Show Me the Carbon: Accounting for Inherent Emissions

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May 2025

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Abstract

Current carbon accounting systems lack mechanisms that enable the detection of errors in emission measurements through physical examination of goods and assets. This paper proposes to extend these systems by accounting for inherent emissions — carbon that is embedded in materials and may be released in the future through chemical processes. The inclusion of inherent emissions will bridge the gaps between real-world emissions, changes in physical assets, and accounting records, allowing verification of carbon data through physical examination and thereby improving the reliability and the auditability of carbon disclosures. This novel carbon accounting extension is illustrated here by numerical examples that show how inherent emissions can help to identify inconsistencies in carbon data and to support comprehensive carbon audits. Hence, inherent carbon accounting aims to improve error detection and to provide a tangible connection between carbon accounting and real-world emission quantities, ultimately promoting carbon accounting practices that are more accurate and more trustworthy than they currently are.

Keywords: *Carbon Accounting, Inherent Emissions, Carbon Auditing, Environmental Management Accounting, Sustainability Accounting*

1. Introduction

Corporate carbon accounting is progressively gaining importance for the management and disclosure of companies' carbon emissions. Driven by increasing regulatory requirements for mandatory sustainability reporting (Wagenhofer, 2024), by carbon emission taxation (Jacob & Zerwer, 2024), and by a growing demand for assured sustainability data (Luo et al., 2023), corporate carbon disclosure has significantly intensified over the last few years. This trend reflects today's heightened expectations from investors, consumers, and regulatory bodies, who are increasingly factoring environmental performance into their decision-making processes (Beyer et al., 2024; Cohen et al., 2023). Furthermore, by issuing high-quality sustainability reports, companies credibly signal their dedication to transparency and to the improvement of their environmental impact. This behavior aligns with signaling theory, whereby detailed and assured disclosures serve as credible signals of a company's dedication to addressing environmental concerns despite the associated preparation and proprietary costs (e.g., Connelly et al., 2025; Hummel et al., 2019; Spence, 1973, 2002). However, as carbon emission reporting continues to become more important for companies and for the addressees of these reports, the accuracy and the verifiability of reported emissions data are becoming increasingly critical for preventing misrepresentation and greenwashing practices—an issue exacerbated by the inability to validate reported emissions through existing systems (Gipper, Ross, et al., 2024).

Assurance can help to improve the credibility of reported sustainability and carbon information (Hodge et al., 2009). While financial reporting portrays the financial performance of a company that is relevant for its shareholders, sustainability reporting documents the impact of companies on their stakeholders and on the environment (Christensen et al., 2021; Dechow, 2023). Compared to financial accounting, regulatory frameworks for carbon accounting are less rigorous (Wegener et al., 2019), which consequently enables reporting practices that companies can employ to influence information content in their own favor (Free et al., 2024). Therefore, it is sensible to be skeptical of the reported information and to request third-party assurance.

Sustainability assurance is a new market that differs from financial assurance although it is often conducted by the same (external) assurance teams (Dal Nial et al., 2024; Datt et al., 2020). The findings of a study among non-financial companies listed on the New York Stock Exchange (Bui et al., 2021) suggest that companies that voluntarily seek carbon assurance are more committed to long-term sustainability performance than they are to short-term maximization of their shareholder interests. O'Dwyer (2011) conducted interviews in two major assurance companies. He found that complete assurance is difficult to provide due to the lack of cooperation from the reporting company or to deficient documentation of the information to be assured. Reported information content requires a clear connection between the externalities of a company and its accounting and information systems. In this vein, O'Dwyer (2011) describes the data that the assurors have to work with as often being "diverse", "vague", and "disconnected". Assurance can also help to improve carbon accounting practices by identifying and solving a company's implementation issues (Gipper, Sequeira, et al., 2024).

Despite advancements in current corporate carbon accounting systems—such as the emission liability (E-Liability) system proposed by Kaplan and Ramanna (2021), the accrual carbon accounting system introduced by Reichelstein (2024), and the societal carbon balance sheet developed by Penman (2024)—these systems remain susceptible to errors and intentional misreporting. Most of them focus predominantly on recorded emission flows without enabling physical verification, which creates a critical gap in the auditability of emissions data. Since the recorded emissions are not physically observable after they have been emitted and recorded, auditors are left without adequate measures to verify the data. Specifically, scope 1 emissions—emissions emitted directly by companies (GHG Protocol, 2004)—are often recorded without sufficient traceability or physical proof, causing discrepancies and inaccuracies to remain undetected (Glenk, 2023). This gap allows companies to engage in greenwashing by misrepresenting or intentionally understating their environmental impact (Free et al., 2024) without the possibility of proving the greenwashing companies' claims to be false. The lack of verifiability thus compromises the reliability and the transparency of carbon disclosures (de Freitas Netto et al., 2020).

Similarly, carbon offsets need to be accounted for correctly. Carbon offsets are "a quantifiable reduction or removal of greenhouse gases, which are purchased by entities to compensate or neutralize their own GHG emissions occurring elsewhere" (Trencher et al., 2024, p. 2). While carbon offsets are an important part of companies' net-zero strategies, they are often criticized for being of low quality (Dhanda & Hartman, 2011; Trencher et al., 2024) or for their real effect being overstated (Badgley et al., 2022). Hence, a carbon accounting system is needed that accounts for carbon offsets, that accurately assesses the total changes in emissions, and that offers the possibility to audit changes in offset carbon over time in order to adjust the numbers correctly (Brander et al., 2021).

To address the beforementioned shortcomings, this paper introduces the concept of *inherent emissions* as an extension to existing carbon accounting systems. Inherent emissions are defined as carbon that is embedded within materials and that may potentially be emitted through future combustion or other chemical processes. In contrast, current carbon accounting systems only account for *past emissions*. Past emissions—as they are referred to in this paper—include scope 2 emissions (indirect emissions from purchased energy), upstream scope 3 emissions (indirect emissions occurring in the supply chain upstream of the focal company) (GHG Protocol, 2004), and scope 1 emissions that are already in the atmosphere in the form of CO_2 and other greenhouse gases. Accounting for inherent emissions creates a tangible link between physical assets and carbon accounting systems, allowing verification through physical examination, similarly to the process in traditional financial audits. Hence, through the incorporation of inherent emissions into carbon accounting frameworks alongside past emissions, auditors and stakeholders gain the opportunity to physically reconcile reported carbon data with actual observable carbon stored in a company's materials and products. Furthermore, since carbon offsetting has a physically observable effect on the assets of a company, it is rendered auditable. Therefore, inherent carbon accounting significantly improves the reliability of reported emissions data and enhances auditability, thereby counteracting any misreporting and greenwashing practices.

