Verifiable Carbon Accounting:

Systems, Methods, and Auditability

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Introduction

The verifiability of carbon emissions, a fundamental aspect of greenhouse gas emission disclosure, has become a critical and increasingly discussed issue in carbon accounting (Borghei, 2021; Bowen and Wittneben, 2011; Glenk, 2023; Heiss et al., 2024). As carbon metrics have begun to shape regulatory compliance (Bui and Fowler, 2019; Imoniana et al., 2018), capital market decisions (Chapple et al., 2013; Jaggi et al., 2018), supply-chain coordination (Becker, 2025; Liew and Cao, 2025), and internal decarbonization strategies (Asam et al., 2025; Johnson et al., 2024), the credibility of the underlying information becomes pivotal. The growing concern over greenwashing emphasizes the importance of this problem (Du, 2015; Free et al., 2025; Seele and Gatti, 2017). Greenwashing undermines the credibility of sustainability claims and poses a significant risk to the integrity of carbon information. Yet, carbon accounting differs from many established accounting domains. Once emissions are released, they disperse into the atmosphere and are no longer traceable to their emitter. This physical characteristic of greenhouse gases makes it difficult to detect errors or intentional misreporting after the emissions have been released, and it constrains both external assurance and internal control.

Providing credible carbon accounting information is important because it increasingly carries economic and institutional consequences, while remaining vulnerable to misstatements. Externally, disclosures influence investor assessments (Aswani et al., 2024; Griffin et al., 2017), consumer choices (Beyer et al., 2024; Lohmann et al., 2022), and corporate legitimacy (Akhter et al., 2022; Qian and Schaltegger, 2017). Internally, carbon information is required for operational control (Bui et al., 2022; Johnson et al., 2024), product and process design (He and Yu, 2021; Peng et al., 2019), supplier selection (Harju et al., 2025; Hsu et al., 2013), and investment decisions (He et al., 2022a; Vesty et al., 2015). If the data used for these purposes cannot be verified, then stakeholders might not trust the disclosure and firms face both reputational and regulatory risks. Inside the company, weak verifiability also undermines managerial learning. Organizations face challenges to optimize processes based on numbers that are not sufficiently trustworthy, or they may underinvest in decarbonization initiatives if reported baselines and progress measures are not reliable. The empirical indications, including frequent Scope 1 corrections and observed misreporting cases (Aobdia et al., 2025; Cohen et al., 2026), highlight that the challenge is not theoretical. It is a practical barrier to effectively managing carbon emissions and, in a broader sense, to credible sustainability transitions. Therefore, this dissertation treats verifiability not as a purely technical measurement issue but as a methodological accounting problem. It asks the question which concepts, balances, and system structures are required so that carbon information can be audited with evidence that is independent, reproducible, and practically scalable?

This dissertation consists of three chapters[1] that approach this overarching problem from complementary angles and with different levels of analysis. The first chapter provides a systematic literature review on verifiability in carbon accounting and carbon disclosure. To capture the breadth of the analyzed literature, the literature review adopts a topic modeling approach. Hence, it organizes and synthesizes insights from multiple research streams, including auditing and assurance, economics and governance, and technical innovations such as blockchains, remote sensing, satellite imaging, and artificial intelligence. The review identifies where existing verification approaches face limits, and which solution pathways have been proposed across disciplines. By integrating these perspectives into a framework, the chapter establishes both the depth and relevance of the verifiability challenge and the need for interdisciplinary solutions that link accounting knowledge with physical and technological realities.

The second and third chapters develop a specific response to the gap that carbon accounting systems often record emissions without providing robust mechanisms to detect errors through accounting logic and observable evidence. Chapter 2 addresses the problem *inside* the firm, at the level of environmental management accounting and process information. This chapter focuses on Material Flow Cost Accounting (MFCA), a method based on physical input-output balances that has been widely used to quantify material flows and costs and has also been extended to energy and emissions contexts (Christ and Burritt, 2016; Dekamin et al., 2022; Schmidt, 2015). The chapter shows that even when MFCA produces emissions data, these emissions often cannot be validated using input-output balances. In particular, misestimation of Scope 1 emissions may remain undetected because the balancing logic does not systematically account for emissions within processes that emit CO_2 through combustion or other chemical processes. To resolve this, Chapter 2 introduces the concept of inherent carbon and formally extends MFCA input-output balances allowing the detection of inconsistencies and validating emissions data through balances of input and output emissions. The proposed extension is formally introduced and illustrated with numerical examples. It is discussed under different responsibility regimes as the interpretation of inherent carbon depends on how accountability for emissions is assigned across the supply chain.

[1] Please note that each chapter refers to itself as “this paper”.

Chapter 3 extends recently introduced carbon accounting systems (Kaplan and Ramanna, 2021; Penman, 2024; Reichelstein, 2024). Current corporate carbon accounting frameworks predominantly track emissions that have already occurred, while leaving auditors and stakeholders with limited means to reconcile reported Scope 1 emissions against physically observable evidence once those emissions have been released. This auditability gap is particularly important in light of recurring Scope 1 misstatements and subsequent corrections documented in practice, as well as publicized cases of underreporting across industries and jurisdictions (Aobdia et al., 2025; Cohen et al., 2026). The chapter proposes to complement existing carbon accounting systems by accounting for inherent emissions: potential emissions embedded in materials and goods under a company's control that may be released in the future through chemical processes. Chapter 3 also extends the concept of inherent carbon from CO_2 to other greenhouse gases (inherent emissions). By treating inherent emissions as a physical stock, the accounting system can track emissions associated with a company's assets that can be examined through physical inspection, weighing, and other forms of material assessment. Accounting for inherent emissions enables a physical reconciliation between accounting records and observable states that allows for reliable tracking of emissions similarly to established auditing standards in financial accounting. Using numerical illustrations, the chapter demonstrates how this extension improves error detection and supports more comprehensive and physically auditable carbon audits, strengthening the reliability and credibility of carbon disclosures.

In summary, the three chapters advance carbon accounting from a domain that often relies on plausibility and fragmented controls toward one that is verifiable by design. Chapter 1 frames the problem and clarifies why verifiability remains constrained even when reporting and assurance markets expand. As the proposed solutions are still dispersed across disciplines, the still dominating single-discipline approaches struggle to address the full challenge. This overview and synthesis motivate the *internal* accounting-based approach developed in Chapter 2 on the process level based on material flows and Chapter 3 on the firm level, focused on both *internal* and *external* reporting with corresponding audits. Chapter 2 demonstrates how extended MFCA balances enable validation to be operationalized within internal process accounting at the point where emissions data is produced and used for managerial decisions. Chapter 3 then generalizes the underlying logic to a broader accounting architecture for firms, linking carbon emissions information to observable stocks and thereby improving auditability and the potential for credible assurance. The chapters follow a deliberate progression - from synthesis, through internal method extension, to the broadening of firm-level carbon accounting systems - while maintaining a consistent emphasis on detectability of errors and the credibility of carbon accounting information.

Accounting is particularly well suited to tackle these challenges because verifiability is one of its core organizing principles. Financial accounting, management control, and auditing have developed a mature infrastructure for producing decision-useful information that can be audited, challenged, and reproduced on a sound evidence basis. This infrastructure includes concepts of recognition and measurement, documentation and internal control, reconciliation and balancing, and independent assurance. Carbon accounting has adopted parts of this infrastructure, but often without fully addressing the physical uniqueness of emissions. The dissertation's central contribution lies in translating accounting's verification logic into a domain in which the underlying phenomenon is no longer naturally observable after it occurs. Rather than treating carbon information as a separate technical dataset that can only be improved through better measurement devices or more sophisticated estimation, the dissertation shows how accounting design can create verification capacity by connecting records to physically meaningful stocks and stock-flow relationships.

Taken together, the dissertation contributes to a structured understanding of why carbon verifiability remains difficult and offers an accounting-centered pathway to improve it. Chapter 1 clarifies the problem space and the fragmented nature of existing solutions. Chapter 2 introduces a validation approach for MFCA as a tool for internal carbon management. Finally, Chapter 3 presents a novel methodological approach to integrate physically observable carbon stocks into carbon accounting systems, enabling physical audits. All three chapters establish an interdisciplinary understanding that improving trust in carbon accounting is not only about better sensors, more detailed standards, or stronger external assurance markets. Moreover, this dissertation shows that verifiable carbon information for internal and external purposes requires well-designed accounting systems that create auditable traces and validation checks, so that carbon information can meet the rising demands placed upon it by markets, regulators, and organizations themselves.

1. Verifiability of Carbon Information: A Systematic Literature Review with Topic Modeling

Abstract

Verifying carbon information is critical for enhancing the trust and transparency of carbon disclosures. So far, confidence in carbon disclosures by companies has been constrained by frequent misstatements and false claims. Improving the reliability and trustworthiness of carbon information demands an interdisciplinary approach combining business and technical knowledge. This article investigates how different pathways in auditing, assurance, economics, and emerging technical solutions – including blockchain, satellite data, and artificial intelligence – may help overcome the challenges of carbon verification. Through a systematic review of the literature, enhanced with a topic modeling analysis, we find that different approaches are proposed across different research streams. This review stresses the importance of integrating financial, environmental, and technical expertise to develop credible verification mechanisms. By synthesizing these findings in a framework, this review identifies different elements of a verification system that increase credibility in reported carbon information. It underlines the necessity of looking beyond single disciplines to support verifiable and trustworthy carbon disclosure.

Keywords: *carbon accounting, verification, auditing, assurance, environmental management accounting, topic modeling, literature review*

1.1. Introduction

Accurate and independently verifiable carbon data form the empirical foundation for evidence-based climate policy, enabling corporate decision makers, investors, and regulatory bodies to assess progress toward net-zero targets and hold emitting entities accountable under international frameworks such as the Paris Agreement. The accuracy of carbon information originates from the choices firms make regarding how they define organizational boundaries and the reliability of reported carbon information depends on its verifiability, which can be supported by third-party assurance (Berg et al., 2024). However, recent studies suggest that the measuring, reporting, and verification (MRV) processes, which are responsible for measuring, tracking, verifying and confirming emissions data, can be insufficient and lack transparency (Körner et al., 2025).

In particular, verification of carbon information is a critical issue that has not been sufficiently addressed in research and practice. Verification is defined and treated as a broad concept in this article. Verification addresses the overarching process from transparently generating carbon information, including internal and external confirmation of its correctness, up to the credibility of the information. Audits and assurance, as internal/external checks and as a third-party appraisal, respectively, are important elements of carbon information verification. Verification affects both the effectiveness of carbon information in reducing corporate carbon footprints (Berg et al., 2024) and the credibility of carbon emission disclosure (Abhishek et al., 2024; Borghei, 2021; Bowen and Wittneben, 2011; Glenk, 2023; Heiss et al., 2024). Although there have been several advances to improve carbon accounting systems (Kaplan and Ramanna, 2021; Penman, 2024; Reichelstein, 2024) through data collection using automatic sensors (Fay et al., 2024; Liu et al., 2020), IT systems (Distler et al., 2025) and large Microsoft Excel spreadsheets (Glenk, 2025), problems associated with these practices may remain undetected in the absence of verification mechanisms. Without reliable verification mechanisms, companies might be tempted to manipulate data in their favor, undermining the credibility of reported carbon information (Di Vaio et al., 2024). Understanding how to improve the verifiability of carbon information is therefore a key concern to ensure that it can be used effectively to support decision-making processes, comply with regulation or market requirements, prevent stakeholders' distrust of disclosure (Free et al., 2025; Marquis et al., 2016), and mitigate reputational and financial risks arising from inaccurate or low-credibility disclosure (Du, 2015; Free et al., 2025; Seele and Gatti, 2017).

To detect false data or to confirm that the data are correct, the information needs to be verifiable. Additionally, to prevent firms from generating false data within the firm, internal verification mechanisms need to be implemented (Trotman and Trotman, 2015). Moreover, assurance through third-party assurance providers can increase trust in the reported information. However, this depends on whether assurance is limited or reasonable, as limited assurance mainly assesses the plausibility of reported carbon information, whereas reasonable assurance requires a more detailed examination and sufficient evidence to confirm the absence of misstatements (Riva and Bavagnoli, 2022). Nevertheless, sustainability reports often contain non-standardized and subjective information, which makes it more difficult to verify them through established procedures typically applied in financial assurance (Channuntapipat et al., 2019).

