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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 transactional 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 sheet 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.

Keywords Net-zero pledges · Carbon emissions · Carbon accounting · Carbon reporting

JEL classification M41 · M48 · Q53 · Q54

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1 Introduction

Recent years have witnessed numerous companies around the world issue voluntary net-zero pledges regarding their Greenhouse Gas (GHG) emissions.[1] 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, companies increasingly advertise select products as being already "carbon neutral."[2] 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.[3]

This article argues that the adoption of a transactional carbon 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 (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.

In contrast to financial reporting, the asset side of the CE balance sheet does not report monetary 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.[4] In accordance with this broader corporate social responsibility perspective, the accounting system described here postulates that product carbon footprints (PCFs), that is, tons of carbon dioxide per unit of the product, encompass

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

[2] 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 2023b). In the United States, companies like Delta Airlines face litigation over sweeping carbon neutrality claims (Greenfield 2023).

[3] See, for instance, Tollefson (2022), Fankhauser et al. (2021), and Aldy et al. (2023).

[4] 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).

all emissions from a product's cradle(s) to the company's gates.[5] Provided this approach is increasingly adopted by companies along a supply chain, the resulting cradle-to-gate PCF 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).[6]

The transactional accrual accounting system introduced here distinguishes between 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 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.[7]

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. Without significant negative emissions in the form of carbon removals, CEGS will be a positive number that provides a measure of the damage that products currently sold by the firm have contributed to the global climate. At the close of the accounting cycle, this damage measure is added to owners' equity on the CE balance sheet. At the same time, the ratio of CEGS to COGS becomes a measure of the current average carbon intensity of a company's sales products.[8]

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.[9]

[5] The chemical company BASF refers to its PCF measures as cradle-to-gate product carbon footprints (BASF 2022; 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.

[6] 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 carbon accounting system described here integrates the resulting cradle-to-gate PCFs into CE statements comprising both a balance sheet and a flow statement.

[7] 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).

[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. 2021).

[9] See Appendix C for a comprehensive list of all acronyms.

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 2021; Pichai 2020). Companies seeking to highlight the trajectory of their recent direct emissions and removals can do so by providing line-item information by breaking down 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, for example, 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 of on assets the CE balance sheet generates a lower bound for the emissions that the company will report in connection with its future product sales.[10]

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 (CCFs) only comprise direct net emissions. For a firm to drive CEGS to zero, both its direct emissions and the indirect emissions acquired from suppliers must go to zero, unless one of these emission sources turns 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, for example, divesting itself of in-house power generation.

Because the transactional carbon accounting system described here builds directly on the principles of historical cost accounting, it should be relatively straightforward to adapt existing accounting enterprise software to keep the books for carbon accounting (Sessar 2023; Distler et al. 2024). Further, it should take only limited 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 tied to a product's assessed PCF. The European Union, in particular, has decided to impose such import duties 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. Section 3 formally introduces a double-entry accounting system for CO_2 emissions, resulting in CE balance sheets and CE flow statements.

[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 reported in future PCFs because these will also include the firm's actual direct emissions in future periods.

[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 European Union's charge on carbon emissions (European Commission 2023a).

Section 4 takes the perspective of an analyst examining a company's CE statement to assess the company's progress on its decarbonization path. Section 5 discusses several remaining issues regarding carbon accounting, and Section 6 concludes.

2 Current carbon reporting frameworks

The Greenhouse Gas Protocol has been the common reference framework for reporting 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_2 equivalents, frequently abbreviated as CO_2e.[12]

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

Many jurisdictions around the world, including the United States and Europe, require major CO_2 emitters to report their annual direct (Scope 1) emissions 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 et al. (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).[13]

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,

[12] For a recent reference, see TfS (2024).

[13] Bolton and Kacperczyk (2021), 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.

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, reductions in actual emissions achieved by a company and its suppliers will typically not be reflected in the company's reported carbon footprint metrics (Kaplan et al. 2023a).