Using illustrative numerical examples, this paper explores how the extension of current carbon accounting frameworks with inherent emissions can address critical verification gaps. The central research question guiding the investigation is: *How can the reliability and the auditability of carbon accounting information be enhanced through the inclusion of inherent emissions in carbon accounting systems?* The current study not only contributes theoretically to the existing literature by expanding carbon accounting practices but also provides practical guidance for those companies and auditors who aim to achieve rigorous, trustworthy, and transparent environmental disclosures.

The remainder of this paper is structured as follows. Section 2 describes current advances in carbon accounting, the relevant theory behind them, and their improvement opportunities. Section 3 introduces inherent emissions into these carbon accounting systems. Section 4 discusses the implications of this addition, answers the research question, and concludes with directions for future research.

2. Background

2.1. Carbon accounting: definitions, users of information, and current advances

Companies are being increasingly pressured to measure and report their environmental impacts and emissions on both the company and the product levels due to mandatory reporting requirements, customer pressure, investor pressure, and carbon taxation requirements (Beyer et al., 2024; Konar & Cohen, 1997; Tang & Demeritt, 2018). New regulatory frameworks, such as the Corporate Sustainability Reporting Directive (CSRD) of the European Union (European Union, 2022) and similar mandates in other regions around the world (Carrots & Sticks, 2023), have intensified demands for rigorous carbon disclosures. This often leads to reporting companies reducing their emissions (Downar et al., 2021; Tomar, 2023). Additionally, changing consumer preferences are significantly influencing this increased reporting pressure. For example, Beyer et al. (2024) find that clear carbon footprint labeling has an impact on consumer behavior by driving reduced emissions through altered consumption patterns. Furthermore, shareholders also utilize sustainability information, enabling the market to price external costs into the valuation of the company (Greenstone et al., 2023). Due to these diverse user demands, topics, and measurement standards, carbon reporting has not only become more prominent but is also posing challenges for those companies which want to meet the needs of all relevant stakeholder groups (Christensen et al., 2021).

Traditionally, carbon accounting has been guided by frameworks like the Greenhouse Gas (GHG) Protocol, which categorizes emissions into three scopes: scope 1 emissions, scope 2 emissions, and scope 3 emissions (GHG Protocol, 2004). Scope 3 emissions in the GHG protocol—in contrast to those included in past emissions—also include emissions of the supply chain downstream of the focal company, such as emissions of its customers. Building on the GHG protocol, innovative approaches have emerged, drawing from traditional financial accounting principles to enhance carbon accounting reliability:

- Kaplan and Ramanna (2021) introduced the E-Liability system, which assigns an E-Liability to products, capturing all upstream scopes 2 and 3 emissions generated in the production process. These liabilities are transferred along the supply chain, accumulating each company's scope 1 emissions at each stage, thus avoiding any double counting of emissions, which is an issue when accounting for emissions in accordance with the GHG protocol (Kaplan & Ramanna, 2021).

- Reichelstein (2024) proposed an accrual carbon accounting system that incorporates emissions into traditional accounting structures, creating carbon emission statements that track both emission stocks and emission flows over extended periods. This system documents emissions associated with assets such as buildings and machinery, similarly to financial accounting. Hence, it helps companies to assess their long-term emission responsibilities and to track their progress towards carbon neutrality goals.
- Penman (2024) developed a carbon accounting model from a societal perspective, creating a carbon balance sheet. Here, emissions are accounted for as liabilities, while carbon offsets, removals, and investments for future emission reductions are recognized as assets. Penman's approach quantifies a company's overall impact on atmospheric CO_2 levels as equity, highlighting positive or negative contributions to carbon emissions. Both approaches emphasize the measuring and managing of emissions at the organizational level, offering frameworks to track and report a company's transition towards net-zero emissions.

Efforts to reduce CO_2 in the atmosphere, known as carbon offsets, are also addressed in the beforementioned carbon accounting systems. The carbon offsets are netted against emissions to achieve net-zero or even net-negative emissions (Bednar et al., 2021). Carbon offsets can be used to decrease a product’s E-Liability (Kaplan & Ramanna, 2021), to offset current or historic emissions and to move closer to net-zero goals (Reichelstein, 2024), or to reduce the negative impact or even increase the positive impact of a company on society through its emissions and investments (Penman, 2024). In all these carbon accounting systems, the offset is included as a value of emissions taken out of the atmosphere and is netted against past or current scopes 1, 2, or 3 emissions. Carbon offsets, specifically avoidance offsets where a credit is granted for not emitting emissions rather than taking them out of the atmosphere, are often criticized (e.g., Brander et al., 2021; Dhanda & Hartman, 2011; Trencher et al., 2024). Hence, Brander et. al. (2021) have called for a carbon offset accounting system to solve issues of offsets like accuracy, (non) permanence, and temporal distribution of offsets and emissions. In this vein, Kaplan et al. (2023) have presented requirements for offsets to be recognized in carbon accounting systems. They lay out principles to ensure that accounted offsets represent the real atmospheric changes due to the CO_2 taken out of the atmosphere and are matched with CO_2 by the respective organization or other organizations.

2.2. Lack of auditability of carbon emissions

The implementation of rigorous carbon assurance and auditing practices is essential for fostering trust in carbon accounting and disclosure and for ensuring the reliability of carbon information. The adoption of assurance has increased significantly over the last decade (Gipper, Ross, et al., 2024). Furthermore, it is associated with higher-quality carbon accounting data and improvements in the carbon performance of companies (Berg et al., 2024; Gipper, Sequeira, et al., 2024; Lee et al., 2025). Also, it addresses frequent issues of misstatements and false claims (Luo et al., 2023). Interdisciplinary teams of accountants, engineers, and specialists are crucial, however, biases necessitate improved team training and structured processes (Ekasingh et al., 2019; Kim et al., 2016). Technological innovations can enhance data integrity (Boedijanto & Delina, 2024; Li et al., 2024). However, credible carbon assurance is often difficult to achieve with the current information within carbon accounting systems and the related physical stocks of the companies.