Compared to financial assurance, sustainability assurance requires a broader and more interdisciplinary set of skills to assess, verify and assure the stated effects of activities on the natural environment. Indeed, the market for sustainability assurance involves two types of assurance providers. There are traditional financial statement assurance providers such as auditing companies and non-accounting technical assurance providers, who often rely on skill sets from the engineering disciplines (Alsahali et al., 2024; Boiral et al., 2019; O'Dwyer, 2011). Distinguishing between assurance providers' knowledge and expertise is critical, as it influences the disclosure quality and the application of specific assurance approaches (Farooq and de Villiers, 2019). While frameworks exist for sustainability assurance, such as the International Standard on Assurance Engagements (ISAE) 3000, the AccountAbility (AA) 1000 (IFAC, 2024), and the International Standard on Sustainability Assurance (ISSA) 5000, which is effective for assurance on or after December 15, 2026 (IAASB, 2026), they are not yet widely used (Channuntapipat et al., 2019).

Several literature reviews on carbon accounting and disclosure have been published. However, most of them provide an overview of carbon accounting practices without specifically addressing verification-related concerns (Ascui, 2014; Di Vaio et al., 2024; Stechemesser and Guenther, 2012; Zheng et al., 2022). In this vein, Zhu et al. (2025) survey the effect of corporate governance on carbon disclosure quality. Borghei (2021) and He et al. (2022b) focus respectively on carbon disclosure and accounting to discuss drivers and barriers of carbon assurance adoption. Hazaea et al. (2023) review the literature on sustainability assurance, including the dimensions of environmental, social, and governance, with only a brief mention of carbon assurance. Furthermore, Hazami-Ammar (2025) looks at sustainability reporting from the exclusive perspective of institutional investors. Finally, Free et al. (2025) focus on the interplay of greenwashing and assurance.

This article provides a systematic literature review supported by topic modeling to examine how the verification of carbon information has been addressed in the literature and how different aspects of verification can affect the credibility of carbon information and disclosure. Specifically, we answer the following research question: *"What is known about the verification of carbon information and how can the different aspects of verification be used to improve the credibility of carbon information?"* To answer this research question, we analyze an interdisciplinary body of literature by considering articles published in journals of different disciplines. As carbon accounting draws insights from different disciplines, this research area requires the integration of studies from multiple and diverse fields, such as business, engineering, and data science, which together can provide a more comprehensive understanding of how verifiable carbon accounting systems can be developed. Given the complexity of studying approaches from different fields, we adopt a quantitative methodology based on topic modeling with a latent Dirichlet allocation (LDA) algorithm to identify the topics that have received the most attention in the literature, as well as to discuss similarities and differences across and within disciplines. A topic, in this context, is a group of words that tend to appear together across documents. Ultimately, we propose an integrated framework that addresses several challenges related to the verifiability of carbon information and identifies emerging solutions that may suggest practical improvements and new avenues for future research.

This study provides multiple theoretical and practical contributions. It highlights theoretical developments around the verification of carbon information from different disciplines. Furthermore, it identifies different elements of verification required to make carbon information credible, both internally, for managers, and externally for stakeholders such as investors, consumers, policymakers, and assurance providers. Finally, it integrates these elements into a framework of requirements and approaches for the verification of carbon information across different settings. In doing so, the review shows that the verification of carbon information is an interconnected system involving information creation, measurement integrity, auditability, external assurance, verification support systems, and digital enablers. These findings are relevant for verifiers, researchers, practitioners, and policymakers.

The following section outlines the research method, which combines a systematic literature review with topic modeling analysis. Section 1.3 presents the descriptive results and provides an overview of the identified topics. Section 1.4 discusses the literature and develops the integrated framework. Finally, section 1.5 summarizes the main contributions and outlines avenues for future research.

1.2. Research method

This study conducts a systematic literature review using a structured and replicable process to identify, evaluate, and synthesize relevant research articles on the verifiability of carbon information. Tranfield et al. (2003) divide the process of conducting a systematic literature review into five steps: identification of research, selecting studies, study quality assessment, data extraction, and data synthesis. These steps and their execution in this review are outlined in Table 1.1.

Step	**Conducting a review**	**Description based on Tranfield et al. (2003)**	**Operationalization in this paper**
1	Identification of research	Develop inclusion and exclusion criteria. Then, conduct a comprehensive search using predefined keywords in multiple databases.	Definition and application of keywords related to carbon accounting, disclosure, verification, auditing, and assurance. Search for academic documents in Scopus and Web of Science.
2	Selecting studies	Apply the inclusion and exclusion criteria rigorously in the document selection process.	The selected articles are peer-reviewed articles and reviews, written in English and published in academic journals. No yearly limit was set. However, the oldest selected paper is from 1998. Conference papers and books were excluded from the search.
3	Study quality assessment	Assess the quality of included studies.	Papers published in high-quality ranked journals (FT50, AJG 4*/4/3, ABDC A*/A/B, VHB A+/A/B) were included in the search. Then, papers whose objective is related to the research question of this review were retained.
4	Data extraction	Collect data systematically from each included study.	Application of preprocessing through text mining and topic modeling analysis using the LDA topic modeling algorithm.
5	Data synthesis	Synthesize findings qualitatively and/or quantitatively, and identify patterns, gaps, and trends.	Use of content analysis, word clouds, topic assignments and other descriptive techniques.

Table 1.1: *Steps of a literature review according to Tranfield et al.* (2003).

1.2.1. Identification and selection of studies

According to Tranfield et al. (2003), the first step in conducting a literature review is to identify studies that address the research question under review. For this purpose, it is necessary to carefully define keywords for the search and search strings to identify papers related to the scope of the review. Thus, key terms on carbon accounting, verification and disclosure were selected to retrieve relevant papers. A first group of terms was intended to capture studies focused on carbon emissions. Accordingly, we selected several terms commonly used in the literature to refer to this concept (He et al., 2022b): carbon, CO_2, GHG, greenhouse gas. A second group of terms was intended to capture studies focused on the preparation and disclosure of data (Borghei, 2021). The identified keywords were: accounting, disclosure and reporting. Finally, the third group of terms was established to identify studies focused on audits, the verifiability and reliability of carbon information (Luo et al., 2023). These terms were: verification, auditing, and assurance. Additionally, we captured related credibility dimensions that might be used in studies that include verification of carbon information (Marlowe and Clarke, 2022). To achieve this, we additionally included the terms reliability and transparency.

The combination of these groups ensures the inclusion of studies that deal with carbon-related disclosures and explicitly address their verification or assurance. Searches were performed in Scopus and Web of Science, two multidisciplinary databases with extensive peer-reviewed coverage. On both platforms, the results were filtered to the ISSN numbers of the included journals as described in the next section. The applied search string was designed to allow for variations in wording and spelling, ensuring that relevant literature was not accidentally excluded.

TITLE-ABS-KEY (carbon OR co2 OR ghg* OR "greenhouse gas*") AND TITLE-ABS-KEY (account* OR disclos* OR report*) AND TITLE-ABS-KEY (verif* OR audit* OR assur* OR reliab* OR transparen*) AND (LIMIT-TO (DOCTYPE,"re") OR LIMIT-TO (DOCTYPE,"ar"))

The same search logic was applied in Scopus and Web of Science at the end of 2025[2]. While the Scopus search led to 1,431 articles, the Web of Science search led to 1,363 articles. The DOI of these 2,794 articles was used as a unique identifier to remove duplicates. This led to a total of 1,760 unique articles. For articles without a DOI, duplicates were removed

[2] The shown search string has the syntax of Scopus. The Web of Science search string is functionally identical but has a slightly different syntax. The final search string filtered on journals that are included in the quality assessment outlined in the next section. As there were over a thousand included journals, we do not include the full syntax here. This was done by adding "AND ISSN(...)" to the search string.

manually. Figure 1.1 shows the number of articles after removing duplicates alongside the number of articles after other search steps.

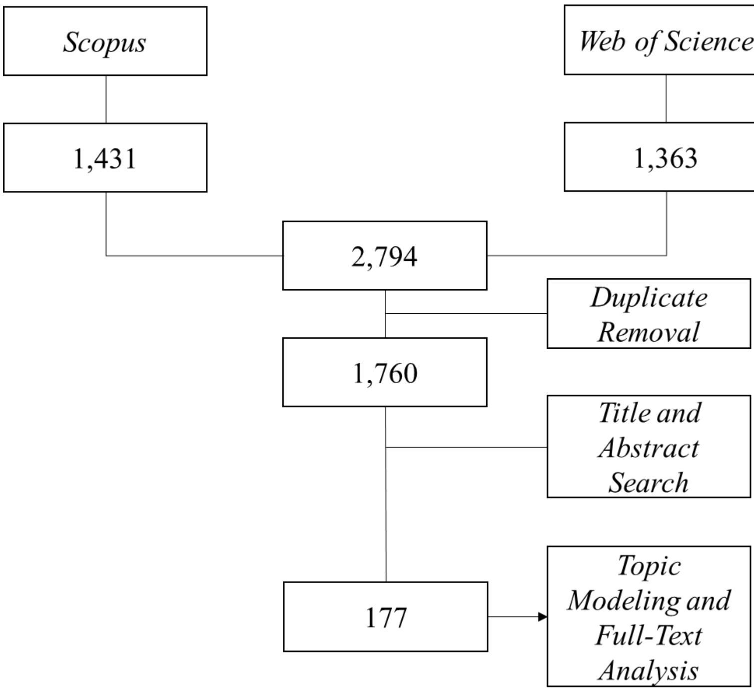


Figure 1.1: *Number of articles after each search step from the individual database search, across the removal of duplicates to the final sample after the title and abstract search.*

1.2.2. Study quality assessment and final selection

Study quality assessment and final selection were conducted in two stages. The first stage involved selecting only peer-reviewed articles and reviews published in high-quality journals. The second stage consisted of selecting studies relevant to the research question of this review.

Note that already in the search step, only articles published in specific journals were considered. We retained only papers published in: a) the Financial Times (FT50) journals; b) journals classified as 4*, 4, and 3 in the Academic Journal Guide (AJG by the Chartered ABS) ranking; c) journals classified as A*, A, and B in the Australian Business Deans Council (ABDC) ranking and A+, A, and B in the VHB-JOURQUAL (Prod, OR, Nama, Rech) ranking. These rankings ensure that reputable journals across business, sustainability, and production management are included in the search. The selected journals also span several disciplinary areas that are relevant to carbon emissions accounting verification.

In the second stage, inclusion and exclusion criteria were established to ensure a suitable selection of studies. Only papers that explicitly examine the verification, auditing, or assurance of carbon information were retained. Analyzed studies address at least one of the following aspects: methods or technologies used for verification and assurance; adoption and implementation of specific verification approaches and assurance types; standards and frameworks for verification, auditing, and assurance of carbon information; consequences of verification, related policies, assurance adoption, and type and characteristics of verifying and assuring bodies. Exclusion criteria were applied to remove studies that did not meet these criteria. Specifically, studies were excluded if they focused solely on sustainability themes other than carbon or if their focus was not on verification, auditing, or assurance. These inclusion and exclusion criteria ensured that the final sample of studies is directly related to the research question, while maintaining a consistent thematic and methodological scope. The aforementioned inclusion and exclusion criteria were applied after the search with the introduced search strings in Scopus and Web of Science. As titles, abstracts, and keywords were searched, there were numerous articles that included the keywords, but did not specifically fit the theme of the literature review. Hence, the articles were independently analyzed and manually coded by the authors, applying the inclusion and exclusion criteria at the title and abstract level. Discrepancies in coding were discussed and resolved afterward. This process left the final sample of 177 articles remaining for the full-text analysis. An overview of the search steps and a summary of the number of papers after each step of the analysis are provided in Figure 1.1.

1.2.3. Data extraction using topic modeling

Once the most relevant studies were identified, we downloaded and converted them into text files for preprocessing using text mining. The programming language "R" and R-packages were used for text mining. This stage stripped white spaces, numbers, problematic symbols and punctuation, and English stop words from the corpus of articles and applied stemming (reducing words to their base or stems) to allow better categorization. We also removed customized stop words, mostly related to academic publications (such as "abstract", "keywords", and "wwwemeraldcom") from the corpus to avoid jeopardizing the cohesion of topics due to their high frequency. Finally, we removed words included in the initial search string, as they would otherwise dominate the sample, since they would be part of every article. After this process, we generated a term–document matrix summarizing word frequencies in each document. At this initial stage, the matrix included a total of 42,353 terms, with 97% sparsity, indicating that most terms had little representation in the corpus (the full text of all articles). In line with previous studies that have applied topic modeling to the literature (e.g., Gaston-Breton and De Stefano, 2025), we set the document-term matrix to have a sparsity at a maximum of 90%, thus reducing the number of terms in the matrix to 2,513 with a sparsity of 67%. In other words, very rare terms that only appeared in very few articles were removed to only include terms that appeared across articles more frequently. Reducing sparsity is important for topic modeling to reduce noise and to create more stable and meaningful topics.

