' equity on the CE balance sheet. At the same time, the ratio of CEGS to COGS becomes a contemporary measure of the average carbon intensity of a company's sales products.[9]

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 that the company has accumulated after some reference date.[10] Cumulative emissions, as opposed to current emissions, are a key performance indicator 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

[8] In the public discussion about climate change, German companies and analysts frequently refer to "Klimabilanzen"(which translates to "climate balance sheets"). Yet, these references generally do not pertain to balance sheets that indeed balance debits and credits, but simply to a list of a company's product related emissions (Omnicert, 2023).
[9] 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).
[10] See Appendix C for a comprehensive list of all acronyms.

removals can do so by providing line-item information by decomposing the cumulative values in those balance sheet accounts into 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 emissions embodied in inventories. The significance of this carbon metric 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.[11]

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 CCFs only comprise direct net emissions. In order for a firm to drive CEGS to zero, both its direct emissions and the indirect emissions acquired from suppliers in its production inputs must go to zero, unless one of these turns carbon negative. In comparison to DNE, the CEGS metric is 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.

Because the carbon 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 (Amran, 2023). 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

[11] The tons of CO_2 recorded on the asset side of the CE balance sheet only provide a lower bound for emissions to be reported in future PCFs because these will also include the firm's actual direct emissions in future periods.

for regulatory compliance such as the determination of carbon import duties tied to a product's assessed PCF. The European Union has decided to impose such import duties by the year 2026 under its Carbon Border Adjustment Mechanism.[12]

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 in order to assess the company's progress on its decarbonization path. We discuss several remaining issues regarding carbon accounting in Section 5. Conclusions are presented in Section 6.

2. Current Carbon Reporting Frameworks

The Greenhouse Gas 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 different GHG emissions to so-called CO_2e, or CO_2 equivalents.[13]

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

[12] 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 European Union's price on carbon emissions (European Union, 2022).
[13] For a recent reference, see Together-for-Sustainability (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 (Tomar, 2023). 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).[14]

It is widely acknowledged that assessing a company's Scope 3 emissions entails enormous data collection challenges. Most companies hire outside consultants that perform a life-cycle analysis, frequently based on input-output tables, for the emissions associated with 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 company and its suppliers will not be fully reflected in the company's reported carbon footprint metrics (Kaplan, Ramanna and Reichelstein, 2023).

[14] 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 value chain 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).[15]

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. 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 acquired production inputs Ideally, these balances are calculated in a recursive manner by the firm's upstream suppliers. Some multinational firms have recently developed internal carbon accounting systems that calculate cradle-to-gate PCFs through a recursive process (BASF 2021, Kurtz, 2022; Meier, 2022). Further, as detailed in Appendix A, industry consortia, like Catena-X for the automotive industry and TfS for the chemical industry, have formulated industry-specific standards ("rulebooks") for the measurement of PCFs (TfS, 2022; Catena-X 2023).[16]

[15] The model analysis in Mahieux et al (2023) suggests that national regulators in different jurisdictions should coordinate the disclosure requirements for direct and indirect emissions.
[16] Guidance for the calculation of PCFs is also provided in the so-called Pathfinder Framework of the World Business Council for Sustainable Development (2023).

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. Ideally, this figure reflects the actual 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 individual 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 accounting system can determine the emissions required for an individual 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 annual Carbon Emissions in Goods Sold (CEGS).

Reliance on primary firm-level data for determining product carbon footprints in a recursive manner along a firm's supply chain is crucial with regard to firms' incentives to reduce CO_2 emissions. Any reduction a firm obtains in its actual direct emissions will be fully reflected in the current PCF metrics. Further, firms will be in a position to exert pressure on their suppliers to reduce the PCF of inputs purchased by the firm. Companies like Microsoft, for instance, have 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 our focus on 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.[17] By their very nature, these assessments must

[17] In contrast to our historical cost perspective, Penman (2023) proposes a carbon accounting system, focused exclusively on Scope 1 emissions, in which assets and liabilities can include forward looking estimates. Companies can capitalize the emission reductions that are anticipated from investments in carbon mitigation. These assets are counterbalanced by corresponding liabilities such that any subsequent variances in the level of actual emission reductions achieved are reconciled in future income statements.

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 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.[18]

3. Accrual Accounting for Carbon Emissions

This section illustrates the 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 initiated a carbon accrual accounting system in a previous period, there will be an opening CE balance sheet with beginning balances, as illustrated in Table 1.

CE in Assets		CE in Liabilities and Equity	
Buildings	BB_{BLD}	BB_{ETI}	**Emissions Transferred In**
Machinery & Equipment	BB_{MAC}	BB_{DE}	**Direct Emissions**
Raw Materials	BB_{MAT}	(BB_{DR})	**Direct Removals**
Work-in Process	BB_{WIP}	BB_{EQ}	**Equity**
Finished Goods	BB_{FG}		

Table 1: **CE Balance Sheet (in tons of CO_2)**

[18] The case study by Lu et al. (2023) suggests that automotive companies may want to take a full value chain perspective focusing on cradle-to-grave emissions of an automobile. As car companies transition to battery electric vehicles, their cradle-to-gate emissions will frequently increase because the manufacture of batteries is still carbon intensive. At the same time, these emission increases are frequently counterbalanced by emission reductions in the use phase of the electric vehicle when compared to vehicles powered by internal combustion engines.

The unit of measurement for all accounts is one ton of CO_2.[19] In direct analogy to a financial balance sheets which maintain the identity:

$$Assets = Liabilities + Equity$$

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

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

We note that the sign of all entries on the CE balance sheet can be either positive or negative, with the exception of Direct Emissions (DE) and Direct Removals (DR), both of which are always positive numbers. As the name suggests, the periodic increment for DR represents 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.[20] Our convention of reporting Direct Removals in a contra liability account, shown with a negative balance on the liability side, is convenient insofar as the left-hand side of the CE balance sheet then 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.