Much of the generated carbon information is difficult to audit; it may be incomplete or include double counting of emissions (Glenk, 2023; Kaplan & Ramanna, 2021). Differences can stem from inaccurate meter readings, incorrect scope of carbon accounting, and missing fuel use data for some equipment (Bellassen et al., 2015; Zhang et al., 2019). Furthermore, when using emission factors, as allowed by the GHG protocol, incorrect classifications of processes and activities can place different emissions values on similar activities (Luers et al., 2022). Errors and inaccuracies like these are often difficult to identify after they have occurred and can complicate the verification of disclosures. Despite the already discussed new carbon accounting systems that include more holistic accounting for carbon emissions of companies' activities and carbon offsets (Kaplan & Ramanna, 2021; Penman, 2024; Reichelstein, 2024), the information provided by these systems is not physically verifiable independently. Additionally, new mandatory reporting requirements, such as the climate risk disclosure rules of the Securities and Exchange Commission or the European Sustainability Reporting Standards of the European Union, require the disclosure of assured sustainability information (Gipper, Ross, et al., 2024). However, detecting errors in accounting for scope 1 emissions is often challenging, as carbon accounting systems lack a direct link between recorded emissions data and the actual physical carbon entering or leaving a company, whether through sales or via emissions into the atmosphere. This issue arises because scope 1 emissions are recorded without a proper source that can be reconciled after their emission, a practice that would be deemed unreliable in financial accounting. As proposed by Reichelstein (2024), emissions are duplicated within carbon emission statements—once in asset accounts and then again in direct emission accounts—representing the same data twice. Within these accounting systems, emissions simply appear without any traceable source or balancing mechanism.

2.3. The example of an aluminum can producer

To illustrate the shortcomings, namely the difficulty of physically examining either intentional (fraud) or unintentional (mistake) errors of current carbon accounting systems, consider the following (illustrative) example of a focal company: an aluminum can producer. With regard to the upstream supply chain, the company buys aluminum sheets and natural gas from a single supplier. The focal company also receives information on the cradle-to-gate emissions of these goods from the supplier. These cradle-to-gate emissions include all scope 2 and upstream scope 3 emissions (from the focal company's perspective) until the supplies enter the company. Assumably, this information is correct in this example. The company then uses the gas for powering the furnaces to produce the finished aluminum cans. The focal company tracks the emissions through a carbon accounting system. This system tracks the information throughout purchasing, internal processes, and sales, and it allocates the emissions to the products.

Producing aluminum cans requires several transactions, each step associated with carbon emissions. When the aluminum sheets and the natural gas are purchased, these goods enter the company and the corresponding carbon information is included in the carbon accounting system. Based on vouchers and as in financial accounting, the company can monitor the arrival of these goods and confirm that the required information is present and reflected in the carbon accounting system. However, the company cannot verify that the information is correct. When the company's processes start and the focal company burns the gas, thereby emitting scope 1 emissions, there is a disconnect between the carbon emissions recorded in the accounting system, where emissions from the gas that have not been previously recorded in an accounting system enter the atmosphere. In order to resolve this problem and to correctly account for the emissions, the company needs to add the scope 1 emissions, which arise from burning the gas, into its carbon accounting system as soon as this process step is performed.

This example uses the terminology and demonstration of Reichelstein (2024), as his presentation of the carbon accounting system draws on and is very close to traditional accounting practices. Moreover, the carbon accounting example (transactions shown in Table 1) of the aluminum can producer builds on the carbon balance sheet and transaction tableau of Reichelstein (2024) in Table 2.

Transaction	Description
I.	Purchase of aluminum sheet for the cans. The aluminum sheets have upstream scopes 2 and 3 emissions of 1,000 kg CO_2. They include some carbon due to their surface treatment (50 kg if emitted)

II.	Purchase of natural gas for the processes. The gas has upstream scopes 2 and 3 emissions of 500 kg CO_2. When burned, the carbon in the gas reacts with oxygen from the air and 3,000 kg CO_2 is emitted into the atmosphere
III.	The aluminum with its emissions is recorded as part of the production process
IV.	The gas is used in the production process to form the aluminum sheets; it is burned entirely within this process, resulting in the already stated 3,000 kg CO_2 of scope 1 emissions
V.	The finished goods are moved from the work-in-process (WIP) to the finished goods (FG) account

Table 1 Carbon accounting transactions in the illustrative example of the aluminum can producer

Table 2 shows the transactions within the transaction tableau. For simplicity, most accounts start without a positive opening balance, except for Plant Property and Equipment (PPE), which starts with emissions of 20,000 kg CO_2 that have been transferred in (this is a fictitious number to demonstrate the example) and were necessary to provide the buildings, machines, and equipment of the company. All input materials are used in the process and end as finished goods (in this case, aluminum cans), thus increasing the emissions in this account. Table 2 shows that when correctly recording scope 1 emissions, the carbon accounting system provides correct information.

Accounts	CE in Assets						CE in Liabilities			
	PPE	**MAT_{Alu}**	**MAT_{Gas}**	**WIP**	**FG**		**ETI**	**DE**	**DR**	**EQ**
Opening Balance	**20,000**	**0**	**0**	**0**	**0**	**=**	**20,000**	**0**	**0**	**0**
Transactions										
I.		1,000				=	1,000			
II.			500			=	500			
III.		-1,000		1,000		=				
IV.			-500	3,500		=		3,000		
V.				-4,500	4,500	=				
Closing Balance	**20,000**	**0**	**0**	**0**	**4,500**	**=**	**21,500**	**3,000**	**0**	**0**
				Sum	24,500				Sum	24,500

Table 2 Transaction tableau for the purchase of materials, production of aluminum cans, and sale of these, using the carbon emission balance of Reichelstein (2024). Abbreviations: PPE = Plant Property and Equipment; MAT = Material; WIP = Work-in-Process; FG = Finished Goods; ETI = Emissions Transferred In; DE = Direct Emissions; DR = Direct Removals; EQ = Equity.