At this point, we undertook the extraction and synthesis of the content of selected studies by applying topic modeling. Topic modeling is a machine learning methodology that uncovers the hidden semantic structure of documents through a Bayesian analysis of text, revealing common topics from documents under review (Blei and Lafferty, 2007). A topic is a statistical pattern of a probability distribution of terms that appear together across documents. This is done by applying the latent Dirichlet allocation (LDA) algorithm (Blei et al., 2003), which identifies topics in the corpus of the selected documents. LDA assumes that each article is a "bag of words" without considering the word order. From this bag of words, LDA extracts a topic distribution by analyzing the frequency and the word co-occurrence distributions of terms that constitute the corpus of each document. At the end of the assessment, all documents in the collection share the same set of topics, but with a different probability calculated and assigned to them by the algorithm (Blei et al., 2003). After computing probabilities, LDA connects a document with the topic having the highest probability. Although LDA's effectiveness in segregating document collections into relevant topics is well demonstrated, a central issue is the extraction of the optimal number of topics before they are identified (Zhao et al., 2015). The choice of the number of topics is essential in model building to balance model overfitting (when topics become too specific) and underfitting (when topics remain too broad). In the first case, the selection of a high number of topics can indeed cover and better represent the document collection being analyzed but it can also diminish their informative value and make the interpretation more complex. By contrast, the extraction of only a small number of topics can undermine the advantages of having separate topics generated by LDA (De Battisti et al., 2015; Zhao et al., 2015). In line with previous studies that have used topic modeling, we applied a heuristic approach based on the perplexity score to determine the appropriate number of topics to extract (Griffiths and Steyvers, 2004; Guerreiro et al., 2016). The perplexity score is equivalent to the geometric-mean-inverse-per-word likelihood and indicates the uncertainty in predicting a single word. Thus, lower values denote a better probabilistic model (Griffiths and Steyvers, 2004). We applied the rate of perplexity change method proposed by Zhao et al. (2015), which determines the most appropriate number of topics at a point when the slope of the perplexity curve changes. This method is based on a cross-validation Gibbs sampling (Griffiths and Steyvers, 2004) that divides corpus data into different subsets (usually five or ten) and uses one sample as a validation set and the remaining samples as a training set. As

Figure 1.2 shows, the point at which the slope of the perplexity curve changes most strongly is at 6 topics. For six topics, the topics also show no overlap in an intertopic distance map, which is shown in Figure 1.A1 in the appendix. We selected six topics because it balances perplexity reduction, interpretability, and non-overlap in the intertopic distance map.

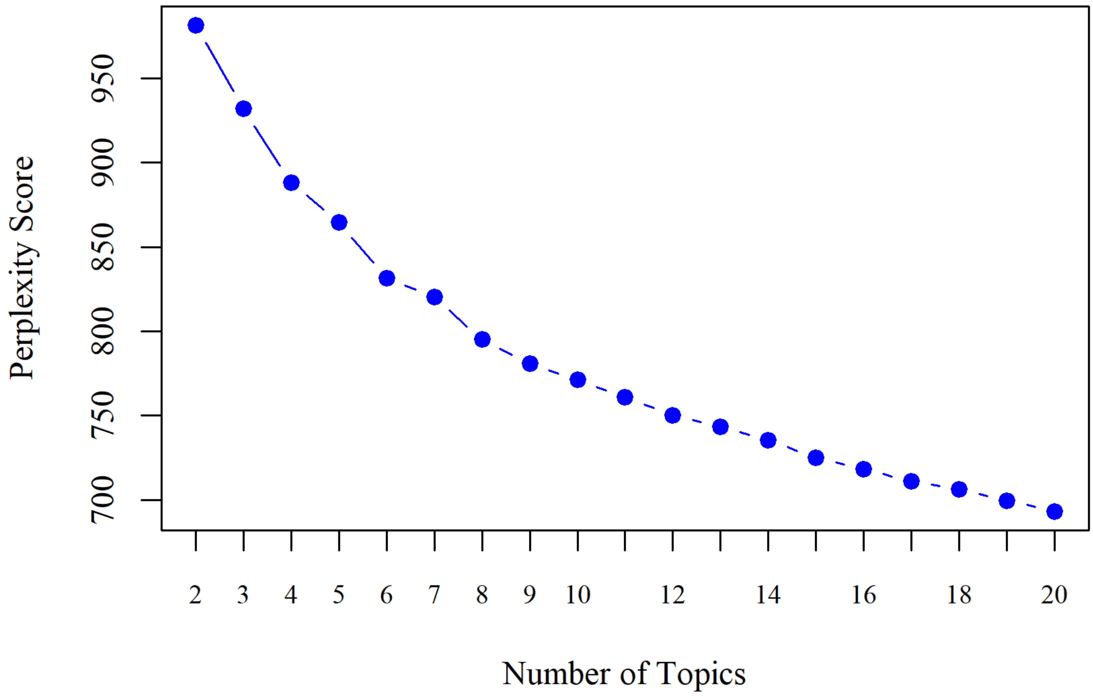


Figure 1.2: *Perplexity analysis leading to the choice of 6 topics for the topic modeling analysis.*

1.3. Results

1.3.1. Descriptive results

The systematic literature search led to a total of 177 articles published in 83 different academic journals spanning different disciplines. Table 1.2 shows the 25 journals that published at least two articles in our sample, along with the subject areas assigned to each journal by Scimago (2026).

Journal	Number of articles	Subject area
1) Journal of Cleaner Production	20	Business, Management and Accounting; Energy; Engineering; Environmental Science
2) Environmental Science and Technology	15	Chemistry; Environmental Science; Medicine
3) Environmental Science and Policy	9	Environmental Science; Social Sciences
4) Journal of Environmental Management	9	Environmental Science; Medicine
5) Applied Energy	7	Energy; Engineering; Environmental Science
6) Accounting and Finance	5	Business, Management and Accounting; Economics, Econometrics and Finance
7) Australian Accounting Review	5	Business, Management and Accounting
8) Business Strategy and the Environment	5	Business, Management and Accounting; Environmental Science; Social Sciences
9) Energy	4	Energy; Engineering; Environmental Science; Mathematics
10) Energy Economics	4	Economics, Econometrics and Finance; Energy
11) Sustainability Accounting, Management and Policy Journal	4	Business, Management and Accounting; Energy
12) Auditing: A Journal of Practice and Theory	3	Business, Management and Accounting; Economics, Econometrics and Finance
13) British Accounting Review	3	Business, Management and Accounting
14) Energy Policy	3	Energy; Environmental Science
15) Forest Policy and Economics	3	Agricultural and Biological Sciences; Economics, Econometrics and Finance; Environmental Science; Social Sciences
16) Foundations and Trends in Accounting	3	Business, Management and Accounting; Economics, Econometrics and Finance
17) International Journal of Auditing	3	Business, Management and Accounting; Economics, Econometrics and Finance
18) Journal of Applied Accounting Research	3	Business, Management and Accounting; Decision Sciences; Economics, Econometrics and Finance
19) Abacus	2	Business, Management and Accounting
20) Accounting and Business Research	2	Business, Management and Accounting; Economics, Econometrics and Finance
21) Ecological Economics	2	Economics, Econometrics and Finance; Environmental Science

Journal	Number of articles	Subject area
22) Finance Research Letters	2	Economics, Econometrics and Finance
23) International Journal of Accounting	2	Business, Management and Accounting; Economics, Econometrics and Finance
24) International Journal of Disclosure and Governance	2	Business, Management and Accounting; Economics, Econometrics and Finance
25) Renewable and Sustainable Energy Reviews	2	Energy
Total	122/177	

Table 1.2: *Journals publishing at least two of the 177 papers in the sample. The subject area of the journal has been taken from Scimago (2026).*

As Table 1.2 indicates, carbon emissions verification is a research area of interest across multiple disciplines including business, management and accounting, behavioral and ecological economics, economics, econometrics and finance, agricultural and biological science, sustainability management, environmental science, engineering, energy, policy, and resource management. This initial result of the literature search anticipates that the topics identified through the topic modeling analysis reflect a multidisciplinary scope. Figure 1.3 also shows the number of articles published per year increased over the period from 1998 to 2025. Specifically, the years 2024 and 2025 show a strong interest in this field with more than twice as many articles published compared to the peak in the years before (15 articles in 2022).

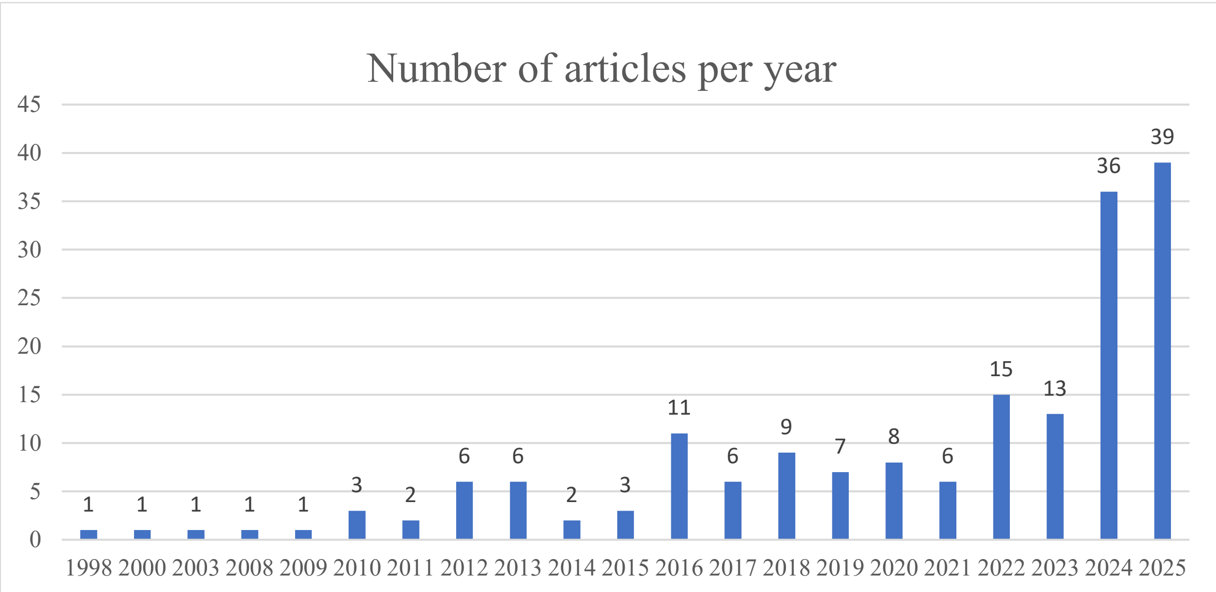


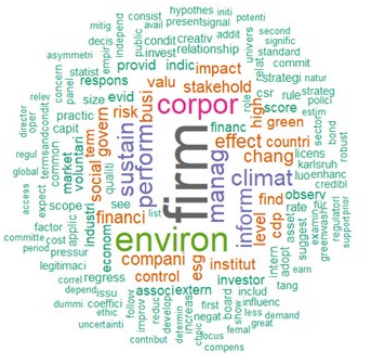
Figure 1.3: *Time series analysis of articles included in this systematic literature review. Note that only years with at least one article published are shown, for example, before 2008 only the years 1998, 2000, and 2003 are included in the figure.*

1.3.2. Topic overview

Table 1.3 shows the word clouds obtained from the application of the topic modeling. We extracted six topics and organized them from the most prominent (Topic 1) to the least prominent (Topic 6) based on the number of articles that the LDA model, through posterior probability estimation, assigned to each topic. Then, a word cloud was generated for each topic to display the most salient terms, i.e., the terms most likely to predict each topic. The importance of each term in the word cloud is depicted by its size, determined by its probability of appearing in a specific topic.

Topic 1 (45 papers)

Stakeholder-Focused Carbon Credibility



Topic 2 (35 papers)

Assurance and Verification Regimes

Topic 3 (35 papers)

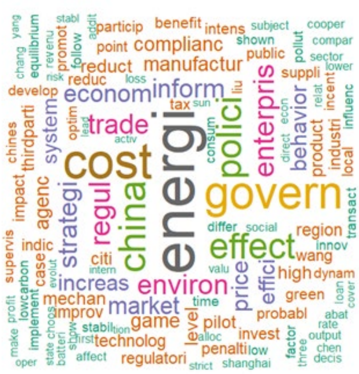
Strategic Reporting under Uncertainty

Topic 4 (22 papers)

Measurement Integrity and Auditability

Topic 5 (20 papers)

From Monitoring to Decision-Usefulness



Topic 6 (20 papers)

Credibility in Fragmented Carbon Systems

Table 1.3: *Word clouds of the word stems (i.e. words like company, companies get shortened to compani) of the most salient terms by topic, along with topic titles.*

Based on the terms highlighted in the word cloud, complemented by the analysis of the articles with the highest topic probability, as assigned by the LDA algorithm, we inferred a name and a description of the content of each topic, as presented below.