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 the emissions embodied in the firm's operating assets. The company effectively assumes responsibility for 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.

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

[20] As discussed in more detail in Sections 3 and 5 below, the accounting for CO_2 removals, and more for broadly for carbon offsets, is already controversial. It therefore seems prudent to record direct removals in a separate account rather than net these negative emissions against direct emissions.

The firm's direct (Scope 1) emissions and the carbon balances of goods and services acquired from suppliers in any given period are added to BB_{DE} and BB_{ETI}, the beginning balances of the DE and ETI accounts, respectively. In case the company has acquired inputs with negative carbon balances, the balance in the ETI account may not increase from one year to the next.[21] When the firm sells finished goods to customers, it absorbs the loss associated with the emissions embodied in the goods sold in its Equity (EQ) account. The negative balance in EQ will therefore increase from one year to the next unless goods sold have a negative carbon balance which would require direct removal activities by the company in question or by its suppliers.

Companies that seek to give the public a better understanding of the recent history of its liability accounts can do so by reporting the recent annual increments of the accounts ETI, DE, DR and EQ as separate line items on the CE balance sheet. For instance, if EB_{DE}^{2023} represents the cumulative DE balance (accumulated relative to some initiation date) at the end of the year 2023, the CE balance sheet can provide line-item information on the recent annual increments in direct emissions by reporting an entire vector:

$$\left(y_{DE}^{2023}, y_{DE}^{2022}, \ldots . y_{DE}^{20xx}, EB_{DE}^{prior}\right),$$

where y_{DE}^{2023} denotes the firm's direct emissions in the year 2023, while EB_{DE}^{prior} denotes the cumulative direct emissions at the end of the year prior to 20xx. Further, the entries in the above vector sum up to EB_{DE}^{2023}.

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.

[21] Consistent with this approach, Catena-X (2023) and TfS (2023) recommend that inputs with a demonstrated biogenic CO_2 uptake, e.g., biomass, be included with a negative sign. Doing so will have a net-zero effect on the PCF of the final product PCF as the emissions caused by combusting the biomass will be included in the company's direct emissions.

Table 2: TRANSACTIONS TABLEAU

	CE in Assets								=	CE in Liabilities			
Accounts	**PPE**	**MAT**	**WIP_1**	**…**	**WIP_m**	**FG_1**	**…**	**FG_n**		**ETI**	**DE**	**DR**	**EQ**
Beginning Balance	BB_{PPE}	BB_{MAT}	BB_{WIP_1}	…	BB_{WIP_m}	BB_{FG_1}	…	BB_{FG_n}		BB_{ETI}	BB_{DE}	BB_{DR}	BB_{EQ}
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_{MAT}	EB_{WIP_1}	…	EB_{WIP_m}	EB_{FG_1}	…	EB_{FG_n}		EB_{ETI}	EB_{DE}	EB_{DR}	EB_{EQ}

Changes to the 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. To economize on the number of columns in Table 2, the accounts Buildings as well as Machinery and Equipment from Table 1 have been combined into Plant, Property and Equipment (PPE) in Table 2. Thus, $BB_{BLD} + BB_{MAC} = BB_{PPE}$.

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:

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

and

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

Among the seven sample transactions featured in Table 2, transaction T_1 pertains to the purchase of material inputs. If the suppliers of these materials have adopted their own certified carbon accounting system capable of assigning these materials individual PCF measures, the buyer can rely on these figures to debit its own MAT account(s). Otherwise, the buyer will need to estimate the emissions embodied in purchased materials based on secondary industry-level data.[22] 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

[22] In direct communication, the chemical company BASF has indicated that as of late 2022 only a minority of the company's suppliers provided PCF figures based on primary data regarding the actual emissions incurred by the supplier. In order for BASF to include these supplier reported PCF figures in its own carbon footprint calculations, the supplier's PCF measurement system must be certified by BASF (Kaplan, Ramanna and Reichelstein, 2022; TfS, 2023).

no change in liabilities associated the internal transfer of emissions across operating assets. Further, since the total emissions embodied in inventories remains constant, we have:

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

The beginning balance of the PPE account, i.e., BB_{PPE}, represents the current carbon book value, that is, the emissions that were initially capitalized when the long-term assets were acquired, less depreciation charges accumulated in previous periods. In Transaction 3, no additional liabilities are incurred when depreciation charges reduce the book value of the PPE account. 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 are first assigned 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, will generally be based on internal allocations akin to cost accounting rules that assign overhead costs to different products. In the context of carbon accounting, a *PCF measurement system* can be conceptualized as a mapping:

f: (Current DE, Current DR, CE Inputs) → CE Outputs.

Here, *CE Inputs* reflects the indirect emissions embodied in the firm's production inputs. These 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 can be split into annual depreciation charges. For multi-stage production processes, the mapping $f(\cdot)$ will be a composite mapping such that *CE Outputs* reflects the carbon balances of the intermediate products going through the different stages of the production process, and ultimately to finished goods. Appendix A illustrates how well-established product costing rules, such as activity-based costing, joint cost allocation rules and ISO rules, have been adapted to configure the internal carbon allocation systems for companies in the cement, chemicals and automotive industries.

A central role of the PCF measurement system, as represented by the mapping $f(\cdot)$ above, is to assign Scope 1 and Scope 2 emissions, which generally fall into the category of overhead items for multi-product firms, to different sales products. In order to capture the *causal relation* between emissions associated with specific production activities and the extent to which different products require these activities, the allocation rules should reflect the specific configuration of the underlying production processes. The extensive literature on product costing suggests that companies can choose "carbon pools" (the equivalent of overhead cost pools) and "drivers" (allocation bases) that capture the relation between resources consumed and their associated carbon emissions.[23] Similar to the discretion companies have in tailoring their inventory costing rules to the specifics of their own operations, PCF measurement systems will generally be company-specific. In order to be certifiable, the measurement system may also need to be compliant with industry-specific standards such as those articulated by industry associations, e.g., Catena-X (2022) and TfS (2023).[24]

One universal balancing constraint on PCF measurement systems is that in each period the sum of direct emissions and indirect emissions embodied in production inputs, less applicable direct removals, must equal the emissions assigned to WIP and FG inventories. This balancing property was maintained for the sample transactions T_2 and T_3 above, as total debits were in both cases equal to total credits. Similarly, the allocation of the firm's Scope 1 emissions to the different WIP accounts in transaction T_4 is balanced provided:

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

[24] The case study by Landaverde et al. (2023) points to possible inconsistencies and under-counting of emissions when different industry associations 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).