Table 3 shows the transactions within the transaction tableau again, now including a measurement error for the scope 1 emissions of burning the natural gas, which demonstrates the basic problem that this paper addresses, i.e., a potential lack of verifiability of reported emissions information. As before, all opening balances and transactions are the same, and all input materials are used in the process and end up as finished goods (again, aluminum cans). As before, the company adds the upstream scopes 2 and 3 emissions of the gas to the WIP (500 kg CO_2), but this time the emissions of 3,000 kg CO_2 during the production processes are intentionally not recorded in order to improve the product carbon footprint of the cans. As Table 3 shows, this leads to unrecorded direct emissions (DE) and a decrease in emissions of finished goods to 1,500 kg CO_2 (compared to 4,500 kg CO_2 when correctly accounted for). Hence, the key issue here is: the measurement error in Table 3 is undetectable. Everything is balanced and seems to be in order. Although this problem might seem very obvious here, the example demonstrates how errors can occur. For more complex value chains and production systems, the risk of errors or intentional misreporting is even higher.

Accounts	CE in Assets						CE in Liabilities			
	PPE	**MAT_{Alu}**	**MAT_{Gas}**	**WIP**	**FG**		**ETI**	**DE**	**DR**	**EQ**
Opening Balance	**20,000**	**0**	**0**	**0**	**0**	**=**	**20,000**	**0**	**0**	**0**
Transactions										
I.		1,000				=	1,000			
II.			500			=	500			
III.		-1,000		1,000		=				
IV.			-500	500		=				
V.				-1,500	1,500	=				
Closing Balance	**20,000**	**0**	**0**	**0**	**1,500**	**=**	**21,500**	**0**	**0**	**0**
				Sum	21,500				Sum	21,500

Table 3 Transaction tableau for the purchase of materials, production of aluminum cans, and sale of these, using the carbon emission balance of Reichelstein (2024) with unrecorded scope 1 emissions. Abbreviations: PPE = Plant Property and Equipment; MAT = Material; WIP = Work-in-Process; FG = Finished Goods; ETI = Emissions Transferred In; DE = Direct Emissions; DR = Direct Removals; EQ = Equity.

As everything sums up and one cannot physically measure the error, this example demonstrates the general point of the lack of verifiability and the inability to physically examine assets for their emissions. If scope 1 CO_2 emissions are not correctly recorded, it is not possible to find the error through the numbers in the accounting system, even if these numbers were to be monitored by an auditor shortly after production. This is due to CO_2 emissions being invisible, i.e., inventory counting is not possible. Also, they are also not measurable after their occurrence[1]. This problem is caused by the lack of connection between the information in the carbon accounting system and the time-independent observability of assets. As the information on scope 1 emissions needs to be (manually) entered into the carbon accounting system, it is not connected to the existing information in that system before this addition. Given the complexity of production processes and the lack (and sometimes inapplicability) of

[1] Satellite imaging can identify large amounts of carbon emissions (Carbonmapper, 2024; Gu et al., 2023; Planet.com, 2021). However, using this technology to track small emitters and discrepancies in their carbon accounting is not feasible. Additionally, such tracking is not possible after emissions have been emitted, and it requires constant monitoring.

measurement systems, this approach is prone to errors and to overlooked emissions. Then, when the product is sold, the customer receives it together with the emission information. The customer can physically examine the product on arrival and the existence of the information without being able to verify the reported emissions of the product. However, even an internal auditor with full access to the supplier's information cannot verify that information without there being gaps in it. Therefore, emissions stemming from the use of machinery, heating, burning, etc. may be unobserved and overlooked because current carbon accounting systems require the (manual) addition of information that was previously not present in the carbon accounting system before the scope 1 emissions were emitted. In principle, any omission of the recording of scope 1 emissions is unobservable after the emission has occurred, which makes the accounting system prone to errors and misreporting.

To be able to verify that the information provided by carbon accounting is correct, a connection between a company's carbon accounting system and emission information on inputs, outputs, inventories, and scope 1 emissions is necessary. As shown, it is difficult to link the information about the assets of a company in the carbon accounting system to the physically existing assets of that company. This missing link leads to the consequence that past emissions in the carbon accounting system cannot be observed by physically examining the assets. In contrast to carbon accounting, in financial accounting, an assessment of what is under the control of a company can be carried out time-independently by taking inventory of the accounts in the company's accounting system. The counted inventory quantities are then compared with the quantities booked towards financial assets (e.g., bank accounts and cash) and physical assets, such as machines, buildings, and inventories, which can be observed as evidence through physical examination (Fotoh, 2025; Salterio & Koonce, 1997). Even intangible assets can be traced to a company and their value can be unambiguously recorded (Barker et al., 2022). Consequently, the stated numbers can be verified by an auditor at any point in time. The auditor does not need to constantly monitor a company's cash flows and valuation changes.

In sharp contrast to established financial accounting practices, when auditing the carbon emissions of a company, their observability is not given. This problem is becoming even more pronounced because emissions do not trigger voucher-based business events such as those that are recorded in a company's bookkeeping system. Although information about emissions of a product provided by a supplier (analogously to a price paid in financial accounting) can be recorded in the carbon accounting system, these emissions occur within a company, and whether these are accounted for correctly is not observable after the emissions have been emitted. Moreover, as the emissions in the atmosphere are not traceable to a specific company, an auditor would not be able to detect emission reporting errors, i.e., the carbon accounting system needs to rely on a correct recording of emissions in the system at each point in time that a company emits carbon into the air by burning or through other chemical processes. In summary, in case some emissions were not accounted for, the auditor would have no way of checking whether the data in the carbon accounting system is correct (complete), i.e., current carbon accounting practices lack the general opportunity to physically verify carbon emission information.