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, for example, kerosene versus sustainable aviation fuels.

The experience companies have in tailoring the design of costing systems to their internal operations 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 2022; Kurtz 2022; Meier 2022). Further, as detailed in Appendix A, industry consortia, like Catena-X for the automotive industry and Together for Sustainability for the chemical industry, have formulated industry-specific standards ("rulebooks") for the measurement of PCFs (TfS 2024; Catena-X 2023).[14]

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, that is, 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 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

[14] Guidance for the calculation of PCFs is also provided in the so-called Pathfinder Framework of the World Business Council for Sustainable Development (2023).

emissions will be fully reflected in the current PCF metrics. Further, firms will be in a position to pressure 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).

The adoption of a system that measures upstream Scope 3 emissions in a recursive and decentralized manner in no way prevents companies from issuing separate estimates for the probable emissions associated with the future use of their products.[15] 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 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.[16]

Regarding mandatory carbon reporting, the Security and Exchange Commission in the U.S. adopted in early 2024 a requirement for most publicly listed companies to disclose their Scope 1 and Scope 2 carbon emissions in their annual reports (Security and Exchange Commission 2024). Going further, the European Sustainability Reporting Standards, as adopted by the EU Commission, mandate the reporting of Scope 1–3 emissions for 'public interest entities' based in Europe (European Commission 2023c). The emission figures emerging from the carbon accounting system described in this paper should prove useful for firms having to comply with recent disclosure mandates. Further, these emission figures should prove increasingly reliable as they reflect a growing share of primary data on emissions actually incurred.[17]

3 Accrual accounting for carbon emissions

This section illustrates the bookkeeping underlying CE statements through a sequence of sample transactions that a business would undertake as part of its normal operating cycle. The illustration is applicable for both manufacturing and service businesses. Assuming the company has adopted such an accounting system in a previous period, there will be an opening CE balance sheet with beginning balances, as illustrated in Table 1.

[15] In contrast to our historical cost perspective, Penman (2024) proposes a carbon accounting system, focused exclusively on Scope 1 emissions, in which assets and liabilities 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.

[16] The case study by Lu et al. (2022) suggests that automotive companies may want to take a full value chain perspective focusing on cradle-to-grave emissions of an automobile. As these 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 vehicles when compared to vehicles powered by internal combustion engines.

[17] The model analysis in Mahieux et al. (2023) points to the need for national regulators in different jurisdictions to coordinate the disclosure requirements for direct and indirect emissions.

Table 1 CE Balance Sheet (in tons of CO_2)

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}		

The unit of measurement for all accounts is one ton of CO_2.[18] 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:

$$CE \text{ in } Assets = CE \text{ in } Liabilities \text{ and } Equity.$$

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. 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 accumulated direct (Scope 1) emissions or those that have been incurred by the firm's upstream suppliers.

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 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.[19] 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 become part of the firm's emissions in goods sold in future periods.

[18] 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.

[19] As discussed in more detail below in Sects. 3 and 5, the accounting for CO_2 removals, and more broadly for carbon offsets, is becoming controversial. This suggests to record direct removals in a separate account rather than net 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.[20] 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 their 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 Fig. 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 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, ...,FG_n). Reconciling these with the notation in Table 1, it follows that:

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

and

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

[20] Consistent with this approach, Catena-X (2023) and TfS (2024) 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 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}

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 their 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.[21] 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 with 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, that is, BB_{PPE}, represents the current CO_2 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

[21] 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. 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 et al. 2022; TfS 2024).