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

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.[25] 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 sufficiently long period of time, say for at least several hundred years.[26]

While the assignment of direct emissions to individual products (WIP accounts) should reflect the causal link between production activities and their associated CO_2 emissions, there will generally be no such causal link for direct removals. This naturally raises the question 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 entries 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 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.[27] Concerns about selective "greenwashing" will be

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

[26] Parts of the literature on carbon dioxide removals insist on "permanent" rather than "durable" removals, requiring that subsequent CO_2 releases will not occur for at least 1,000 years (Microsoft, 2021).

[27] As of 2023, a cost of $100 dollars per ton of CO_2 was widely considered the "holy grail" of carbon removals (Ma, 2022; Frontier 2023). Compliance markets currently 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 required to cover a company's direct emissions.

mitigated by requiring disclosures that disaggregate the reported cradle-to-gate PCFs into their constituent components, i.e., direct emissions, direct removals and carbon emissions embodied in upstream production inputs. Section 5 below discusses several remaining issues in connection with the accounting for carbon offsets.

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 PCF_i of product *i*. Thus, PCF_i can be interpreted as the carbon accounting analogue of a product's (historical) unit cost.

The final transaction T_7 in Table 2 pertains to the sale of finished goods. If the carbon balance of the i-th product in Finished Goods 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 the corresponding "expense" (if u_7 is positive) in its flow statement and subsequently absorbs this "loss" in its equity account (EQ):[28]

$$-u_7 = -CEGS \equiv EB_{EQ} - BB_{EQ},$$

with

[28] The carbon accounting identity $-CEGS \equiv EB_{EQ} - BB_{EQ}$ corresponds to the *clean surplus relation* in financial accounting (Penman, 2013, Chapter 2). This relation is usually represented as $BV_t - BV_{t-1} = I_t - D_t$, where BV_t represents the book value of equity, while I_t and D_t represent income and distributions to shareholders (dividends) in period *t*, respectively. This relation is met in the context of carbon accounting, because there no dividends, income can be equated with the current CE flow, i.e., $-CEGS$, and the equity book values at the beginning and end of the period are given by BB_{EQ} and EB_{EQ}, respectively.

$$CEGS \equiv \sum_{i=1}^{n} PCF_i \cdot s_i = \sum_{i=1}^{n} u_{7i} = u_7.$$

By disaggregating CEGS into different product groups, the CE Flow Statement conveys essential information about a firm's current product related emissions. Table 3 illustrates fully granular line item reporting for each one of the firm's *n* sales products.[29]

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*)
$\boldsymbol{u_7}$	=	**CEGS**

Table 3: CE Flow Statement

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 suppliers. CEGS provides an aggregate measure of a firm's entire "Upstream Scope 3" (including its Scope 1 and 2) emissions.[30] 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. The ratio CEGS/COGS thus tracks the carbon intensity of a firm's sales products. [31]

[29] Firms with a diverse portfolio of product groups, e.g., manufacturers of chemical products, are likely to aggregate homogeneous product groups into single line items on the CE flow statement.

[30] In contrast to the CE Flow Statement illustrated in Table 3, the E-liability flow statement proposed by Kaplan and Ramanna (2021) does not attribute emissions to individual products, nor does their E-liability flow measure reconcile with a balance sheet.

[31] Breuer, Greenstone and Leuz (2023) examine a corporate damage measure, calculated as the ratio between the cost of a company's emissions to society and its operating profit. The cost of

To report "value creation" in the sense of having made a positive contribution to the global climate, the CEGS metric would need to turn negative. That would require direct emissions incurred along the links of a firm's supply network to be more than offset by negative emissions associated with direct removals. In any such year, businesses would then show an improvement in their equity position, EQ, on the CE balance sheet.

As noted above, 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 robust 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, alternative allocation rules result in the same aggregate CEGS figure, provided the assignments and allocations at different steps are always balanced. This balancing requirement in particular requires that current direct emissions, less current direct removals, are fully absorbed by the WIP and FG accounts on the CE balance sheet.[32]

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 sheet account. For instance, $EB_{PPE} = BB_{PPE} - u_3$ and $EB_{DE} = BB_{DE} - u_4$.

As more companies along a supply's chain adopt their own internal PCF measurement system, the resulting cradle-to-gate PCFs 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

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a company' emissions to society is calculated as its periodic Scope 1 emissions multiplied by the so-called social cost of carbon.

[32] The carbon balances of goods sold must be included in CEGS regardless of their sales value. In particular, the carbon balances of a batch of goods must be included in CEGS even if that batch became obsolete and therefore had to be written off financially.

based on actual emissions incurred at each stage, while avoiding double counting of emissions at the product level.[33]

The lack of double counting at the level of individual cradle-to-gate PCFs is readily illustrated in the simplified setting of a hierarchical supply network. Suppose there is a unique firm at the vertex of an inverted tree (network). This firm assembles components from its Tier 1 suppliers in order to produce one unit of a final sales product. The Tier 1 suppliers, in turn, each receive one unit of some intermediate product from the each of the Tier 2 suppliers in the hierarchical network, and so forth up to the final k-th tier of the tree. In producing their one unit of an intermediate product all companies in the network thus assemble components received from their immediate suppliers. In doing so, they incur direct emissions and may also engage in direct removals. We refer to the difference between a firm's current direct emissions and its current direct removals as its current Direct Net Emissions (DNE). Suppose further that the production processes requires no capital goods and therefore there are no intertemporal allocation issue in the form of periodic amortization charges. In such a simplified setting without intertemporal or cross-sectional allocation issues, the cradle-to-gate PCF of each product i, be it an intermediate or the final sales product, is exactly equal to the sum of the current DNE of all firms comprising the nodes of the unique subtree originating at i.