3. Extension

3.1. Extended carbon emission statements: inherent carbon

To enable internal and external auditors to physically examine assets for their carbon content, this paper introduces inherent emissions into the existing carbon accounting systems (Kaplan & Ramanna, 2021; Penman, 2024; Reichelstein, 2024). Inherent emissions, in the paper at hand, are defined as the amount of CO_2 that can be released from the material of the physical asset through combustion or other chemical processes due to the reaction of carbon atoms within the materials or fuels with oxygen atoms from the air. Inherent emissions do not necessarily imply that these are emitted into the atmosphere by the focal company, e.g., when the material is not burned or used in chemical processes and the material continues to store all of the inherent carbon. Still, inherent emissions represent the emission quantities to be expected if the asset is burned or combusted in the respective processes. All past CO_2 emissions have been inherent in materials as carbon atoms at some point in time before reacting and combining with two oxygen atoms to form carbon dioxide. This is true for everything that contains carbon (i.e., natural gas, oil, wood, etc.). Hence, there is a point of time where the complete carbon is still in the material. At this point, 100% of the emissions are inherent emissions (Welsby et al., 2021). Through chemical processes (such as combustion), these inherent emissions can be released into the atmosphere, reducing the amount of inherent emissions still in the material by the amount of CO_2 emitted during these processes, i.e., inherent emissions become actual emissions. Consequently, the total emissions of a material (past emissions and inherent emissions added together) stay the same for the entire life of the material. This is also true for incoming and outgoing material and products of a company. Furthermore, in the case of carbon offsetting in the form of carbon sequestration, there is a transfer of CO_2 from the air into a form of material

(Gibbins & Chalmers, 2008). In this case, CO_2 is taken out of the air (negative emissions) and inherent emissions are built up within the material.

Demonstrating the extension of carbon accounting with inherent emissions requires a common terminology. This paper uses the following terminology adopted from Reichelstein (2024) to illustrate the accounting for inherent emissions: emissions transferred in (ETI) include scopes 2 and 3 emissions that were assigned to incoming goods bought by the company from suppliers. Direct emissions are scope 1 emissions that are emitted directly by the company to produce its goods and services through chemical processes, such as combustion processes. Direct Removals (DR) are negative scope 1 emissions removed by the company, taking CO_2 out of the atmosphere through carbon capture and storage or other solutions. Equity (EQ) describes the total impact of the company on atmospheric CO_2 levels. A positive value for EQ indicates that the company has taken out more CO_2 from the atmosphere than it has added, while a negative value reports how much CO_2 was added by the company (Reichelstein, 2024). However, accounting for inherent and past emissions alongside each other does not rely on a specific carbon accounting system being used. Hence, the extension is also applicable to the E-Liability concept of Kaplan and Ramanna (2021) and the carbon accounting system of Penman (2024) as well as other carbon accounting approaches.

Through the extension of accounting for inherent emissions, the information in the accounting systems becomes physically observable, as it is an inherent part of the respective recorded assets. The assets bought, owned, and sold by a focal company can be observed, physically examined, and assessed at different points in the supply chain. This physical examination allows the amount of carbon within the material to be determined and it corresponds to the resulting emissions that would be emitted if all the carbon within the material reacted with oxygen to become CO_2 emitted into the atmosphere. This information is already available for nearly all fuels and gases in emissions factor databases. For other materials, the amount of carbon can be calculated or estimated through the chemical composition of the respective materials. This is often done for the assessment of carbon stocks in forests or carbon capture facilities (e.g. Murugan et al., 2020; Neumann et al., 2016; Patenaude et al., 2005). In summary, the content of carbon can be determined for all physically existing carbon with emissions factors or through an analysis of the chemical composition of materials, depending on the knowledge of the material's composition.

Figure 1 shows that inherent carbon can be observed and physically examined when an asset is bought, when it is stored, during production, and when the product or asset is sold. The observation can be used to measure the inherent emissions in the materials of the assets, i.e., the amount of emissions that are emitted through the consumption of the assets under the control of the company when their carbon content fully reacts with oxygen.

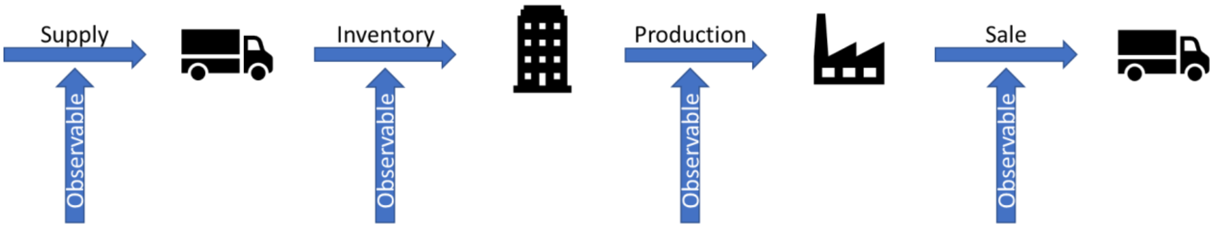

Figure 1 Assets and products can be observed, physically examined, and recorded at different points throughout the processes.

Extending current carbon accounting systems to account not only for past emissions but also for inherent emissions provides a way for both internal and external auditors to physically examine whether the accounting information is correct. The auditors can observe and physically examine the assets and their inherent emissions under a company's management at any point in time. Therefore, the auditor does not need to constantly monitor a company's emissions, which limits the room for reporting errors and misrepresentation.

The proposed extension adds a value for inherent emissions to each account, recorded in additional positions in the carbon balance sheet and extra columns in the transaction tableau. For direct emissions and direct removals, there is a change of inherent emissions in the material consumed, i.e., inherent emissions are emitted into the atmosphere and become past emissions, or emissions from the atmosphere are captured and become inherent emissions. In the example, the inherent emissions in the natural gas are released into the atmosphere and become past emissions when the gas is burned. This results in a transfer from inherent emissions to past emissions. Table 4 shows the carbon emission balance sheet of the extended model with inherent emissions for each account. The sum of past emissions needs to be the same on the asset and the liability side. In this extension, the same is true for the sum of inherent emissions. This procedure is comparable to the double-entry book-keeping system in financial accounting and allows time-independent assurance of emissions data.

CE in Assets		**CE in Liabilities and Equity**	
Buildings	BLD	ETI	Emissions Transferred In
	$BLD_{inherent}$	$ETI_{inherent}$	
Machinery & Equipment	MAC	DE	Direct Emissions
	$MAC_{inherent}$	$DE_{inherent}$	
Raw Materials	MAT	(DR)	Direct Removals
	$MAT_{inherent}$	($DR_{inherent}$)	

Work-in-Process	WIP $WIP_{inherent}$	EQ $EQ_{inherent}$	Equity
Finished Goods	FG $FG_{inherent}$		

Table 4 Carbon Emission Balance Sheet of the extended model with inherent emissions. Based on Reichelstein (2024).