1.3.2.1. Topic 1: Stakeholder-Focused Carbon Credibility

The articles assigned to this topic focus on stakeholder-focused carbon credibility and discuss how carbon information can become credible enough to be reported, audited, compared, traced, and, consequently, used by investors and other stakeholders. A first group of studies analyses the creation and disclosure of carbon information. These papers find that disclosure depends on internal governance, including internal audits (Abdalla et al., 2025), public pressure (T. Sun et al., 2025), and regulation (Liu et al., 2025), while missing comparability raises audit costs (Ling et al., 2024). A second group of studies treats assurance and verification as trust enhancing mechanisms that reduce information asymmetry and influence financing outcomes such as the cost of capital and green bonds (Datt et al., 2025a, 2025b; Distadio and Johl, 2025), including carbon auditing, independent assurance, the choice (and background) of assurance providers, and external verification (Olson, 2010; Tang, 2019). A third group of studies shows that the credibility of carbon information also depends on the specific context. This group proposes and examines technical verification and monitoring approaches. Studies within this cohort compare monitoring methods, reveal gaps between projected and realized carbon outcomes, and analyze verification approaches for methane emissions (Olczak et al., 2022), forestry and forest carbon emissions (Aggarwal, 2022; Blanton et al., 2024; Li and Zhang, 2024; Ochieng et al., 2016a, 2016b), and carbon market pilots (Yan et al., 2025; Zhang et al., 2017). Finally, several papers propose technical approaches to make carbon information verifiable throughout the supply chain, including transactional carbon accounting (Asam et al., 2025), blockchain adoption (Ashley and Johnson, 2018; Babaei et al., 2025; Li et al., 2024; Patro et al., 2025), and supply chain tracing architectures (Puschmann and Quattrocchi, 2023).

1.3.2.2. Topic 2: Assurance and Verification Regimes

Articles in this topic domain concentrate on market dynamics of assurance, verification, and what makes carbon information decision-useful and relevant to stakeholders. A central focus of this topic is carbon assurance. Firms seek voluntary carbon assurance when (1) carbon risk, governance, and disclosure incentives are strong (Datt et al., 2018), (2) country- and firm-level institutions shape both the demand for carbon assurance and the choice of (accounting vs. non-accounting) provider (Zhou et al., 2016), (3) perceived assurance quality depends especially on ethics, integrity, and technical knowledge of the assurance team (Green and Taylor, 2013), and (4) carbon assurance is associated with higher disclosure quality and with capital-structure benefits such as greater leverage and longer debt maturity (Bugshan et al., 2024; Luo et al., 2023). A second group of articles addresses the regulatory requirements to make carbon information verifiable. These articles examine systems for forest carbon and emission trading system implementation (Baker et al., 2010), emphasizing standards and disclosure rules for the creation of emission data as essential for credible trading and compliance (Usapein and Chavalparit, 2017; Wu et al., 2014). A third group of studies proposes operational monitoring architectures, such as real-time energy-efficiency monitoring in the maritime industry, that enable more timely carbon reporting systems (Chi et al., 2018). Finally, one paper focuses on a technical approach of decentralized monitoring of emissions using the chemical mass balance to verify annual emission reductions of regions (Blanchard et al., 2013).

1.3.2.3. Topic 3: Strategic Reporting under Uncertainty

Articles in this topic domain center on the shortcomings of carbon information. Inventories are incomplete, vague, or systematically underestimated across city inventories (Davison et al., 2021; Li et al., 2017), aviation emissions (Gössling et al., 2025), and national inventories. Hence, credibility depends on stronger estimation and validation methods (De Oliveira et al., 2025; Reershemius et al., 2023; Shi et al., 2020).

A second group of articles reflects on who can make such information trustworthy. The assurance literature documents (1) an expectation gap between shareholders, companies and assurance providers (Green and Li, 2012), (2) an examination of the diverse landscape of international assurance providers (Green and Zhou, 2013; Huggins et al., 2011), and (3) benefits from assurance and auditor expertise for credit ratings, disclosure quality and reduced greenwashing (Chen and Chu, 2024; Pham et al., 2024; Safiullah et al., 2025).

A third group of articles discusses the role of carbon disclosure as an impression management tool. Reports may be tailored to mask undesired outcomes (Talbot and Boiral, 2018), carbon emissions are priced by the market (Ott and Schiemann, 2023), and truthful disclosure depends on incentives, supervision, and third-party assessment (Xia et al., 2023). Finally, several papers shift from (1) firm reporting to system design, showing that digital verification (Christiansen, 2025), (2) external support for measuring, reporting and verifying carbon emissions (Herman, 2024), (3) pilot trading systems (Li et al., 2021), and (4) blockchain-enabled supply chain tracing (Yang et al., 2025). All these approaches try to stabilize trust in carbon claims but introduce new costs and financing burdens (Köhl et al., 2020).

1.3.2.4. Topic 4: Measurement Integrity and Auditability

This topic addresses how minimizing measurement error and preventing manipulation form the basis for reliable carbon information. As current approaches face measurement issues such as the lack of comparability across carbon accounting tools in different applications, several papers focus on making carbon information comparable and on technical measures to increase comparability (Ball et al., 2023). Related articles address methane monitoring (Erland et al., 2022) and varying estimates of emissions of land-use changes across different remote sensing approaches (Wang et al., 2022). Moreover, building carbon footprints still lacks a consistent internationally accepted verification approach (Fenner et al., 2018). In this vein, Erland et al. (2022) highlight possible technical approaches to monitor methane emissions.

A second group of articles discuss regulatory and assurance mechanisms that protect data credibility. Y. Sun et al. (2025) analyze collusion in falsified emissions data and show that effective government regulation and credible third-party verification are central to limiting fraud. Simic et al. (2024) examine why firms seek carbon assurance, showing that executive incentives and compensation structures shape voluntary assurance demand, while audits become more effective when combined with target setting, information provision, and organizational responsibility (Yajima and Arimura, 2022).

A third group of articles examines blockchain approaches for trustworthy carbon markets and records. Through a literature review, blockchain is highlighted as a tool for many environmental technologies, including carbon emissions, carbon offsetting, and carbon credits (Rani et al., 2024). Muzumdar et al. (2022) suggest improving the credibility of carbon credits in emissions trading systems through blockchain and smart contracts.

1.3.2.5. Topic 5: From Monitoring to Decision-Usefulness

A first group of articles in this topic domain is oriented at the monitoring of carbon sequestration and offset monitoring. They develop or apply tools to detect, monitor, and validate emissions or storage outcomes, including urban source-account models (Dong et al., 2014), low-cost methane sensing (Domènech-Gil et al., 2024), carbon storage monitoring with unsupervised learning (Gonzalez and Misra, 2022), and direct quantification of carbon mineralization in geologic storage (White et al., 2020). Jagger and Rana (2017) extend this logic by showing how publicly available social and spatial data can be used to monitor social effects of forest preservation for carbon credits.

A second group of articles moves from measurement to reporting quality and assurance. Braam et al. (2016) show that poorer performers report more overall, while external assurance is associated with more rigorous and verifiable reporting. Sánchez-Sancho et al. (2025) further show that professional and rigorous sustainability assurance is linked to lower idiosyncratic risk in carbon-intensive firms.

A third group of articles highlights why this information matters for external users. Aldy et al. (2025) show that emissions disclosure reduces valuation discounts tied to carbon exposure, especially for Scope 1 and Scope 2 carbon information. The literature review by Hazami-Ammar (2025) emphasizes that institutional investors need more consistent, reliable, and better-assured sustainability and carbon information, while He et al. (2022b) map carbon accounting as a field spanning disclosure, management, performance, and assurance.

1.3.2.6. Topic 6: Credibility in Fragmented Carbon Systems

The literature of this topic highlights the difficulty of producing trustworthy carbon information when emissions are dispersed across technologies, sites, suppliers, and reporting layers. Several papers show that underlying data are often biased. Methane emissions are heavily underreported relative to direct measurements (Festa-Bianchet et al., 2023), emission values used in biofuel regulation lack completeness, transparency, and representativeness (Bicalho et al., 2019), and Scope 3 reporting faces major transaction costs and coordination barriers across value chains (Patchell, 2018). In parallel, research focusing on carbon capture and storage stresses that monitoring, verification, and accounting depend on understanding subsurface CO_2 distribution and detectability under geological heterogeneity (Behzadi et al., 2011).

A second group of articles examines how credibility can be strengthened within a firm. Multidisciplinary carbon assurance is more effective when teams sufficiently elaborate different expert perspectives (Ekasingh et al., 2019) while environmental audits are positively associated with the volume and quality of carbon-emissions disclosure in UK higher education institutions (Saha et al., 2021).

A third group focuses on emerging tools and risks in disclosure systems. Artificial intelligence tools can help to improve environmental disclosure quality through stronger internal controls and external monitoring (Zhao et al., 2025), blockchain is proposed as infrastructure for traceable carbon-credit and supply chain records (Basu et al., 2024), yet greenwashing remains a central threat because carbon performance can diverge from actual decarbonization outcomes (Li et al., 2025).

1.4. Discussion and framework development

1.4.1. Toward an integrated framework for the verification of carbon information

The topic modeling analysis and the discussed themes within and across topics reveal that verification, audits, and assurance require a whole system, not a single measurement or verification approach, as each approach, individually, is not capable of solving all challenges. Hence, carbon verification is not a single step applied to already reported or accounted carbon information. Credible verification requires several steps that begin when the information is created until it is verified. First, carbon information has to be produced with internal capabilities that enable internal controls, validation, and the ability to identify strategic (or misleading) reporting. Then, the information needs to be measured through systems that are comparable and auditable (by providing comprehensive audit trails across transactions). Next, external assurance and verification can reduce information asymmetry, especially if the assurance providers possess the necessary (interdisciplinary) skills and training. To ensure that companies report their carbon information truthfully, regulatory incentives need to be strong and, ideally, tested against evidence not generated by the reporting firm. These steps are supported by technical tools, regulatory frameworks, and external evidence as system conditions to provide information that is decision-useful for investors, managers, regulators, and consumers. The framework in Figure 1.4 presents these steps and their connection. In this sense, verified carbon information represents the outcome of interacting organizational, technical, and institutional conditions.

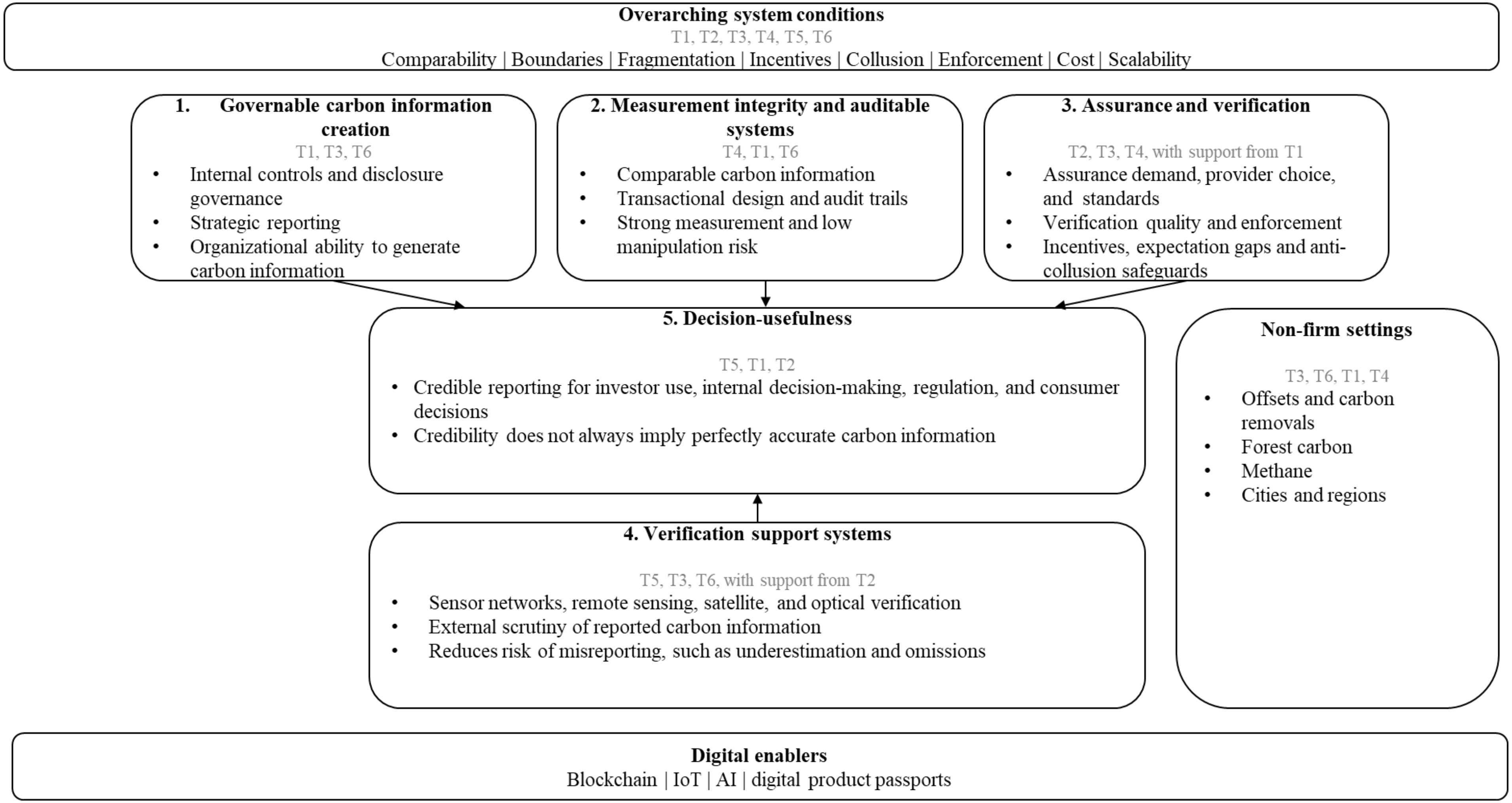


Figure 1.4: *Framework of the elements for building a credible carbon verification system. T1, …, T6 refer to the topics (1, …, 6) that have mainly informed each box.*