The preceding observation suggests an accounting identity that links the aggregate measures of CEGS to the "real" carbon flows corresponding to direct net emissions. A firm's direct emissions in any given time period may be interpreted as a cash outflow to the atmosphere (a cost is incurred), while direct removals can be interpreted as a cash inflow received from the atmosphere. For the cradle-to-gate carbon footprint accounting system described here, the net cash flows (i.e. the DNEs) are ultimately absorbed by the income measures, i.e., the CEGS figures of all end products sold to consumers. Therefore the aggregate measure of CEGS, when

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[33] Avoiding double-counting of emissions will be crucial in connection with regulations that tie governmental subsidies to a product's assessed PCF. Under the U.S. 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 late 2023, the IRS had yet to specify acceptable methodologies for calculating the carbon content (PCF) of hydrogen.

added up across time periods and all firms selling end products to consumers must be equal to the sum of all direct net emissions when added up across all time periods and firms in the economy. Appendix B introduces the notation required for a formal statement of this identity.

Much like cash flows can be reconciled with income figures over time at the level of an individual firm, the CEGS measure can be reconciled with DNE for an individual firm, if the carbon accounting system considers firms responsible for their own DNE, but not for the emissions embodied in production inputs acquired from suppliers. With an exclusive focus on Scope 1 emissions, the CE balance sheet has no account Emissions Transferred In (ETI). At the same time, the carbon balances of long term assets (PPE) as well as raw materials are identically equal to zero.[34] CEGS in any given period then aligns with current Direct Net Emissions (DNE), subject to adjustments that reflect timing differences in the incurrence of these emissions and the sale of goods. [35] Thus, when added across time periods up to a terminal date, each firm's aggregate DNE will be equal to the sum of its CEGS figures. Observation 2 in Appendix B states this identity formally.

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; Comello et al., 2023). CE balance sheets and flow statements provide an ex-post

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[34] As discussed in Appendix A, the industry consortium Catena-X appears to favor cradle-to-gate PCF measurement systems that do not include the emissions embodied in capital goods. For instance, the carbon balance of electricity procured from a utility would then include the emissions from combusting fuels but not the emissions embodied in constructing the power plant. As a consequence, the carbon balances of long term assets (PPE) on the CE balance sheet are identically equal to zero, while product components and other consumable inputs procured from suppliers have generally positive carbon balances.

[35] Similarly, in the accounting framework proposed by Penman (2023), the measure of income is actual DNE in the current period.

reporting framework that enables society at large to assess a firm's progress on its decarbonization path. The interested public can hold firms accountable for their carbon reduction pledges by comparing self-selected reduction targets to the carbon KPIs that emerge from the reported CE statement.

In today's reporting environment, a company's current direct net emissions remain the most common measure of its corporate carbon footprint. Current DNE emerges from two consecutive CE balance sheets as the difference $EB_{DE} + EB_{DR} - (BB_{DE} + BB_{DR})$. Further, this metric is directly reported on the balance sheet of a particular year if companies disaggregate EB_{DE} and EB_{DR} into the annual increments realized in recent years. Providing line-item information on the recent annual direct emission and direct removal increments gives analysts a clearer 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, current DNE is a crucial metric 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 to the atmosphere (Comello et al. 2023, Heal 2023, Penman 2023). Yet, DNE is arguably an incomplete metric at the level of individual firms because outsourcing carbon-intensive activities will allow a business to claim significant emission reductions without any real operational changes.

In contrast to the DNE metric, CEGS is robust to outsourcing emission-intensive activities, precisely because companies assume responsibility for their 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 DE as well as the carbon balance in acquired assets, i.e., $EB_{PPE} + EB_{MAT}$, to 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 current DNE 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 detectable on the asset side of the CE balance sheet.

Firms seeking to convey information about improvements in their recent CEGS figures can do so by providing line item information for the recent annual additions to Equity. For instance, the ending balance in the carbon equity account for the year 2023, say EB_{EQ}^{2023}, can be decomposed into $\left(CEGS^{2023}, CEGS^{2022}, \dots, CEGS^{20xx}, EB_{EQ}^{prior}\right)$, such that EB_{EQ}^{prior} denotes the ending balance in the carbon equity account for the year prior to 20xx, and the entries in the above vector sum up to EB_{EQ}^{2023}.

To assess whether a company is on a significant carbon reduction trajectory in terms of the CEGS metric, the recent increments in direct emissions and direct removals are informative in combination with the asset side of the CE balance sheet. These emissions, i.e., CE in Assets, will be absorbed in future CEGS figures. In conjunction with the trajectory of the firm's recent direct net emissions, CE in Assets therefore generates a forecast of future CEGS values. The exact nature of this forecast will depend on the relative magnitude of the company's 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.[36]. This target is to be achieved on average across the company's different cement recipes. In the notation of Table 3 above, the constraint of 400 kg of CO_2 per ton of cementitious material can be represented as:

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

[36] See Cement News (2023). For Heidelberg Materials, achievement of this target would correspond to an approximately 50% reduction in the carbon intensity of its cement products relative to 1990 levels.

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 a particular product already has a PCF of 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).[37]

Some technology firms, including Google, Microsoft and Stripe, have articulated CO_2 reduction goals that go beyond simply achieving a net-zero position 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 their legacy emissions in terms of cumulative direct net emissions, the sum of the account balances $EB_{DE} + EB_{DR}$ would need to turn negative at the target date and stay negative thereafter.