In this vein, accounting for both past emissions and inherent emissions enables audits of carbon accounting information due to the observable inventory of assets and the respective asset-inherent emissions accounted for. The total scope 1 emissions of a company are the total inherent emissions transferred in minus the emissions still inherent in the assets of the company, namely buildings, machinery & equipment, materials, work-in-process, finished goods, and in the equity account. Hence, mathematically, this can be expressed as

$$scope\ 1\ emissions\ =\ ETI_{inherent} - (BLD_{inherent}\ +\ MAC_{inherent}\ +\ MAT_{inherent}\ +\ WIP_{inherent}\ +\ FG_{inherent}\ +\ EQ_{inherent}).$$

Following this, an auditor can enter a company at any given time and simply request the company to “Show me the carbon!”. If the accounting is correct, *the physically examined carbon will have the same value as the inherent carbon in the balance sheet.* Any difference between inherent emissions in the accounting system and inherent emissions of the observable assets are likely to be the scope 1 emissions of the company. Large (material) differences would then lead to declined confirmation of correct disclosure with (potential) corresponding consequences.

For a carbon offsetting company, being able to demonstrate that the sequestered carbon has been taken out of the atmosphere is crucial as well. By accounting for inherent emissions, a carbon sequestering company effectively accounts for the amount of CO_2 taken out of the atmosphere and stored in material form. This material can be physically examined and audited to assess the amount of carbon within the material. This allows audits to be conducted once the sequestering has taken place and enables a reliable recording of the sequestered carbon over time, thus solving the issue of the uncertainty of the durability of carbon offsets. The carbon accounting for carbon capture and storage is demonstrated in section 3.2.2. Hence, the extension enhances not only the auditability of CO_2 emitted into the atmosphere but also that of CO_2 taken out of the atmosphere through capturing or sequestration.

3.2. Numerical examples

3.2.1. Aluminum can producer

We return to the numerical example of the aluminum can producer from section 2.3. to demonstrate how accounting for inherent emissions helps to detect errors in accounting for all scope 1 emissions in a process. To demonstrate this, the same five transactions as in Table 1 are used.

As in section 2.3., Table 5 shows the situation where the scope 1 emissions of the company are not (or falsely) reported. This leads to finished goods with 1,500 kg CO_2 of past emissions and 3,050 kg CO_2 of inherent emissions. However, it is known (and can physically be proven) that the actual inherent emissions of the finished goods are only 50 kg CO_2, which are then transferred to the customer. As inherent emissions can be physically examined, either by the quality control of the aluminum can producer, by inventory counting, by an auditor, or by the customer, the false reporting of inherent emissions of the finished goods can be detected and the data can be corrected. This connection between physically observable inherent emissions and accounting for inherent emissions enables early detection of errors internally or by supply chain partners. Table 6 shows the correct values in the transaction tableau with the correct amount of both past and inherent emissions. Hence, the direct emissions—emitted when the gas is burned—are now deducted from the inherent emissions and added to the past emissions of the WIP and FG accounts. The differences between Table 5 and Table 6 are highlighted in bold font in transactions IV. and V. of Table 6.

Accounts	CE in Assets **PPE**	**PPE inherent**	**MAT$_{Alu}$**	**MAT$_{Alu}$ inherent**	**MAT$_{Gas}$**	**MAT$_{Gas}$ inherent**	**WIP**	**WIP inherent**	**FG**	**FG inherent**		CE in Liabilities **ETI**	**ETI inherent**	**DE**	**DE inherent**	**DR**	**DR inherent**	**EQ**	**EQ inherent**
Opening Balance	**20,000**	**5,000**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**=**	**20,000**	**5,000**	**0**	**0**	**0**	**0**	**0**	**0**
Transactions																			
I.			1,000	50							=	1,000	50						
II.					500	3,000					=	500	3,000						
III.			-1,000	-50			1,000	50			=								
IV.					-500	-3,000	500	3,000			=								
V.							-1,500	-3,050	1,500	3,050	=								
Closing Balance	**20,000**	**5,000**	**0**	**0**	**0**	**0**	**0**	**0**	**1,500**	**3,050**	**=**	**21,500**	**8,050**	**0**	**0**	**0**	**0**	**0**	**0**
								Sum	Past	21,500							Sum	Past	21,500
									Inherent	8,050								Inherent	8,050
									Total	29,550								Total	29,550

Table 5 Transaction tableau for the purchase of materials, production of aluminum cans while leaving some direct emissions unrecorded, and sale of these using the extended carbon emission statement with inherent emissions. Abbreviations: PPE = Plant Property and Equipment; MAT = Material; WIP = Work-in-Process; FG = Finished Goods; ETI = Emissions Transferred In; DE = Direct Emissions; DR = Direct Removals; EQ = Equity.

Accounts	CE in Assets											CE in Liabilities							
	PPE	**PPE inherent**	**MAT$_{Alu}$**	**MAT$_{Alu}$ inherent**	**MAT$_{Gas}$**	**MAT$_{Gas}$ inherent**	**WIP**	**WIP inherent**	**FG**	**FG inherent**		**ETI**	**ETI inherent**	**DE**	**DE inherent**	**DR**	**DR inherent**	**EQ**	**EQ inherent**
Opening Balance	**20,000**	**5,000**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**=**	**20,000**	**5,000**	**0**	**0**	**0**	**0**	**0**	**0**
Transactions																			
I.			1,000	50							=	1,000	50						
II.					500	3,000					=	500	3,000						
III.			-1,000	-50			1,000	50			=								
IV.					-500	-3,000	**3,500**	**0**			=			**3,000**	**-3,000**				
V.							**-4,500**	**-50**	**4,500**	**50**	=								
Closing Balance	**20,000**	**5,000**	**0**	**0**	**0**	**0**	**0**	**0**	**4,500**	**50**	**=**	**21,500**	**8,050**	**3,000**	**-3,000**	**0**	**0**	**0**	**0**
								Sum	Past	24,500							Sum	Past	24,500
									Inherent	5,050								Inherent	5,050
									Total	29,550								Total	29,550

Table 6 Correct transaction tableau for the purchase of materials, production of aluminum cans, and sale of these using the extended carbon emission statement with inherent emissions. The difference in the last two transactions is highlighted in bold font. Abbreviations: PPE = Plant Property and Equipment; MAT = Material; WIP = Work-in-Process; FG = Finished Goods; ETI = Emissions Transferred In; DE = Direct Emissions; DR = Direct Removals; EQ = Equity.