1.4.2. Verification begins with governable carbon information creation

The literature (Topics 1, 3, and 6) shows that carbon information requires firms to be able to measure and create credible carbon information within their organizational structures. These studies show that verification begins when the carbon information is created. This implies that verification problems are created before any formal verification is carried out. Carbon information is easier to verify when firms have defined responsibilities, stronger internal controls around carbon accounting and disclosure, and carbon expertise. The framework in Figure 1.4 captures this in Block 1, showing that verification requires disclosure that is produced in a way that can later be verified.

Stronger internal and external scrutiny is associated with higher disclosure. These enabling factors include types of audit committee expertise (Abbasi et al., 2024, Topic 1), internal audit capacity (Abdalla et al., 2025, Topic 1; Trotman and Trotman, 2015, Topic 1), and environmental audit activity (Saha et al., 2021, Topic 6), which are positively related to disclosure[3]. Furthermore, the environmental commitment of the country the firm operates in and institutional settings shape the quality of disclosures at least as much as underlying environmental performance (Alrazi et al., 2016, Topic 6). The literature presents these results from several angles. Environmental management accounting, as a management-focused extension of environmental accounting, is associated with an improvement of carbon management and disclosure quality (Qian et al., 2018, Topic 2), audit-partner climate expertise is associated with more comprehensive climate-risk disclosure (Pham et al., 2024, Topic 3), and digital or AI-enabled control environments can strengthen internal-control and external-monitoring channels for environmental disclosure (Albert et al., 2025, Topic 1; Zhao et al., 2025, Topic 6).

Governable information creation is necessary but not sufficient, as carbon disclosure can be strategically and selectively framed, and only loosely connected to actual emissions outcomes. Talbot and Boiral (2013, Topic 1) show that trust in corporate carbon information is undermined by technical complexity, weak transparency, and deficiencies in verification practice itself. Furthermore, Callery (2023, Topic 4) shows that climate ratings can be influenced by engaging in strategic disclosure while Chen and Chu (2024, Topic 3) find that higher carbon emissions are associated with more greenwashing behavior. However, stronger controls and oversight can weaken that undesirable link (Chen and Chu, 2024, Topic 3). Li et

[3] Please note that the citations are presented with their associated topic in this section. This is done deliberately to show the reader which topics mainly influenced the framework development. The associated topic is shown after the year of the publication.

al. (2025, Topic 6) add that firms can get high environmental, social, and governance scores even when they have high emissions and high emission intensities. Talbot and Boiral (2018, Topic 3) also show that sustainability reports can use strategic disclosure for impression management rather than neutral representation of the actual environmental impacts. Even more formalized disclosure does not fully solve the problem. Carbon-neutrality disclosures often remain weak on boundaries, reductions, offsets, and monitoring, leaving users of the information uncertain about what has actually been measured and what remains omitted (Boiral et al., 2024, Topic 6).

In summary, the literature shows that governable information creation is necessary as a first step to create verifiable and credible carbon information, but that it is not sufficient as even extensive disclosure can remain strategically managed, weakly specified, and only partially representative of actual carbon emissions.

1.4.3. Verification depends on measurement integrity and auditable systems

Across the literature (Topics 1, 4, and 6), comparability problems arise before verification or assurance because the measurement systems use different boundaries, data sources and emissions factors while being too aggregated and without audit trails. These challenges motivate the second block of the framework, measurement integrity and auditable systems. Carbon information cannot become robustly verifiable if the data-generating system produces information that is weakly comparable, weakly documented, or can be manipulated. Hence, the carbon accounting system needs to be designed to enable verification.

The credibility of carbon information and its verifiability depend on the integrity of the measurement system. In emissions trading system research, the availability of firm-specific (Wu et al., 2014, Topic 2) or sector-specific emissions factors (Usapein and Chavalparit, 2017, Topic 2), and strict enforcement of the regulations are named as conditions for credible reporting (Li et al., 2021, Topic 3) while the responsibility to pay for external verification (firm or regulator) could also influence independence of firm and assurance providers, a problem well known from the auditing literature (Zhang et al., 2017, Topic 1). Similar problems appear in other contexts. City inventories can differ because of missing data, heterogeneity of measurement approaches, and inconsistencies (Li et al., 2017, Topic 3). In the same vein, carbon methodologies in the construction sector also diverge in boundaries and methods (Fenner et al., 2018, Topic 4), and Scope 3 reporting remains difficult and prone to errors because cross-organizational measurement and verification depend on data sharing that many value chains do not sufficiently engage in (Patchell, 2018, Topic 6). With regards to methane emissions and shipping, the problem is at the source. Reliable primary data, responsibilities, and valid operational datasets are often missing or of low quality (Olczak et al., 2022, Topic 1; Poulsen and Johnson, 2016, Topic 1).

The literature specifically calls for auditable carbon accounting architectures to enhance the audit trail they leave behind. Such architectures could draw on established standards from financial accounting and double-entry bookkeeping that generate book records for each physical and/or financial transaction, often documented in enterprise resource planning-based ledgers (Asam et al., 2025, Topic 1). Similarly, Distler et al. (2025, Topic 4) argue that sustainability information becomes directly connected to financial information when carbon values are attached at the same transactional level of granularity as financial entries. Related proposals build carbon-accounting architectures around a carbon balance-sheet logic (Reichelstein, 2025, Topic 6), making carbon information more traceable, more structured, and more susceptible to familiar audit procedures (Easton et al., 2025, Topic 1). These studies are design-oriented but they emphasize that carbon information becomes more verifiable when it is embedded in systems, which create transaction-level audit trails rather than only accounting for carbon in aggregated disclosures.

Overall, block 2 of the framework treats measurement as an important building block that emphasizes measurement standards similar to established accounting standards. Based on these standards, comparable carbon information, transactional design, and audit trails generated by the carbon accounting system can be achieved.

1.4.4. Sustainability assurance is an interdisciplinary verification mechanism

The literature (Topics 2, 3, and 4, with support from Topic 1) positions sustainability assurance as more than an extension of financial audit. While it also helps to build credibility through external verification, the required skills are very different from financial assurance. Sustainability assurance requires different assurance providers, standards, and more diverse assurance teams. As emissions inventories involve boundaries, offsets, removals, emissions factors, operational records, and supply chain dependencies that differ materially from the logic of traditional financial statements, accounting assurance providers may not be perceived as credible as they are for financial assurance due to the interdisciplinary aspects of sustainability assurance (Olson, 2010, Topic 1; Simnett et al., 2009, Topic 4). The necessity of assurance is captured in Block 3 of the framework in Figure 1.4, highlighting the importance of third-party verification for building credibility.

When assurance is not mandated by regulations, firms might only seek it when disclosure alone is perceived to be less credible to their stakeholders. Voluntary carbon assurance is more common when firms face higher carbon risk (Datt et al., 2018, Topic 2), greater information asymmetry (Fan et al., 2021, Topic 1), more complex carbon profiles, and greater scrutiny by stakeholders (Luo and Zhang, 2025, Topic 3). Demand for voluntary assurance is influenced by stakeholder pressure (Rohani et al., 2023, Topic 1), legal enforcement (Zhou et al., 2016, Topic 2), corporate governance, and internal incentives such as executive compensation structures (Simic et al., 2024, Topic 4).

Furthermore, the literature shows that sustainability assurance is not a homogeneous market or signal. Provider choice is important as the assurance market includes both accounting and non-accounting providers. Whether firms choose accounting or non-accounting providers depends on legitimacy pressures (Datt et al., 2020, Topic 1) but also on the different (interdisciplinary) skills required by assurance providers when assuring carbon information in contrast to financial information (Green and Zhou, 2013, Topic 3; Huggins et al., 2011, Topic 3). Perceived provider quality depends on ethics, integrity, and carbon-specific expertise rather than on reputation alone (Green and Taylor, 2013, Topic 2). Martinov-Bennie (2012, Topic 1) further argues that as carbon reporting systems and controls are still evolving, more rigorous governance around assurance is necessary.

The literature also shows that the expectation for assurance differs. Green and Li (2012, Topic 3) document an expectation gap between companies preparing their carbon information, assurance providers, and shareholders about what assurance covers and how reliable assured statements are. Inside assurance teams, educational diversity (such as technical and business backgrounds) can improve effectiveness when differing expert perspectives are elaborated (Ekasingh et al., 2019, Topic 6). Reviewer expertise can also change how evidence is weighted and, in some cases, intensify biased evidence rather than reduce it due to discipline-specific foci (Kim et al., 2016, Topic 2).

In summary, carbon assurance quality depends on expertise, team composition, evidence processing, and interpretation. Therefore, the framework treats assurance as an important element of building credibility while being only a part of the overall verification framework in Block 3 of Figure 1.4.

1.4.5. Verification support systems offer an additional control layer

The literature (especially Topics 3, 5, and 6, with support from Topic 2) shows that verification quality depends not only on technical design and professional expertise, but also on incentives, costs, enforceability (risk of the regulatory enforcement through external verification), and institutional context. Independent external verification support systems can be supported through sensor networks, remote sensing, satellite, or other optical verification. However, verification of carbon information can be expensive and verification costs can limit coverage, especially for smaller emitters that might be financially constrained (Coria and Jaraitė, 2019, Topic 2; Wang et al., 2018, Topic 6). Therefore, verification systems have to be robust while being affordable to operate. Block 4 of the framework focuses on how independent external verification support makes carbon information more credible, as it compares reported carbon information to evidence not produced by the reporting system itself.

Independent external evidence helps to uncover misreporting, greenwashing, or errors made when carbon emissions are reported. Sensor networks, satellite data, optical verification, and multi-system monitoring systems can reveal misreporting or underestimation. Urban sensor-network studies show that independent observation can reduce uncertainty relative to bottom-up inventories and verify emissions changes (Asimow et al., 2024, Topic 2; Kim et al., 2022, Topic 2). Studies involving methane monitoring show that direct measurements often exceed reported emissions, especially when large emitters are not included (Erland et al., 2022, Topic 4; Festa-Bianchet et al., 2023, Topic 6). In carbon capture and storage and removal settings, researchers consistently conclude that robust verification depends on combining multiple indicators rather than relying on a single measurement technique (Knapp et al., 2023, Topic 1; Reershemius et al., 2023, Topic 3; White et al., 2020, Topic 5).

Looking at incentives to misreport, several studies examine how verification can be undermined if the incentive system rewards concealment, rent-seeking, or illegal cooperation between firms and assurance providers. This has been investigated through game-theoretic analyses. In emissions trading settings, firms and assurance providers may collude to underreport emissions (Pan et al., 2019, Topic 1; Y. Sun et al., 2025, Topic 4; Yong et al., 2024, Topic 3). The probability of re-verification needs to be high, along with penalties to clearly disincentivize them (Pan et al., 2019, Topic 1; Yong et al., 2024, Topic 3). Related studies investigating fraud distinguish falsification of monitoring data, fabrication of emission reports, and distortion or omission in third-party verification, and consistently find that stronger penalties, higher responsibility awareness, and stricter supervision improve truthful reporting incentives (Y. Sun et al., 2025, Topic 4; Wang et al., 2025, Topic 3; Wu et al., 2024, Topic 3). While continuous monitoring systems do not automatically solve this problem (Wang et al., 2025, Topic 3), externally, independently generated information, such as through the mentioned sensor networks, satellites, and optical verification, can help to increase the probability of detecting fraudulent behavior.