For companies that include the indirect emissions acquired through their upstream supply networks in their legacy emissions, “climate neutrality” becomes a more stringent goal. The firm’s balance in its equity account, EB_{EQ}, must then turn positive at the target date and remain positive thereafter. By decomposing EB_{EQ} into its recent annual increments, firms can effectively point to a trajectory that is convergent to that particular net-zero goal.

[37] A 2023 court ruling in Germany affirmed the right of companies to advertise select consumer products as “CO_2 neutral”, even if such claims are partially based on the purchase of carbon offsets. The court emphasized in its ruling that the defendant directed customers to a website that substantiated the company’s zero PCF claims (Zajonz, 2023).

From an incentive perspective, it will be essential that firms can take full credit for any emission reductions they may have achieved in the short run. The carbon 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, frequently provided by outside consultants.

4. Discussion

The accounting framework laid out in the previous sections is suggested directly by the time-tested practice of both 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 businesses providing transportation service.[38] 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 should be included in the count of indirect emissions.[39] On the output side, a firm's direct and indirect emissions associated with R&D activities do not necessarily have to be absorbed in current CEGs, but could instead be capitalized on the CE balance sheet and amortized in future PCFs according to some predetermined amortization schedule.

[38] 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).
[39] Technology firms like Google limit their count of Scope 3 emissions to employee travel and commuting (Comello et al., 2022). In contrast, the Catena-X "Rulebook" suggests that employee commuting be considered outside the boundaries of cradle-to-gate PCFs (Catena-X, 2023).

Recycling. In the transition to a circular economy, recycled products will provide an increasing share of the raw materials used in industrial production. The carbon accounting system described in this paper is centred on the notion that carbon balances, accumulated at various stages of the supply chain, stay with a product until its delivery to the 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 therefore only reflect the emissions that the suppliers of these materials incurred for their delivery to customers.

Carbon Offsets have recently become increasingly important yet also increasingly controversial in the discussion about a timely transition to a net-zero economy. As more firms report measures of their corporate- and product carbon footprint that subtract offsets from gross emissions, two central questions emerge: what types of offsets are eligible for recognition on the company's carbon accounting 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.[40] Yet, the majority of carbon offsets currently traded in the voluntary carbon markets are so-called avoidance offsets. These can be generated, for instance, through investments in renewable energy facilities. The reasoning underlying such offset accounting is that the renewable energy facility enables other parties to avoid the emissions associated with grid-based electricity.

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[40] Direct air capture of CO_2, combined with mineralization in volcanic rock, is considered to be a prime example of a permanent removal (Wilcox, Kolosz, and Freeman, 2021).

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 in the renewable energy facility 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 would have absent the investment in the renewable energy facility (Comello et al., 2022; TfS, 2022).

Avoidance offsets are generally based on counterfactual claims. The party recognizing the offset claims that its intervention resulted in fewer emissions, e.g., a forest was conserved rather than logged. These considerations have led multiple non-governmental organizations like the Science-Based Target Initiative and companies like Microsoft and Stripe not to recognize avoidance offsets in the calculation of PCFs and CCFs (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).[41] 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 (Smith, 2021). For carbon removals that are not necessarily durable and may suffer a partial reversal within a ”short” period of time, companies might nonetheless recognize the removal activity, provided there is a commitment mechanism in place ensuring that any reversal would be reflected in subsequent CE statements . Specifically, there would have to be an assurance that the status of past removal activities is regularly monitored and verified so that any reversal that may have occurred prior to the stated duration period will be added back to the company’s direct net emissions.

[41] Kaplan, Ramanna and Roston (2023) suggest that carbon removals should be allowed to offset a company’s gross emissions only if the GHG has been removed from the atmosphere and indefinitely sequestered.

Regarding the accounting for carbon removals that are eligible for recognition, a common issue will be that there is no causal link between the CO_2 removal and the production and delivery of the firm's sales products. The absence of such causal links provides justification for giving companies discretion in allocating the tons of CO_2 removed from the atmosphere among their 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. A less discretionary accounting treatment would specify a proportional adjustment of the direct emissions emanating from the company's different operational facilities. The proportional adjustment factor could be given by the overall ratio of current direct net emissions to direct emissions[42].

It seems plausible that the incentives to acquire costly carbon removal credits will be considerably stronger if companies have discretion in applying any acquired carbon credits to targeted product groups with a higher carbon elasticity of demand. Conversely, companies might be more reluctant to acquire carbon removals if these are netted in a lump-sum fashion against CEGS in the annual CE flow statement.

Consolidation. Companies with multiple business segments can prepare consolidated CE statements on the basis of individual segment-specific CE statements. Since all transactions are accounted for "at cost", the asset side of the consolidated CE balance sheet is obtained by summing up the carbon balances of the operating assets of the individual segments. However, the consolidated CEGS figure is generally less than the sum of the individual CEGS figures, as the emissions associated with any intracompany sales must be eliminated from the aggregate CEGS figure. The same adjustment is made to the accounts Emissions Transferred In (ETI) and Equity

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[42] 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*.

(EQ) on the consolidated CE balance sheet. In contrast, the ending balances for Direct Emissions (DE) and Direct Removals (DR) on the consolidated balance sheet are fully additive across the individual business segments.

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 calculate their own PCF figures based on primary data, corporate buyers can still rely on PCF estimates based on secondary data that reflect industry-wide averages.[43]

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.[44] It would be understood that these figures represent 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.

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[43] The guidelines provided by Catena-X and TfS for the automotive and chemical industries, respectively, encourage companies in these industries to prioritize primary data in the calculation of PCFs, while relying on secondary data proxy measures for those inputs where the suppliers have not yet developed and obtained certification for their own PCF measurement systems.

[44] The equity account EQ could effectively serve as a "plug variable" in equating CE in Assets and CE in Liabilities on the initial balance sheet.