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3.2.2. Carbon offsetting company

Carbon offsetting can also be accounted for and becomes observable with the introduction of inherent emissions into carbon accounting systems. The amount of carbon offset can be observed and physically examined as the total inherent emissions within the physical output of a carbon capture company (i.e., crystalized carbon, wood in a newly grown forest, etc.). To illustrate this, this paper uses a simple example of a carbon offsetting company that captures carbon from the atmosphere by using electricity and employing some assets. Therefore, the example starts with some past and inherent emissions in Plant Property and Equipment (PPE). The opening balances of other assets are zero. In this carbon capture example, the following transactions occur to demonstrate the case of carbon capturing as shown in Table 7:

I. Purchase and usage of electricity to power the carbon capture machines. The electricity carries scope 2 emissions of 1,500 kg CO_2.
II. Extraction of 8,000 kg CO_2 from the atmosphere and storage of the resulting carbon in solid form.
III. Sale of the certificate for the carbon offset while keeping the carbon within the company. The total amount of captured CO_2 is kept track of in the account "CO_2 Captured inherent".

An audit of the physical existence of the inventories of carbon is, again, always possible and should report the total number kept in this account. Note that the amount of carbon offsets sold should not exceed the inherent carbon minus all CO_2 that is emitted to enable the processes of capturing and storing the carbon.

Again, the inherent emissions are kept in the carbon balance sheet and will remain observable to auditors. This ensures that the integrity and durability of the offsets are accounted for. Therefore, the amount of inherent carbon should be examined regularly and possibly be reassessed. When part of the captured carbon is re-emitted into the atmosphere, the offsetting company needs to compensate for this (reverse) change. Hence, the total volume of sold offset certificates should not exceed the positive value of the equity of the carbon offsetting company.

Accounts	CE in Assets					CE in Liabilities							
	PPE	**PPE inherent**	**CO_2 Captured**	**CO_2 Captured inherent**		**ETI**	**ETI inherent**	**DE**	**DE inherent**	**DR**	**DR inherent**	**EQ**	**EQ inherent**
Opening Balance	**20,000**	**5,000**	**0**	**0**	**=**	**20,000**	**5,000**	**0**	**0**	**0**	**0**	**0**	**0**
Transactions													
I.			1,500		=	1,500							
II.			-8,000	8,000	=					-8,000	8,000		
III.			6,500		=							6,500	
Closing Balance	**20,000**	**5,000**	**0**	**8,000**	**=**	**20,000**	**5,000**	**0**	**0**	**-8,000**	**8,000**	**6,500**	**0**
		Sum	Past	20,000							Sum	Past	20,000
			Inherent	13,000								Inherent	13,000
			Total	33,000								Total	33,000

Table 7 Transaction tableau for the carbon offsetting example using the extended carbon emission statement with inherent emissions. Abbreviations: PPE = Plant Property and Equipment; ETI = Emissions Transferred In; DE = Direct Emissions; DR = Direct Removals; EQ = Equity.

3.3. Extending other carbon accounting systems

Accounting for inherent emissions in addition to past emissions can also be extended to other carbon accounting systems. In the extended E-Liability accounting system (Kaplan & Ramanna, 2021), inherent emissions are added to the information transferred between companies in a supply chain. Thus, each company receives information about past and inherent emissions of its assets and supplies when it purchases them from its suppliers. Then, existing (financial) accounting systems are used to pass the emission information through the company and allocate it to its products. By adding inherent emissions to the E-Liability system, the accounting system includes two values for each transaction: the E-Liability and the inherent emissions associated with the corresponding asset. While some transactions—such as buying a service from another company—might have a positive value for E-Liabilities but no inherent emissions, transactions that involve physical assets will often carry some inherent emissions. In the extended E-Liability system, the total emissions of an asset (E-Liability + inherent emissions) will always stay the same, as there can only be scope 1 emissions from inherent emissions of the asset. Finally, as shown in section 3.1, the information about both the E-Liability and the inherent emissions of a product is passed on to the company's customers with the transfer of the physical product. A physical examination of the products or work-in-process is possible at different points in time or during the process, such as receiving, storage, and selling, as shown in Figure 1.

In Penman's (2024) carbon accounting system, the accounts are not as closely aligned to the financial accounts. Here, assets represent investments in carbon abatement with expected future reductions. This could be expanded to include inherent emissions that will build up over the lifetime of these assets. For example, the "Direct Carbon Removal" account will have inherent emissions equal to the CO_2 emissions removed from the atmosphere. Accounts such as "Purchased Carbon Credits" and "Avoidance Assets" will not have corresponding inherent emissions accounts. However, the provider of the credits should have inherent emissions in their accounts at least equal to the credits sold minus the emissions emitted to remove the carbon from the atmosphere. For avoidance assets, after the avoidance has occurred, there should be a material with inherent emissions equal to the claimed avoidance that have not been emitted either inside or outside of the company and that would otherwise have been emitted. As in the other systems, only inherent emissions that have been transferred into the company can be emitted as the company's scope 1 emissions. Hence, the inherent emissions that are transferred into the focal company provide the maximum of the potential scope 1 emissions of the company. On the other hand, inherent emissions that are built up—through carbon capture and storage—provide a measure to be deducted from the company's scope 1 emissions. Therefore, a measure of the inherent emissions of all assets should be introduced to allow verification of scope 1 emissions and direct carbon removals.

4. Discussion and conclusion

Extending carbon accounting systems with inherent emissions creates a connection between the physical state of the assets under the control of a company and the carbon accounting system, making the information physically auditable and, thereby, more reliable. Documenting the inherent emissions of all materials and supplies that are involved in a process shows the maximum potential emissions of that process. When carbon-containing material, or dominantly fossil fuels, are taken from nature, initially, all the carbon is still in the material. Hence, the process starts with 100% of the total emissions being inherent. Only when the respective materials are used for combustion or other chemical processes, are the emissions released into the atmosphere, leading to a part or all of the previously inherent emissions becoming past emissions. This enables a comprehensive carbon accounting throughout the company or the whole supply chain, as the total emissions are either inherent in the material or have already been emitted (into the atmosphere).