On the policy level, verification is limited when wider reporting systems leave too much discretion for inconsistent boundaries and methods across companies. This is visible across emissions trading pilots (Herman, 2024, Topic 3), IFRS sustainability reporting debates (Yoon et al., 2024, Topic 2), Scope 3 standards (Patchell, 2018, Topic 6), agriculture (Perosa et al., 2023, Topic 2), and monitoring of industrial parks (Huang et al., 2016, Topic 3). These verification support systems help to detect and correct misreporting by creating evidence that has not previously been provided by the reporting firm itself.

1.4.6. Digital enablers provide infrastructure for carbon verification

A recurring theme across the literature (especially Topics 1 and 6 with support from Topics 3, 4, and 5) is the role of digital enablers based on technological advances such as blockchain, Internet of Things (IoT), artificial intelligence (AI) or digital product passports. These tools can support information creation, tamper resistance, measurement, audits, and assurance. In the framework in Figure 1.4 they are shown spanning the base of all blocks.

These digital tools are increasingly presented as solutions to the scalability and lack of transparency of carbon verification. Research focusing on digital verification approaches argues that traditional processes are too manual, periodic, and costly, and that automated data capture, IoT, AI, digital passports, and blockchain can enable more traceable verification infrastructures without gaps or missing information (Körner et al., 2025, Topic 3). Concrete applications use blockchain and related tools to securely and traceably process information on a decentralized secure ledger for renewable-energy credits (Ashley and Johnson, 2018, Topic 1), Scope 3 emissions (Puschmann and Quattrocchi, 2023, Topic 1), distributed abatement investments (Li et al., 2024, Topic 1), aviation emissions (Patro et al., 2025, Topic 1), hydrogen production (Heeß et al., 2024, Topic 5), and carbon-credit ecosystems (Basu et al., 2024, Topic 6).

The literature on digital tools for verification is very explicit about the limitations of the related technologies. Digital traceability does not guarantee that the information entered at each point within the supply chain is correct. Concretely, blockchain can protect the authenticity of recorded data (and uncovers possibly changed or manipulated data), but cannot guarantee the quality of the source where the data is created (Luo et al., 2024, Topic 5; Puschmann and Quattrocchi, 2023, Topic 1). Scope 3 calculations remain only as good as the data of each entity across the supply chain, and digital product passport systems depend on the willingness to share information about the products at each link within the supply chain (Heeß et al., 2024, Topic 5;

Jenkins et al., 2025, Topic 4). Overall, blockchain, IoT, AI, and digital product passports are digital enablers to pass information through the supply chain securely. However, as before, they are just one element of the verification system, as they cannot, by themselves, prove that the underlying information is correct.

1.4.7. Credible carbon information enables decisions

The literature (Topics 1, 2, and 5) shows why verification and the resulting credible carbon information are important economically and organizationally for stakeholders. Studies focusing on the capital and financing markets in combination with carbon information show that carbon assurance and carbon disclosure are associated with lower cost of equity (Datt et al., 2025a, Topic 1, 2025b, Topic 1), better debt outcomes (Bugshan et al., 2024, Topic 2), stronger credit ratings (Safiullah et al., 2025, Topic 3), more favorable market reactions (Distadio and Johl, 2025, Topic 1), and lower idiosyncratic risk in carbon-intensive settings (Sánchez-Sancho et al., 2025, Topic 5). Investors also appear to value specific carbon information more than broad, less specified commitments, especially for Scope 1 and Scope 2 emissions (Aldy et al., 2025, Topic 5). Inside firms, assurance is associated with higher subsequent disclosure quality (Luo et al., 2023, Topic 2), more stringent and more verifiable reporting (Braam et al., 2016, Topic 5), higher investment efficiency (Luo and Pan, 2025, Topic 6), and better carbon performance, even if the effect might be marginal (Alkebsee et al., 2025, Topic 1; Rohani et al., 2023, Topic 1).

On the other hand, credibility gains are always context-specific. A smaller, but visible part of the literature focuses not on firms but on forests, offsets, other greenhouse gases, and cities/jurisdictions. These entities are depicted on the right side of the framework. Forest carbon, offsets, methane, and carbon removals are often difficult to verify because they often require complex verification systems. Even verified forest carbon projects can fall short of projected (and credited) carbon sequestration with audits often finding large deviations from reported carbon information (Aggarwal, 2022, Topic 1; Foster et al., 2017, Topic 3; Li and Zhang, 2024, Topic 1). Stronger verification systems in these settings are also constrained by cost (Baker et al., 2010, Topic 2; Köhl et al., 2020, Topic 3), administrative capacity (Ochieng et al., 2016b, Topic 1), coordination between involved institutions (Ochieng et al., 2016a, Topic 1), and the risk that increasingly stringent verification requirements can become unaffordable (Baker et al., 2010, Topic 2; Köhl et al., 2020, Topic 3).

1.4.8. Overview

The literature across all topics shows that carbon verification is discussed as a multi-layered system to create credibility. The interplay of different features of the verification system is summarized in the framework in Figure 1.4. The overarching system conditions and digital enablers shape the way information is created and verified in a developing system with traditional and new tools. Governance aspects facilitate more dependable carbon information. Measurement integrity and auditable systems explain how those data become comparable, traceable through an audit trail, and less vulnerable to manipulation. Assurance and verification show how different types of assurance providers can lead to different perceptions of the assured information while independent external verification support creates evidence that can be used to validate firm-generated carbon information. Finally, decision-usefulness explains why these layers matter for investors, managers, regulators, and other users but the literature on offsets, removals, methane, and territorial systems also shows why credibility cannot be equated with perfect accuracy.

In summary, the framework advances the literature by integrating the literature across disciplines into an overview of how credible verification of carbon information depends on the interaction of organizational governance and internal information creation, measurement design that enables verification, assurance capacity, verification support systems, and wider system conditions such as boundaries, incentives, collusion risks, enforcement, cost, digital enablers and scalability.

1.5. Conclusion

This article highlights the critical importance of verifiability in carbon accounting as a cornerstone for fostering transparency, accountability, and trust in carbon disclosures. The strong increase in articles published in 2024 and 2025 compared to previous years shows the rising interest and focus of the academic community in verifying carbon disclosures. As companies navigate increasing regulatory pressures and heightened stakeholder expectations, ensuring the reliability and credibility of carbon disclosure becomes increasingly important.

By synthesizing a broad range of research, this review identifies key elements of carbon verification systems that make carbon information credible. These interconnected elements include the creation of carbon information, measurement integrity and the creation of audit trails, third-party assurance and verification, external verification support based on evidence not created within the firm and the resulting improved decision-usefulness.

The framework was developed based on the topic modeling analysis and the synthesis of the literature. It shows that the credibility of carbon information depends on several elements of the verification system. Governable carbon information creation determines whether firms have the ability to internally generate high-quality carbon information, use internal controls, and limit misleading reporting. Measurement integrity and auditable systems determine whether those data are comparable, traceable, and supported by an audit trail that can be validated internally and externally. Assurance and verification, then, add external assurance and verification, akin to financial assurance, but their effectiveness for carbon information depends on the scope of the engagement and on the interdisciplinary expertise brought to the assessment by the assurance provider. Independent external verification support extends this by comparing firm-generated carbon information with evidence not produced by the reporting firm. Thereby, it strengthens the capacity to detect misreporting, omissions, and misrepresentation.

Within the framework, digital enablers (such as blockchain, IoT, AI, and product passports) should be understood as technologies that support and perform different functions. Blockchain and related traceability tools can protect the authenticity of recorded carbon information along the supply chain. AI can support the detection of errors and misreporting through pattern recognition and monitoring. IoT-based systems can improve the timeliness and granularity of carbon information by providing signals in real time. Finally, satellites, sensor networks, and other remote observation systems can provide external information to check and compare firm-reported carbon information. In summary, the framework shows that verifiability in carbon accounting is neither a purely technical problem nor an internal data creation or external assurance problem. It requires an interconnected system that is created when data creation, measurement design, assurance, external evidence, and digital infrastructure are combined in an integrated verification architecture. The literature shows that the central challenge for research and practice is not to identify a single superior verification mechanism but to design combinations of business and technical solutions that make carbon information more credible and, thereby, more decision-useful for investors, managers, and stakeholders while also becoming more resistant to manipulation. Future research should empirically examine how the combination of these tools affects outcomes.

Nevertheless, this study faces limitations. The sole inclusion of peer-reviewed academic articles ensures high quality but limits the scope. As the process of writing an article and having it peer-reviewed takes time, this leads to the exclusion of new and developing solutions by startups, consultancies, or policymakers. This leads to a lag between the formulation of new ideas, new developments, and their publication. While uncovering the underlying topics of the literature that a researcher might otherwise miss, a topic modeling analysis can suppress smaller adjacent themes. Furthermore, as the review shows, the number of articles has increased strongly in 2024 and 2025. This shows that a lot of research is currently being conducted in this area and new technologies, approaches, and standards are likely under development. This makes this review a snapshot of the current verification landscape which might look different in some years.

In conclusion, enhancing the verifiability of carbon information and carbon accounting is not merely a challenge for assurance providers but a fundamental necessity for credible information that investors, internal managers, and other stakeholders can base decisions on. These decisions can help to tackle the climate crisis only when based on credible and dependable carbon information. Going forward, interdisciplinary collaboration among policymakers, academics (of different disciplines), and industry stakeholders will be important in making carbon information more credible to enable effective decarbonization.

1.6. Appendix

Figure 1.A1: *The figure visualizes the relative similarity of the six topics in an intertopic distance map. Each circle represents one topic, and the size of the circle indicates the topic's prevalence in the corpus (text of all articles). A greater distance between circles indicates a lower similarity between topics, while overlapping or closely positioned circles would suggest thematic proximity. The absence of overlap among the six circles indicates that the selected topic solution produces clearly separated and distinguishable topics. The axes PC1 and PC2 represent the two-dimensional projection used for visualization and do not have a substantive interpretation.*

2. Inherent Carbon – Material Flow Cost Accounting with Extended Input-Output Balances for CO_2 Emissions Data

Abstract

Companies need accurate data on the CO_2 emissions of their activities as the basis for decision-making and management of CO_2 emissions. Material Flow Cost Accounting (MFCA) is a method for quantifying the flows and inventories of materials in processes in both physical and monetary units, and it has been extended for producing data on CO_2 emissions. Building on that, this paper extends MFCA by also including *inherent* carbon, which concerns the carbon atoms that are part of the input material flows, inventories, and output material flows. Inherent carbon essentially captures potential CO_2 emissions. The advantage of including inherent carbon is that it allows validating input-output balances and detecting an underestimation of CO_2 emissions. This is especially important when carbon included in material input flows is released into the atmosphere, or when carbon is captured from the atmosphere in output material flows. The interpretation of the data on inherent carbon depends on the responsibility regime in terms of the extraction-based approach, the polluter-pays principle, or the user-pays principle.

Keywords: *carbon accounting, greenhouse gas emissions, material flow cost accounting, extraction-based approach, polluter-pays principle, user-pays principle*

2.1. Introduction

Reducing global warming is one of the great challenges for environmental sustainability and it requires action on several levels (Schaltegger et al., 2022; Tran et al., 2025). Policymakers and regulators formulate, implement, and enforce policies aimed at reducing CO_2 emissions (e.g., Graupner et al., 2024; Ren et al., 2025; Schlipf et al., 2024; Teixeira and Lefèvre, 2025). Individual companies are confronted with the resulting technical constraints, financial incentives, and disclosure requirements (Qian et al., 2015). Thus, managerial tools for monitoring, analysis, and decision-making around CO_2 emissions are needed (Burritt, 2012; Cheng et al., 2023; Johnson et al., 2024). Companies need information for strategic and operational decision-making in relation to CO_2 emissions, such as for designing products and processes, choosing suppliers, and handling waste (Burritt, 2012).

This paper looks into a particular method that companies can use to account for CO_2 and other greenhouse gas emissions, namely material flow cost accounting (MFCA) (Christ and Burritt, 2015; Schaltegger and Zvezdov, 2015). In general, MFCA enables companies to minimize their material losses by uncovering where waste is incurred (Christ and Burritt, 2015; ISO, 2011; Ulupui et al., 2020). Several case studies investigated MFCA in different settings and with different foci, supporting the practical relevance of the approach (Chang et al., 2014; Hakimi et al., 2021; Kukreti and Ganguly, 2025; Schmidt and Nakajima, 2013). Extensions of MFCA have been developed regarding energy and CO_2 emissions (Bierer et al., 2015; Bierer and Götze, 2012; Nishimura et al., 2021; Schmidt et al., 2015; Schmidt, 2015; Sygulla et al., 2011, 2014; Viere et al., 2010).