5. Concluding Remarks

Businesses across a wide range of industries, spanning traditional manufacturing, services and technology, increasingly 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 credibly convey 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, including commonly accepted principles for inventory costing, can serve as a conceptual template for transparent and comprehensive corporate carbon reporting. These general principles can be supplemented with more specific standards regarding the accounting for carbon removals and the architecture of PCF measurement systems for specific industries.

CE statements identify Carbon Emissions in Goods Sold (CEGS) as the central measure of a firm's current corporate carbon footprint. CEGS summarizes the current damage that 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, the trajectories of recent direct emissions, direct removals, CEGS as well as the emissions embodied in operating assets are indicators of a firm's past and future performance in the domain of carbon emissions.

The cost of adopting a carbon accounting system that enables the preparation of CE statements should prove relatively modest, particularly for firms that have already implemented their own PCF measurement systems. Because the preparation of CE balance sheets and flow statements 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 major conceptual barriers in certifying that a CE 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 in several industries established cost accounting principles have been applied in the design of internal PCF measurement systems. Conceptually, a cost accounting system can be represented as a mapping from cost line items, comprising cash outflows and accruals, to the firm's different sales products and/or services goods (Datar and Rajan, 2019). Individual cost line items are categorized 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 determined according to an *allocation base* (driver) such as a physical measure (e.g., volume, weight, square footage), time, or an economic measure, e.g., 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. In most industries, the inherent jointness of overhead costs makes it impossible to obtain a canonical measure of 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 argued 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 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 "carbon pools" are ultimately assigned to the firm's products. This assignment can be the outcome of a multi-step procedure that reflects a product's usage of different production activities. Companies seeking transparency for their reported PCFs can disclose the architectural blueprint of their PCF measurement system at different production sites and obtain certification for having their PCFs calculated in accordance with the disclosed blueprint.

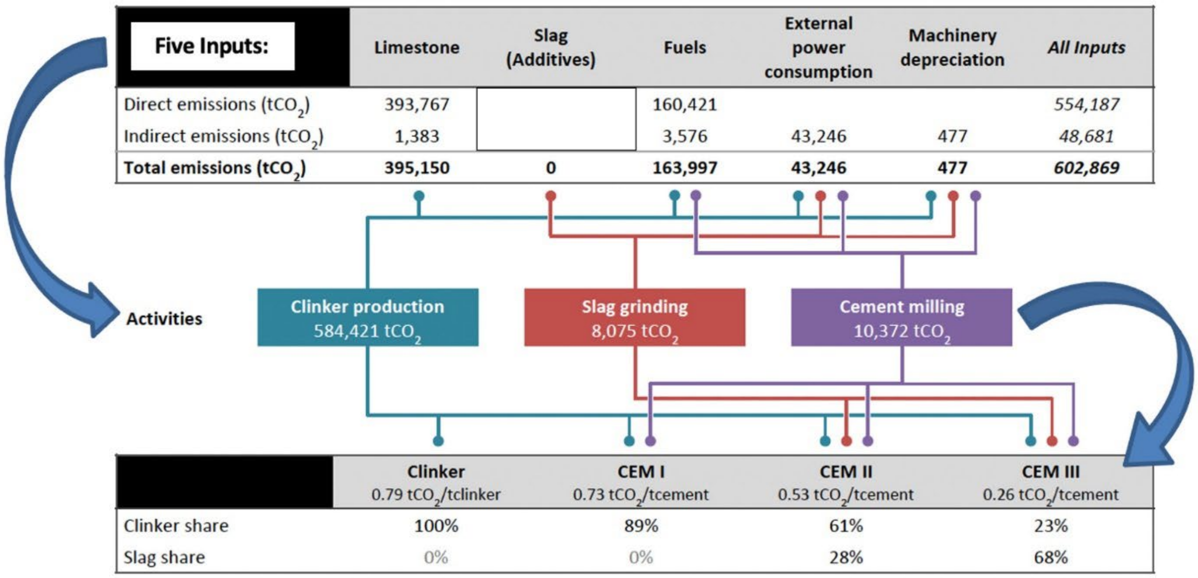
For the **cement industry**, recent studies have argued that the principles of activity-based costing can be adapted for the design of PCF measurement systems.[45] The main ingredient in traditional cement is clinker, which is obtained by heating crushed limestone in a kiln, a process that releases large 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 calculations for cement products at Heidelberg Materials, formerly HeidelbergCement (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. As one might expect for a cement manufacturer, Scope 1 and 2 emissions dominate all other upstream Scope 3 emissions. Except for external power consumption, the indirect emission figures were based on third-party estimates. The relatively minor depreciation charge in Figure 2 reflects that the company confined this category to emissions embedded in the plant 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

[45] See HeidelbergCement AG (2021), Meier (2022) and Landaverde et al. (2023).

considered a waste product, the calculations shown in Figure 1 followed the guidelines of the Energy Accounting and Reporting Standard for the Cement Industry by assigning slag a carbon balance of zero (WBCSD, 2011).

Figure 1: Activity-Based Emission Allocations for Cement Products



Source: Landaverde et al. (2023)

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 are 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.