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:

$$f : (\textit{Current DE}, \textit{Current DR}, \textit{CE Inputs}) \rightarrow \textit{CE Outputs}.$$

Here *CE Inputs* reflects the indirect emissions embodied in the firm's production inputs. These generally comprise consumable goods, like components of 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 $f(\bullet)$ will be a composite mapping such that *CE Outputs* reflects the carbon balances of the intermediate products going through the different stages of production 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 $f(\bullet)$ above, is to assign "overhead emissions" to different sales products. In many industries, Scope 1 and 2 emissions are overhead items, as they cannot be traced directly to individual 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 adopted 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.[22] Similar to the discretion companies have in tailoring their inventory costing rules to the specifics of their own operations, PCF measurement systems should generally be company-specific. However, to become certifiable, the company-specific measurement systems may also need to comply with industry-specific standards, such as those articulated by industry associations, for example, Catena-X (2023) and TfS (2024).[23]

[22] See, for instance, Datar and Rajan (2020), Kaplan and Cooper (1998), and Kaplan and Anderson (2004).

[23] 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 byproduct of steel making. The specific rules adopted for calculating the PCF of slag determine whether this byproduct qualifies as a low-carbon supplementary material for Portland cement (World Steel Association 2014).

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:

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

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.[24] 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, for example, 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, say for at least several hundred years.[25]

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 have discretion 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 high-powered incentives for firms to acquire carbon removals in the first place.[26] Concerns about selective greenwashing will be mitigated by requiring disclosures that disaggregate the reported cradle-to-gate PCFs into their constituent components, that is, 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.

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

[25] 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).

[26] 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.

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)[27]:

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

with

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

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.[28]

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.[29] In analogy to Cost of Goods Sold (COGS) in income statements, CEGS is a cost measure of the damage that products sold by the firm in

[27] 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 for CE statements because there no dividends, income can be equated with $-CEGS$, and finally BB_{EQ} and EB_{EQ} represent the book value of equity at the beginning and end of the period, respectively.

[28] Firms with diverse portfolios 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.

[29] 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.

Table 3 CE Flow Statement

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**

the current period have contributed to the global climate. The ratio CEGS/COGS thus tracks the carbon intensity of a firm's sales products.[30]

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. Finally, a company reporting a value of CEGS = 0 would have justification for the claim to have achieved carbon neutrality, and thereby a corporate carbon footprint (CCF) of zero, in the current period.

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 COGS 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 requires that current direct emissions, less current direct removals, be fully absorbed by the WIP and FG accounts on the CE balance sheet.[31]

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 $EB_{DE} = BB_{DE} - u_4$.

[30] Greenstone et al. (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 a company' emissions to society is calculated as its periodic Scope 1 emissions multiplied by the so-called social cost of carbon.

[31] 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 for financial accounting purposes.

As more companies along a supply 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 based on actual emissions incurred at each stage while avoiding double counting of emissions at the product level.[32]

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 to produce one unit of a final sales product. The Tier 1 suppliers, in turn, each receive one unit of some intermediate product from 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 require no capital goods and therefore there are no intertemporal allocation issues 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 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 (the DNEs) are ultimately absorbed by the income measures, that is, the CEGS figures of all end products sold to consumers. Therefore the aggregate measure of CEGS, when added up across 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 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

[32] 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 (Internal Revenue Service 2022), for instance, the magnitude of the production tax credit available for "clean" hydrogen is based on the product's assessed carbon content.

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 both long term assets (PPE) as well as raw materials (MAT) are identically equal to zero.[33] 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.[34] 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 et al. 2021; Tollefson 2022; Comello et al. 2023). CE balance sheets and flow statements provide a reporting framework that enables society at large to assess a firm's progress on its decarbonization path. In particular, firms can be held accountable for their carbon reduction pledges when self-selected reduction targets are compared to actual results reported in CE statements.

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 timeframe.

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 2022, Penman 2024). 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.

[33] 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 those 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.

[34] Similarly, in the accounting framework proposed by Penman (2024), the measure of income always reduces to actual DNE in the current period.