But even though MFCA can already incorporate data on CO_2 emissions, current extensions of the method face a limitation that could lead to an underestimation of actual Scope 1 emissions. Scope 1 emissions are emitted by a company through its own processes (GHG Protocol, 2004). Specifically, MFCA cannot validate data on Scope 1 emissions using input-output balances. Errors, for example due to measurement problems, could remain undetected. The reason is that MFCA does not check whether *all* carbon leaving the system as CO_2 is consistent with *all* the carbon entering the system as an element within the materials. For the same reason, negative emissions because of carbon offsets (Brander et al., 2021; Gibbins and Chalmers, 2008) may be incorrect. In processes that release carbon from material flows or inventories, or that capture carbon in material flows or inventories, the CO_2 emission information that MFCA produces may contain undetected errors. This shortcoming leads to our research question: *How can the method of MFCA be extended to enable further validation of* CO_2 *emission data?*

The paper presents an extension of MFCA input-output balances by introducing the concept of *inherent carbon*. This refers to the carbon atoms that are part of the input material flows, inventories, and output material flows (such as fuel, wood, or organic polymers), which when released, combine with atmospheric oxygen to form CO_2. We will show in this paper that accounting for inherent carbon can be used to attain validated Scope 1 CO_2 emission information. When also accounting for inherent carbon, the MFCA analysis always has a balance of incoming and outgoing CO_2 emissions, which creates a validation of CO_2 emission data of material flows. Extending MFCA with these balances provides a further check and triggers an investigation if not fulfilled. These validations are of particular relevance, because determining CO_2 emissions is essentially difficult. While there has been extensive research on assurance of CO_2 emissions (Boedijanto and Delina, 2024; Luo et al., 2023; Pitrakkos and Maroun, 2019; Simic et al., 2024), generating accurate, validated, and decision-relevant information about CO_2 emissions is still a challenge. Further, we discuss the interpretation of inherent carbon, which depends on who in the supply chain is held accountable for CO_2 emissions. We discuss various responsibility regimes in terms of the extraction-based approach, the polluter-pays principle, or the user-pays principle (Tukker et al., 2020).

The next section reviews the literature on managing CO_2 emissions within firms and examines the role of MFCA in this context. Section 2.3 then identifies the shortcomings of MFCA for environmental impact assessment. Building on these limitations, section 2.4 extends the MFCA method by introducing the concept of inherent carbon. Finally, section 2.5 discusses the implications of this extension, explains how the results should be interpreted under different regimes, and outlines potential directions for future research.

2.2. Conceptual background

2.2.1. Information on CO_2 emissions for decision-making

Information on CO_2 emissions is crucial to uncover process improvement potentials and analyze the impacts of purchase and investment decisions. The reduction of corporate CO_2 emissions is facilitated by environmental management accounting (Baker and Schaltegger, 2015; Gerged et al., 2024; Johnson et al., 2024). Hence, companies with the goal to incorporate environmental impacts into their decision-making on purchases, investments, process and product design increasingly apply environmental management accounting tools in a decision-relevant, forward looking way (Gunarathne and Lee, 2019). Accurate information of emissions associated with processes and products is especially important for these decisions, as CO_2 emissions are associated with input materials that need to be investigated to identify physically and monetarily relevant inefficiencies (Baars et al., 2022; Busch, 2020). Hence, actively managing a company's environmental impact necessitates incorporating environmental impacts in the internal control systems (Guenther et al., 2016; Gunarathne et al., 2023). This requires analyses of current processes but also of the environmental impact of different future scenarios (He and Bai, 2021; Song and Lee, 2010). These analyses should contain upstream emissions (Scope 3), energy consumption (Scope 2), emissions during the processes (Scope 1), as well as information about the amount and composition of waste generated.

Furthermore, reporting on CO_2 emissions and other dimensions of environmental sustainability can produce positive responses from external stakeholders, such as higher share prices (Bachoo et al., 2013; Berthelot et al., 2012; Friske et al., 2023; Kuzey and Uyar, 2017) or lower cost of capital (Zhou et al., 2017). This aligns with evidence that firms' exposure to climate-related risks and their adaptive capacity are increasingly evaluated through environmental disclosures (Busch, 2020). Also, while in the past consumers may not have cared that much for the CO_2 emissions of the products they purchase (Hornibrook et al., 2015; McKinnon, 2010), they are now incorporating this information into their purchase decisions (Beyer et al., 2024). Consumers who react to positive and negative environmental information with their purchase decisions will have an impact on revenues, a key measure about which investors care when making investment decisions (Dechow, 2023). By calculating accurate information on CO_2 emissions, companies can better manage their emissions and provide more accurate CO_2 emission information to important stakeholders, reducing information asymmetry (Bebbington et al., 2023).

However, producing accurate information on CO_2 emissions is challenging. Data based on the GHG Protocol might be incomplete and include double counting, leading to information that is not decision-useful and inadequate to manage a company's CO_2 emissions effectively (Glenk, 2023; Kaplan and Ramanna, 2021; Wagenhofer, 2024). Comparisons of carbon footprints of company-specific results based on emissions factors show that CO_2 emissions are often underestimated (Gielen and Yagita, 2002; La Motta et al., 2005; Neelis et al., 2005). For example, incorrect classifications of company activities in relation to emission factor databases can lead to vastly different outcomes of carbon accounting across companies (Luers et al., 2022). Furthermore, companies may unintentionally report false data due to errors such as inaccurate sensor and meter readings, incorrect scope of emissions accounting, and missing energy consumption data for equipment which leads to incorrect calculation of CO_2 emissions (Zhang et al., 2019). Hence, methods that integrate physical and monetary material flows—MFCA does this eminently—can help to anticipate and alleviate this challenge. This paper contributes to both environmental management and management accounting by introducing a physically consistent validation mechanism for CO_2 data within the standardized MFCA framework.

2.2.2. Material Flow Cost Accounting

MFCA's central idea is modeling and analysis of the relationship between material flows and their associated costs. It is defined by the International Organization for Standardization (ISO) as a "tool for quantifying the flows and stocks of materials in processes or production lines in both physical and monetary units" (ISO, 2011, p. 19). MFCA is a method to manage costly resources by paying attention to the intended outputs (product) and unintended outputs (material loss) of production processes and assigning the production costs to these outputs (Walz and Guenther, 2021). This economic interpretation addresses a limitation of conventional material flow analyses, which provides limited decision usefulness unless its results are given a value (such as a monetary or emission value) to be translated into actionable insights (Brunner, 2002). The method is based on the principle of material and mass balance (Binder et al., 2009; Pauliuk and Heeren, 2020), meaning that the amount of input materials is equal to the sum of the products and material losses (Kokubu and Kitada, 2015). MFCA considers physical and monetary quantities of material flows as two sides of the same coin (Guenther et al., 2015). It provides an economic complement to physical flows (Wenzel and Radgen, 2023) and helps to identify reduction possibilities of environmental impacts, waste, and costs at the same time (Baars et al., 2022; Schaltegger and Zvezdov, 2015; Ulupui et al., 2020; Walz and Guenther, 2021). Prior research has extended the material-driven approach of MFCA with additional layers to also include flows of energy (Bierer et al., 2015; Bierer and Götze, 2012; Nguyen et al., 2025; Schmidt et al., 2015; Sygulla et al., 2014; Wenzel and Radgen, 2023), CO_2 emissions (Schmidt, 2015; Viere et al., 2010), water (Nguyen et al., 2025; Nishimura et al., 2021; Schmidt et al., 2015), and labor (Schmidt, 2015).

Beyond its methodological foundation, empirical studies have examined how companies apply MFCA with different objectives. MFCA is implemented to reduce the CO_2 emissions of production processes or the total CO_2 emissions of a company (Jasch, 2006; Nakajima et al., 2015). Demonstrating its effectiveness as a tool to manage CO_2 emissions, Burritt and Saka (2006) and Burritt et al. (2019) compare CO_2 emissions of companies before and after the introduction of MFCA. They find significant reductions in waste and resource usage, and therefore lower CO_2 emissions, as a result of closely monitoring the material flows. While MFCA is often used to improve a company's environmental performance, this is often achieved alongside an improvement in economic performance (Bux and Amicarelli, 2022; Nishimura et al., 2021; Sahu et al., 2021). Further, MFCA can be used in the context of the adoption of the circular economy through reduced waste and improved environmental performance (Nishitani et al., 2022; Tisserant et al., 2017).

2.3. Limitations of CO_2 emissions data from MFCA

The main issue addressed in this paper is a limitation of MFCA, namely that it produces data on Scope 1 CO_2 emissions that it does not validate using input-output balances. To understand why this issue exists, it is relevant to consider that data on CO_2 in MFCA (ISO, 2011; Schmidt, 2015) always concerns emissions of a supply chain, a company, or a product that have been emitted in all processes leading to the current state of the material inputs of the focal company. Each entity's emissions in the supply chain are its Scope 1 emissions, which, from the perspective of an entity's customer, are added up as their "imported" Scope 2 emissions (for purchased energy) and upstream Scope 3 emissions (for all other purchased inputs) (GHG Protocol, 2004). In the literature, these are also called E-Liabilities (Kaplan and Ramanna, 2021), emission backpack (Schmidt, 2015), or upstream embedded or embodied carbon (IPCC, 2019).

Nevertheless, current MFCA approaches may not produce correct results for Scope 1 CO_2 emissions if carbon included in material input flows is released, or if carbon is captured in output material flows. However, a systematic check of whether such an error has been made is not explicated. Validation in MFCA is generally done by checking that input-output balances are satisfied. However, in the case of CO_2, input-output balances may not be consistent, but that does not necessarily imply the occurrence of an error, which means these balances cannot be used for a systematic check in current MFCA approaches.

A simple example helps to clarify the issue. Consider a furniture manufacturer that purchases timber to produce tables. The covered processes are called the quantity center in MFCA. Within the furniture manufacturer, wood scrap is generated during the cutting and milling of the timber in the table production. The furniture manufacturer also purchases wood chips for heating the facilities. Consistent with MFCA, the wood scrap initially appears as a material loss, because MFCA distinguishes and traces intended outputs and unintended material losses through physical and monetary balances. The problem emerges when the wood scrap is later used informally for heating instead of being treated as waste. If this internal transfer, for example carried out by machine operators or a cleaning crew, is not reclassified from waste handling to a fuel flow in the emissions layer, the resulting combustion may remain unrecorded. In contrast, purchased wood chips are typically visible in procurement and energy records because they are intentionally acquired for heating, whereas internally generated scrap may remain classified only as production waste. As a result, the CO_2 released when the scrap is burned can be overlooked even though the broader MFCA system appears plausible. This leads to understated Scope 1 emissions and makes the production process appear less emission-intensive than it actually is. Suppose the furniture manufacturer buys 900 kg of timber during this period and has an additional 200 kg of timber in its inventory. Furthermore, it buys 200 kg of wood chips and has an additional 400 kg of wood chips in its inventory. Next, the company uses 1,000 kg of timber in the process of producing the tables. In this step, however, only 800 kg of timber is part of the final product, 200 kg get cut off as wood scrap. When cleaning the production area, the wood scrap is collected to be used for heating. During this period, 300 kg of previously purchased wood chips and 200 kg of wood scrap are burned to heat the facilities. At the end of the period, 100 kg of timber and 300 kg of wood chips remain in the inventory. The cost of timber is 200 € per 100 kg, while wood chips cost 75 € per 100 kg. Table 2.1 shows the result using MFCA (ISO, 2011).

Input	Quantity Center		Output
	Initial inventory	**Final inventory**	
Material (Timber): • 1,800 € • 900 kg timber	Material (Timber): • 400 € • 200 kg timber	Material (Timber): • 200 € • 100 kg timber	Product: • 1,600 € • 800 kg tables
Fuel (Wood Chips): • 150 € • 200 kg wood chips	Fuel (Wood Chips): • 300 € • 400 kg wood chips	Fuel (Wood Chips): • 225 € • 300 kg wood chips	Material losses (Waste): • 225 € • 300 kg wood chips • 400 € • 200 kg wood scrap

∑	∑

• 2,650 €
• 600 kg wood chips
• 1,100 kg timber
	• 2,650 €
	• 600 kg wood chips
	• 1,100 kg timber
	  ○ 100 kg timber
	  ○ 800 kg tables
	  ○ 200 kg wood scrap

Table 2.1: *Numerical example of costs and material flows of a furniture manufacturer using MFCA.*

Going forward, we assume that each kg of timber carries upstream Scope 3 emissions of 0.5 kg of CO_2 (but this will vary between suppliers, customer locations, etc.) and that the wood chips carry 0.2 kg upstream Scope 3 emissions per kg. Further, we assume each kg of wood (both timber and wood chips) will emit 1.8 kg of CO_2 emissions when burned, originating from the carbon atoms in the wood, which are released when it is burned to heat the facilities, reacting with oxygen in the atmosphere to form CO_2.[4]

Using the extension of MFCA by Schmidt (2015), the results can be seen in Table 2.2. We now account for the incoming Scope 3 emissions of the suppliers and the Scope 1 emissions at each step of the analysis. Using this extension, the aggregated Scope 3 emissions of inputs and initial inventory and the Scope 3 emissions of output and final inventory are balanced. However, Scope 1 emissions and, therefore, total emissions are not balanced[5].