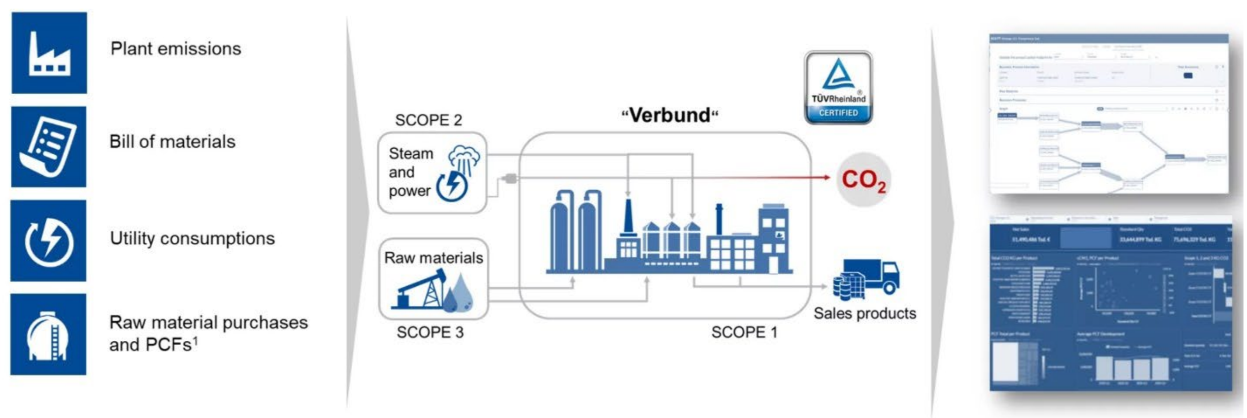
With slag becoming increasingly attractive as a substitute for clinker in the manufacture of cement, the steel industry association has argued that slag is no longer a waste product. Correspondingly, the joint production process that yields steel and slag in fixed proportions should no longer assign 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 (World Steel Association, 2014), the Global Cement and Concrete Association prefers an allocation based on the relative value of steel and slag.[46] The guidelines issued by the industry associations Catena-X (2023, page 16) and TfS (2023, Chapter 5) speak to this dispute as they disallow allocations based on the relative mass of the two products whenever the value of steel exceeds that of slag by a factor larger than five.

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). Globally, BASF operates approximately 700 plants, procures about 20,000 different raw materials and approximately 10 TWh of energy annually from external

[46] Similar issues arise when multiple minerals and metals are jointly extracted in a mining operation and the extracted materials are sold to different industries (Canon et al. 2020). In the context of jointly produced palm oil and palm meal, Sunar and Plambeck (2016) demonstrate the incentive and welfare implications of alternative allocation bases for assigning emissions to individual products.

vendors. Figure 2 illustrates the flow of intermediate products and their accompanying carbon balances through the firm's network of production sites.

Figure 2: Product carbon footprint accounting at a chemical company



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

Source: BASF (2022)

The manufacture of chemicals frequently involves joint production processes, that is, work-in-process batches comprise multiple products moving in tandem through particular production steps. BASF discloses that it relies on standard allocation bases to assign the carbon emissions associated with joint production processes to individual products (BASF, 2021).[47] Applicable examples include both physical- and revenue-based allocation bases (drivers). While these allocation methods are commonly featured in cost accounting textbooks, the use of a particular method for costing purposes does not necessarily mean that the same allocation method is used for carbon accounting purposes.

As mentioned in Section 3, the company's PCF measurement system has been automated through its online tool SCOTT (Strategic CO_2 Transparency Tool). SCOTT enables management at

[47] BASF is a founding member of the Together-for-Sustainability consortium (TfS, 2022). Its guidelines are fairly specific on how to allocate the emissions for joint production processes commonly encountered in the chemical industry, e.g., steam cracker processes and Chlorine-Alkali-Electrolysis.

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 PCFs for its network of suppliers, and more broadly the chemical industry.[48] The company has been explicit that going forward it expects greater transparency and reliability in the reported PCFs of inputs sourced from vendors (BASF, 2021).

The Catena-X industry consortium has formulated standards for PCF calculations for automotive OEMs and their suppliers. The overall objective of Catena-X is to foster consistent cradle-to-gate PCF calculations that are increasingly based on primary data.[49] These data are then to be shared selectively within the network for benchmarking purposes.

The Catena-X Rulebook speaks to both the boundaries of emissions to be included in PCFs and to specific measurement issues. Figure 3 illustrates the boundaries, i.e., the categories of emissions to be recognized. The Rulebook is explicit in the inclusion of emissions associated with the disposal of production waste and those associated with the packaging of vehicle parts and components. In connection with transportation activities, the Rulebook advocates for a general well-to-wheel approach and also provides guidance on which parties are to be charged for emissions associated with shipping parts within a supply network. In contrast to the general

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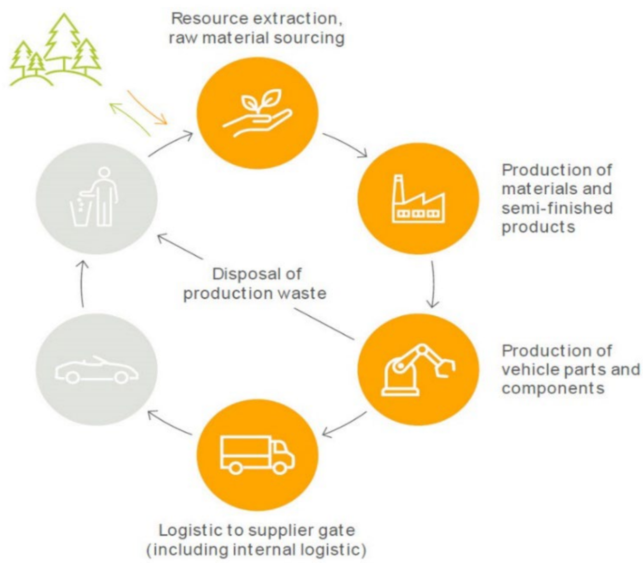
[48] By licensing this tool, the company seeks to make its internal carbon accounting system "interoperable" with the company's suppliers (Luers et al., 2022).

[49] "*Product carbon footprint and life cycle assessment standards and methods exist….. However, these standards and methods are not sufficiently prescriptive and thus leave room for interpretation…. Consequently, product carbon footprints reported from different companies do not follow one consistent approach and comparability is limited. In addition, the current application of well-established methods is mostly based on industry average data. Hence, the status-quo emissions are not specific to a supply chain and deviations between different supply chains remain unrecognized. For the automotive industry, this constitutes a major obstacle to reaching emissions reduction goals. Hence, the automotive industry is in great need of consistent product-specific GHG emissions reporting with comparability across the industry*" (Catena-X, 2023, page 8).