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 remove any CO_2 from the atmosphere. An emissions trajectory for which CEGS goes to zero then also requires both current DE as well as the carbon balance in acquired assets, that is, $EB_{PPE} + EB_{MAT}$, 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 $\left(CEGS^{2023}, CEGS^{2022}, \ldots, CEGS^{20xx}, EB_{EQ}^{prior}\right)$, 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, recent increments in direct emissions and direct removals are informative in combination with the asset side of the CE balance sheet. The carbon emissions embodied 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 versus indirect emissions and the turnover rate of different operating assets.

In addition to long-term carbon reduction goals, such as "net-net zero by 2050," some companies have set interim CO_2 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.[35] 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:

$$\frac{CEGS}{\sum_{i=1}^{n} s_i} = \frac{\sum_{i=1}^{n} PCF_i \bullet s_i}{\sum_{i=1}^{n} s_i} \leq 400 \frac{kg\ CO_2}{t\ cement},$$

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

Well ahead of the 2050 target date, consumer-oriented companies like Shell, Nestlé and Total have increasingly begun to market select products as "carbon neutral" (Bloomberg Green 2021). The accounting framework described here enables

[35] See CemNet (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.

firms to support such claims with additional disclosures. Specifically, any claim that a particular product has already achieved a PCF of zero will be substantiated by reporting the constituent parts of a PCF: 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 Commission 2023b).[36]

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 toward 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 consistent with the stated goal.

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 here 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 emitted by one of the firm's suppliers will be reflected concurrently in 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 rather than on actual measurements.

5 Discussion

The transactional accounting system 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 Sect. 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 services.[37] Regardless of whether the firm's sales products are tangible, any emissions

[36] 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 claims (Zajonz 2023).

[37] 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).

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.[38] On the output side, a firm's direct and indirect emissions associated with R&D 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.

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 here is centered 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 are recycled. 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 recycled, should therefore only reflect the emissions that the suppliers of these materials incurred for their delivery to customers.

Carbon Offsets have become increasingly important, yet also 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 Sect. 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.[39] 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.

The responsibility accounting framework described here 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 2024).

[38] 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).

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

Avoidance offsets are generally based on counterfactual claims. The party recognizing the offset claims that its intervention resulted in fewer emissions, for example, a forest was conserved rather than logged. These considerations have led multiple nongovernmental 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).[40] 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.

Regarding the accounting for carbon removals that are eligible for recognition, a common issue for many types of CO_2 removals will be that there is no causal link between the removal activities 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 rule 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.[41]

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

[40] Kaplan et al. (2023b) argue 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.

[41] 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.

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 recording emissions transferred in (ETI) and equity (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 here 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.[42]

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 accumulated direct emissions, direct removals, emissions transferred in, and CE in Assets.[43] It would be understood that these figures represent estimates of the emissions accumulated between the initial reference date and the year in which the carbon accounting process commences, that is, the year 202x.

6 Concluding Remarks

In the absence of effective carbon pricing in many parts of the world, businesses across a wide range of industries increasingly accept responsibility not only for their own direct 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 toward 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

[42] 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.

[43] 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.

with more specific standards regarding the accounting for carbon removals and the architecture of PCF measurement systems for specific industries.

CE statements identify 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 internal 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 software systems for inventory costing and financial statements and 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 Sect. 3, illustrating 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 (Datar and Rajan 2020). 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, that is, 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, or square footage), time, or an economic measure, for example, market prices of the sales products (Kaplan and Anderson 2004; Datar and Rajan 2020). For external reporting purposes, companies have considerable discretion in structuring their internal cost accounting systems. In most industries, the inherent jointness of overhead costs precludes obtaining 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 Sect. 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 obtain its own proxy measure based on secondary industry-wide data.

A company's Scope 1 and 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, that is, 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.[44] 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 to the design of PCF measurement systems.[45] The main ingredient in traditional Portland 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 Fig. 1 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 Fig. 2 reflects that this category is confined to emissions embodied in the construction of the 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 calculations shown in Fig. 1 followed the guidelines of the Energy Accounting and Reporting Standard for the cement industry by assigning slag a carbon balance of zero (World Business Council for Sustainable Development 2011).