With regard to answering the overarching research question of this paper (*How can the reliability and the auditability of carbon accounting information be enhanced through the inclusion of inherent emissions in carbon accounting systems?*), the results show that the extended carbon accounting system not only accounts for all the past emissions of the assets before entering a company but it also records the inherent emissions that are under the control of the company at any given time. These inherent carbon emissions accounted for are physically inherent to the material and can be observed and physically examined at several points within the supply chain, especially when entering a company, being stored within a company, and leaving a company. This enables both internal and external auditors to enter the company, to ask to be shown the assets, and to estimate the carbon that is part of those assets. This can be undertaken for all kinds of assets via emissions factors, analyses of their chemical composition, or other methods. If the amount of physically observed inherent emissions in the assets is different from the amount provided by the carbon accounting system extended with inherent emissions, there are either emissions that are not accounted for or the labeling of incoming and outgoing emissions is false. Moreover, the total amount of carbon offsets sold needs to correspond to the amount of CO_2 taken from the atmosphere and stored within the control of the offsetting company. The amount of captured carbon can be validated (Murugan et al., 2020), as it needs to correspond to the amount of inherent emissions in the accounting system. This removes the high uncertainty of offsets and adds a layer of control to the process, enhancing the trustworthiness of these otherwise critically discussed measures (Badgley et al., 2022; Trencher et al., 2024).

As shown, accounting for inherent emissions alongside past emissions enables the detection of errors in the quantification of emissions or entirely overlooked (misrepresented) emissions. Customers who receive falsely labeled information about the inherent emissions of their supplies could even file a complaint or refuse acceptance of the goods, just as they would with a defective supply. If they do not do this, the false inherent emissions will become their responsibility and this will indicate that they did not report all of their scope 1 emissions in the case of an audit or any other investigation. The same is true when information about inherent emissions of goods is not available or underreported. This would also lead to differences between the accounting system and the results of a physical examination. Therefore, to avoid these differences, customers have an incentive to check the information transferred to them along with the physical goods. This extended interest of reporting truthful information can also mitigate greenwashing, a malpractice intensively discussed in the literature (de Freitas Netto et al., 2020; Free et al., 2024).

The additional information about inherent emissions can influence a company's decisions with respect to its purchased supplies, materials, fuels, and other assets. As inherent emissions provide information about the emissions that can be emitted with the materials of the assets, this information can influence managers' purchase and design decisions. Some fuels or materials do not include inherent emissions. A prominent example is that of hydrogen: although hydrogen production is energy intensive (Glenk & Reichelstein, 2019) and can, depending on the energy mix, therefore have a large amount of past emissions in the supply chain, it has no inherent emissions. Even after consumption of all the hydrogen purchased, there are no additional scope 1 emissions to be reported. Therefore, a manager might choose to use materials with lower inherent emissions—while also considering past emissions—when purchasing new fuels and materials. Such changes in the decision-making behavior of managers might lead to design changes in products and processes, which would have positive impacts on the mitigation of climate change.

The information generated by comprehensive carbon accounting is relevant to various stakeholders, including investors, especially in combination with other information. Assessing a company's emission intensity requires a comparison of the information about total emissions (both past and inherent) generated by a company with its revenues through measures such as eco-efficiency (Burritt et al., 2002). Such measures provide information about revenue or profit per ton of CO_2 emitted and can be more informative for investors when assessing environmental impacts on society than the value placed on a good by customers and the market. Additionally, such condensed information can help to highlight risks to the company, specifically as the price of CO_2 emissions is expected to increase in the future (Rennert et al., 2022).

Data availability and complexity are two challenges of including inherent emissions in carbon accounting. While the emissions factors for fuels and natural gas are widely available, the inherent emissions of other materials might be more difficult to record initially. Whereas the allocation of inherent emissions to a product is possible with reasonable effort, the initial implementation of this extension will require some effort. Additionally, accounting for inherent emissions introduces more complexity, as there are changes not only for material movements but for scope 1 emissions as well. To ease the implementation of inherent emissions into carbon accounting systems, this additional information needs to be incorporated into existing carbon accounting software. This extension of the software should enable carbon accounting, with a carbon value along each financial transaction performed, not only for past emissions (Distler et al., 2024) but also for inherent emissions. However, for companies that already have transactional carbon information available to them, the additional information needed is only a single value for inherent emissions, since existing data can be used. Furthermore, in financial accounting, assets are physically examined and counted during periodic inventory taking. Hence, companies could take this opportunity to also assess the inherent carbon under their control.

In future research, the extension of carbon accounting with inherent emissions should be assessed via case studies in order to identify any additional barriers to its implementation as well as ways to overcome such barriers in practice. The examples included in this paper are rather illustrative. It should also be noted that intentional malpractices might still be possible and difficult to detect. For example, if companies try to hide their emissions, they could (falsely) allocate inherent emissions to difficult-to-observe internal accounts. However, by aligning financial and carbon accounting transactions (Distler et al., 2024), the opportunity for fraud can be reduced. Additionally, future research can uncover how fraudulent behavior could be detected both conceptually and in practice.

Further opportunities for future research lie in the areas of accounting and interdisciplinary studies. It could be examined how accounting for inherent emissions can be incorporated into a company's decision making. A quantitative analysis of how managers' choice of materials and supplies is influenced by the introduction of accounting for inherent emissions might be a fruitful direction in this vein. In addition, an analysis of the change in (reported and actual) total emissions within a company after implementation would also be interesting. In collaboration with the engineers or the natural sciences, methods to quickly and cost-effectively estimate inherent emissions in supplies would simplify the implementation process for companies and facilitate the introduction of accounting for inherent emissions. The results of these studies would not only expand the understanding of improved carbon accounting but would also be highly relevant for managers seeking to improve their carbon accounting and carbon management.

Adding more information to be disclosed comes with proprietary costs. Proprietary costs are costs that arise from providing more insight into a company through the disclosure of increased internal information (Verrecchia, 1983). The costs of this extension associated with providing third parties with additional insight into the carbon data are limited, as the extra data provided externally (information about the carbon in the material composition provided to customers) could be observed anyway. Proprietary costs also include preparation costs (Prencipe, 2004). However, incurring these additional costs would also yield benefits for a company because the additional information content helps to credibly signal a commitment to transparency and environmental improvement due to more effective audits and assurance of the carbon accounting information. However, as the auditor or assuror does not need to examine emission flows but only to consider a time-independent inventory, the benefits of the more robust information are likely to outweigh the additional costs. Future empirical research could be helpful in determining the actual costs and benefits of implementing inherent carbon accounting.

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