Scope 3 approach taken by many companies, the emissions associated with employee commuting are not to be included in cradle-to-gate measure (Catena-X, 2023).

Figure 3: System Boundaries for Catena-X PCF



Source: Catena-X 2023

Regarding the assignment of Scope 1 and 2 emissions, the Rulebook emphasizes that allocations are to be avoided whenever possible. This prescription is reminiscent of the general observation in cost accounting that through sufficiently granular monitoring of resources consumed in individual production activities companies can shift items from the category of overhead costs to directly traceable costs. There is a general presumption that the carbon balance of identifiable parts that go directly into a product will be included at their reported face value. In settings where the allocation of Scope 1 and 2 emissions is unavoidable, the Rulebook gives general priority to allocation bases tied to physical measures (e.g., mass, volume, energy). Consistent with the TfS (2022) guidelines, physical measures are to be replaced by value-based measure, if there is a sufficiently wide range in the values of the end-products. This is to prevent opportunism in having by-products effectively cross-subsidize the PCF of higher valued products.

To account for the Scope 2 emissions in connection with electricity and heat generation supplied by outside vendors, the Rulebook specifies a hierarchy of measurement approaches. Ideally, the external energy supplier has its own emission tracking system in which case the corresponding emissions associated can be determined directly based on primary data. Absent such a tracking system, the carbon balance balances for electricity and heat consumed are to rely on proxy measures tied to the supplier's overall energy mix in a particular region or the entire regional grid.

Anticipating that for the foreseeable future most PCF calculations in the automotive industry must partially rely on secondary data, Catena-X also recommends the disclosure of a primary data share indicator that captures the percentage of a product's total PCF derived from primary data inputs.

In closing this section, we note that neither Catena-X (2023) nor TfS (2023) envision that PCF measures include the carbon emissions embodied in long-term assets, such as plant property and equipment. Instead, the boundaries for PCF measures are drawn so that only the "variable emissions" embodied in consumable inputs (parts, raw materials and energy) are included. The reason for drawing narrower boundaries presumably is that otherwise companies would need to reach further up their supply chains in calculating comprehensive cradle-to-gate PCFs. While pragmatic, such an approach may also result in material distortions. Consider, for instance, the example of a cement company that reduces the carbon content of its cement products by substituting calcined clays for clinker. By omitting an amortized share of the emissions required in constructing the calcination plant required for processing the clay, the company would overstate the emission savings associated with the use of that substitute material.[50]

[50] Similar reasoning points to including the emissions required in manufacturing lithium-ion batteries when assessing the emission reductions associated with electric vehicles in comparison to vehicles powered by an internal combustion engine (Lu et al., 2022).

Appendix B

This appendix states two identities that link the aggregate Carbon Emissions in Goods Sold (CEGS) in an economy to the aggregate Direct Net Emissions (DNE). Consistent with the accounting rules described in Section 3 above, the first of these identities presumes that companies calculate their CEGS on the basis of cradle-to-gate PCFs that include the emissions incurred by upstream suppliers. In contrast, the second identity presumes direct emissions accounting, that is, PCFs only reflect a company's direct emissions, net of any direct removals.

We consider an economy consisting of producers and consumers. The set of companies in this economy is denoted by N. For simplicity, it is assumed that this set be partitioned into N^+ and N^- such that companies in N^- are producers of intermediate products, that is, they sell their goods and services exclusively to other producers, but not to consumers, i.e., the end users of goods and services. In contrast, companies in N^+ acquire intermediate products from companies in N^- and sell their goods and services to end-users.[51] The economy opens at date $t = 0$ and concludes at a terminal date at $t = T$. The direct net emissions and carbon emissions in goods sold of firm i in period t are denoted by DNE_{it} and $CEGS_{it}$, respectively.

Observation 1: *Suppose at $t = 0$ the companies in N have no operating assets and therefore the beginning balances of all assets on the CE balance sheet are zero. Suppose the same condition holds at the terminal date $t = T$. With cradle-to-gate PCF accounting, the following identity holds:*

$$\sum_{t=1}^{T} \sum_{i \in N^+} CEGS_{it} = \sum_{t=1}^{T} \sum_{i \in N} DNE_{it}.$$

The preceding identity relies on the balancing property that all direct net emissions as well any acquired indirect emissions ultimately flow through to a firm's CEGS. Further, by construction, the carbon emissions in goods sold for all producers of intermediate goods are ultimately absorbed by the firms in N^+, i.e., the producers of consumer products.

[51] Consumer goods may be durable and their use may result in further carbon emissions.

When companies adopt a system of direct carbon accounting, the identity in Observation 1 holds at the level of each individual company. By definition, the direct emissions emanating from other companies do not impact the firm's own measure of CEGS and the carbon balances of long-term assets and acquired materials are identically equal to zero.

Observation 2*: Suppose at dates $t = 0$ and $t = T$ company i has no WIP or FG inventories. With direct carbon accounting, the following identity holds:*

$$\sum_{t=1}^{T} CEGS_{it} = \sum_{t=1}^{T} DNE_{it}.$$

Appendix C

Glossary of Acronyms

BB: Beginning Balance

BLD: Buildings

CCF: Corporate Carbon Footprint

CE: Carbon Emissions

CEGS: Carbon Emissions in Goods Sold

COGS: Cost of Goods Sold

CO_2: Carbon Dioxide

CO_2e: Carbon Dioxide Equivalent

DE: Direct Emissions

DNE: Direct Net Emissions

DR: Direct Removals

EB: Ending Balance

EQ: Equity

ETI: Emissions Transferred In

FG: Finished Goods

GHG: Greenhouse Gases

IPCC: Intergovernmental Panel on Climate Change

KPI: Key Performance Indicator

MAC: Machinery and Equipment

MAT: Raw Materials

PCF: Product Carbon Footprint

PPE: Plant, Property and Equipment

WIP: Work-in-Process

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