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

44 In a supply chain setting, Chen and Pfeiffer (2024) examine the effect of alternative emission allocation rules on firms' production activities and their profitability.

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

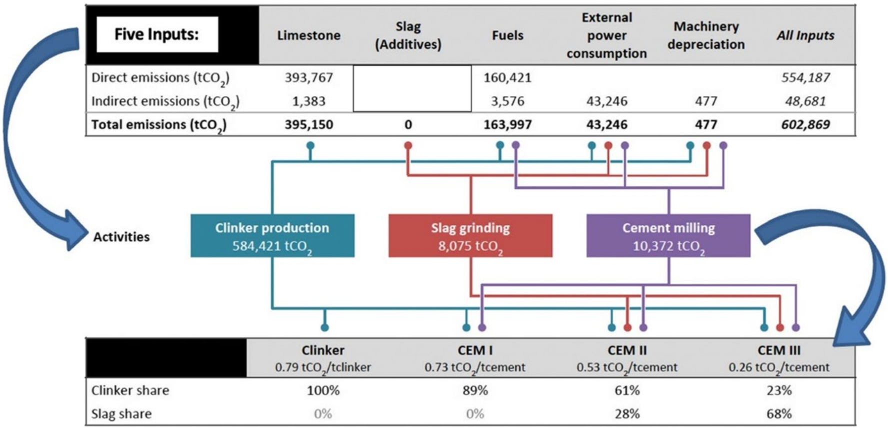

Fig. 1 Activity-Based Emission Allocations for Cement Products. Source: Landaverde et al. (2023)

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 tons of CO_2 per ton of cementitious material, in Fig. 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 trade-off 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

[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.

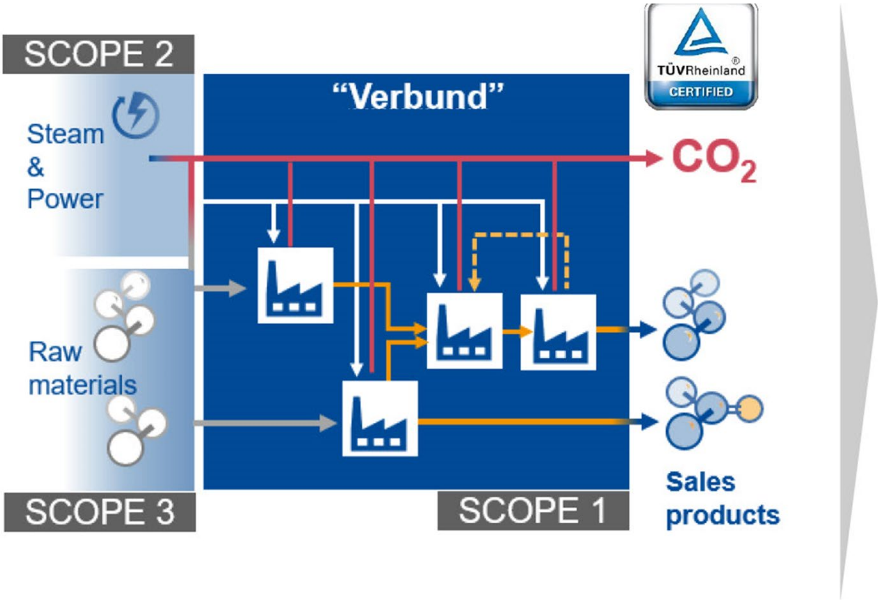

Fig. 2 Product carbon footprint accounting at a chemical company. Source: BASF (2022)

associations Catena-X (2023, p. 16) and TfS (2024, 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. In carrying out its operations at these plants, the company procures about 20,000 different raw materials and approximately 10 TWh of energy annually from external vendors. Figure 2 illustrates the flow of production inputs, intermediate products, and their accompanying carbon balances through the company's network of production sites.

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 2022).[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.

[47] BASF is a founding member of the Together-for-Sustainability consortium (TfS 2024). 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.

As mentioned in Sect. 3, the company's PCF measurement system has been automated through its online tool SCOTT (Strategic CO_2 Transparency Tool). 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 et al. 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 2022).

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.

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, that is, 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 provides guidance on which parties are to be charged for emissions associated with shipping parts within a supply network. In contrast to the general Scope 3 approach taken by many companies, the emissions associated with employee commuting are not to be included in the cradle-to-gate PCF measure (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 echoes the general preference in cost accounting for granular monitoring of resources consumed in individual production activities so that more cost items become directly traceable rather than fall into the category of overhead costs. The rulebook presumes that the carbon balance of parts that become components of a product will be included at their reported face values in the PCF. 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, or energy). Consistent

[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, p. 8).

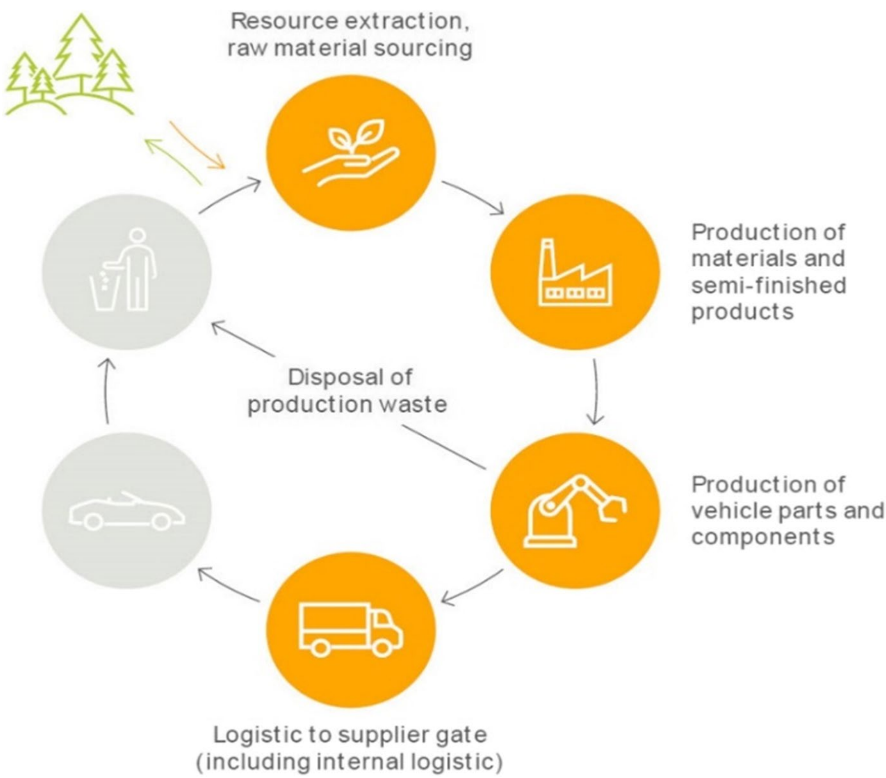

Fig. 3 System Boundaries for Catena-X PCF. Source: Catena-X (2023)

with the TfS (2024) guidelines, physical measures are to be replaced by value-based measures, 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 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 (2024) 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. Presumably, the reason for drawing narrower boundaries 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 the constructing of the calcination plant producing the clay, the company would overstate the emission savings associated with the use of clay as a substitute material.

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 Sect. 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. Thus, 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, that is, 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.[50] The economy opens at date $t = 0$ and operates up to a terminal date at $t = T$[51]. 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* $t = T$. *Given 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 as 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^+, that is, the producers of consumer products.

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

[51] The economy may operate past date T, though no direct or indirect emissions would be incurred past that date.

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. Given direct carbon accounting, the following identity holds:*

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

Appendix C

Glossary of Abbreviations and 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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