[4] The carbon emitted when burning wood is about 1.83 kg CO_2 per kg (rounded to 1.8 for ease of exposition) of wood burned (IINAS, 2014). The exact amount, however, depends on the type and dryness of the wood.

[5] Note that the extension by Schmidt remains balanced as long as no Scope 1 emissions occur. The present example differs from Schmidt's example because it explicitly incorporates Scope 1 emissions. The divergence, therefore, arises only when firms emit CO_2 within their own processes (Scope 1), whereas the Scope 3 balances are consistent with Schmidt's approach.

Input	Quantity Center		Output
	Initial inventory	**Final inventory**	
Material (Timber): • 1,800 € • 900 kg timber • 450 kg CO_2 (Scope 3)	Material (Timber): • 400 € • 200 kg timber • 100 kg CO_2 (Scope 3)	Material (Timber): • 200 € • 100 kg timber • 50 kg CO_2 (Scope 3)	Product: • 1,600 € • 800 kg tables • 400 kg CO_2 (Scope 3)
Fuel (Wood Chips): • 150 € • 200 kg wood chips • 40 kg CO_2 (Scope 3)	Fuel (Wood Chips): • 300 € • 400 kg wood chips • 80 kg CO_2 (Scope 3)	Fuel (Wood Chips): • 225 € • 300 kg wood chips • 60 kg CO_2 (Scope 3)	Material losses (Waste): • 225 € • 300 kg wood chips • 540 kg CO_2 (Scope 1) • 60 kg CO_2 (Scope 3) • 400 € • 200 kg wood scrap • 360 kg CO_2 (Scope 1) • 100 kg CO_2 (Scope 3)
Σ		Σ	
• 2,650 € • 600 kg wood chips • 1,100 kg timber • 670 kg CO_2 ○ 670 kg CO_2 (Scope 3)		• 2,650 € • 600 kg wood chips • 1,100 kg timber ○ 100 kg timber ○ 800 kg tables ○ 200 kg wood scrap • 1,570 kg CO_2 ○ 900 kg CO_2 (Scope 1) ○ 670 kg CO_2 (Scope 3)	

Table 2.2: *Numerical example of CO_2 emissions and balances of a furniture manufacturer with the extension by Schmidt (2015). Scope 3 emissions are balanced, but although everything is correctly accounted for, Scope 1 emissions and, therefore, total emissions are not balanced.*

As the next step, we introduce the error of not considering the emissions of the wood scrap that is actually burned. As they are waste, they do not carry any procurement documentation with them and would need to be reclassified from waste to fuel, but this might easily be missed in the analysis. Table 2.3 remains balanced for Scope 3 emissions and unbalanced for Scope 1 emissions. Hence, the method for internal validation based on input-output balances that classic MFCA offers is not present for this extension.

Input	Quantity Center: Initial inventory	Quantity Center: Final inventory	Output
Material (Timber): • 1,800 € • 900 kg timber • 450 kg CO_2 (Scope 3)	Material (Timber): • 400 € • 200 kg timber • 100 kg CO_2 (Scope 3)	Material (Timber): • 200 € • 100 kg timber • 50 kg CO_2 (Scope 3)	Product: • 1,600 € • 800 kg tables • 400 kg CO_2 (Scope 3)
Fuel (Wood Chips): • 150 € • 200 kg wood chips • 40 kg CO_2 (Scope 3)	Fuel (Wood Chips): • 300 € • 400 kg wood chips • 80 kg CO_2 (Scope 3)	Fuel (Wood Chips): • 225 € • 300 kg wood chips • 60 kg CO_2 (Scope 3)	Material losses (Waste): • 225 € • 300 kg wood chips • 540 kg CO_2 (Scope 1) • 60 kg CO_2 (Scope 3) • 400 € • 200 kg wood scrap • 100 kg CO_2 (Scope 3)

Σ	Σ

• 2,650 €
• 600 kg wood chips
• 1,100 kg timber
• 670 kg CO_2
  ○ 670 kg CO_2 (Scope 3)
	• 2,650 €
	• 600 kg wood chips
	• 1,100 kg timber
	  ○ 100 kg timber
	  ○ 800 kg tables
	  ○ 200 kg wood scrap
	• 1,210 kg CO_2
	  ○ 540 kg CO_2 (Scope 1)
	  ○ 670 kg CO_2 (Scope 3)

Table 2.3: *Numerical example as in Table 2.2, however this time, CO_2 emissions that have occurred during the heating process using the waste of wood scrap are not accounted for.*

A similar issue has been discussed for MFCA applications in agriculture, but this does not solve the problem for CO_2 emissions addressed here. The problem above originates from the circumstance that particular inputs and outputs are neglected, in particular the oxygen in the air and the carbon atoms in the wood, which can lead to input-output imbalances. In agricultural settings, inputs such as oxygen from the air, energy from sunlight, and minerals from the soil are essential for the growing process of crops, but these cannot all be practically included in the MFCA analysis. The typical approach is to focus on inputs and outputs that cause costs for the company, with the aim of balancing input-output only for costs, so the correctness of data about costs can be validated. It is then accepted that other inputs and outputs are not necessarily balanced and cannot be validated in that way (Amicarelli et al., 2022; Dekamin et al., 2022, 2025; Dekamin and Barmaki, 2019; May and Guenther, 2020). For example, the main output in Dekamin and Barmaki (2019) comprises soya beans (in kg) and this vastly exceeds the total mass of all inputs (such as seeds, nitrogen, phosphate, and potassium). In the case of CO_2

emissions, however, having a validation check of the data is essential and giving that up by accepting that inputs and outputs are not necessarily balanced is not a solution.

2.4. Extension of MFCA

This section presents an extension of MFCA input-output balances to include the materials' inherent CO_2 potential (inherent carbon) leading to validated CO_2 emission information. We defined inherent carbon above as the carbon atoms that are part of the input material flows, inventories, and output material flows, which when released combine with atmospheric oxygen to form CO_2. We will show how the method can be used to document the movement of material through the operations, always considering the CO_2 emissions associated with the material. We provide a method that balances incoming and outgoing material and CO_2 of the entire company down to the granularity of each process. With the proposed extension, MFCA satisfies the physical conservation of carbon atoms which cannot disappear nor can they appear from nothing to form CO_2 emissions. The notation is loosely based on the paper of Schmidt (2015). However, cost information has been excluded in the following notation to improve comprehensibility.

2.4.1. Inherent CO_2 potential

To exhaustively account for emissions of the focal company's processes, we also consider the inherent CO_2 potential (inherent carbon) in the chemical composition of the material inputs. This composition is expressed as kg CO_2, so basically the amount of CO_2 that would be emitted if all the carbon in the input material would be released and reacted with oxygen from the atmosphere. The reaction leads to additional mass (more weight) compared to the original weight of the material input's carbon mass. Inherent carbon therefore anticipates the weight of the potential future CO_2 by combining the weight of the carbon atoms within the material and the weight of the oxygen it bonds with to form CO_2. These data on the carbon mass are already available for many fuels and other materials in emission factor databases such as the Intergovernmental Panel on Climate Change (IPCC) Emissions Factor Database (IPCC, 2021), the GaBi Database (Sphera Solutions, 2023), or the ecoinvent Database (Ecoinvent Association, 2023). Applying this logic of anticipating potential future CO_2, the inherent carbon of coal is 1.91 kg CO_2/kg, the inherent carbon of kerosene is 2.61 kg CO_2/liter (EIA, 2024), the inherent carbon of wood is about 1.83 kg CO_2/kg (IINAS, 2014), and one liter of diesel has about 2.65 kg CO_2 inherent carbon (Bundesamt für Wirtschaft und Ausfuhrkontrolle, 2024; EPA, 2023; Hilgers, 2016).

The distinction between inherent carbon introduced here and Scope 1, 2, and 3 emissions in the GHG Protocol is essential. For example, burning one liter of diesel (a mixture of different hydrocarbons) causes 2.65 kg of CO_2. Before combustion, these 2.65 kg of CO_2 are inherent carbon of diesel; after combustion, these inherent carbon emissions have become Scope 1 emissions of a company; and when the company sells its products, these emissions are upstream Scope 3 emissions from the perspective of the customer. No matter whether the emissions are still inherent, Scope 1, or Scope 3, the total amount always reflects the actual change in atmospheric CO_2 of 2.65 kg.[6]

2.4.2. Mathematical model

2.4.2.1. Balances

The calculation of balances requires information about various kinds of input and output flows. The material flows $m = m_1 + \ldots + m_l$, where 1, …, l represent the different types of materials used. Expanding the model to include emission data, we introduce the emissions from various types of materials as $c^u = c_1^u + \cdots + c_l^u + c^e$ whereby c^e represents emissions from various types of energy as $c^e = c_1^e + \ldots + c_k^e$.[7] These energy flows are denoted as $e = e_1 + \ldots + e_k$, where 1, …, k represent the different types of energy used. Furthermore, information about various kinds of material inventories and flows is required. Material input is denoted by m_{input}, output denoted by m_{output}, and waste denoted by m_{waste}. Inventories of material are denoted by m_{start} for the starting inventory at the beginning of the period and by m_{final} for the final inventory at the end of the period. Analogously, the input c_{input}^u, output c_{output}^u, starting inventory c_{start}^u, waste c_{waste}^u, and final inventory c_{final}^u for Scope 3 emissions. Energy inputs (relevant for Scope 2 emissions) e_{input}, outputs e_{output} and waste e_{waste} are included in our model. Note, we assume that no storage of electricity takes place within the process. While Scope 3 emissions generally include upstream *and* downstream Scope 3 emissions (GHG Protocol, 2004), we use this term specifically for *upstream* Scope 3 emissions for the remainder of this article. With these concepts from current MFCA approaches we can define the following balances:

$$\text{(I)}\ m_{input} + m_{start} = m_{output} + m_{waste} + m_{final}$$

[6] The literature also mentions the term "embedded carbon" or "embodied carbon" which may appear to be similar to inherent carbon. However, these are fundamentally different from inherent carbon. Embedded or embodied carbon refers to CO_2 "emissions generated in the production of goods and services regardless of the location and timing of those emissions in the production process" (IPCC, 2019). These emissions are all covered by the GHG Protocol as Scope 1, 2, or 3 emissions.

[7] Intuitively, superscript u refers to the upstream emissions.

$$\text{(II) } c^u_{input} + c^u_{start} + c^e_{input} = c^u_{output} + c^u_{waste} + c^u_{final}$$

$$\text{(III) } e_{input} = e_{output} + e_{waste}$$

However, as shown in the example in the previous section, these balances may be violated or incomplete without accounting for inherent carbon. From here onward, we denote inherent carbon as $c^p = c^p_1 + \ldots + c^p_l$ of the various kinds of materials used.[8] Analogously, we include for inherent carbon the input c^p_{input}, output c^p_{output}, starting inventory c^p_{start}, final inventory c^p_{final}, and waste c^p_{waste}. Used energy does not have any inherent carbon, so energy is not included in the equation. CO_2 emissions (upstream and potential) add up to $c = c^u + c^p$ and we now obtain the following balance:

$$\text{(IV) } c^u_{input} + c^u_{start} + c^e_{input} + c^p_{input} + c^p_{start} = c^u_{output} + c^u_{waste} + c^u_{final} + c^p_{output} + c^p_{waste} + c^p_{final}$$

Materials that are consumed during the process are classified as waste. For example, if wood chips are burned in a heating process, these burned wood chips are documented as waste along with the emissions. This ensures that all emissions are accounted for when comparing inputs and outputs. In accounting for the waste, we need to take into consideration that some of the waste can be turned into byproducts, some can be sold to other companies, and some will be disposed or burned. The disposed or burned waste accounts for Scope 3 emissions and the question is how to consider these. In standard MFCA, these emissions would remain part of the Scope 3 emissions of the waste. However, this harbors the threat of undesirable incentives, because accounting for these emissions within waste would make products appear cleaner, even if considerable emissions occurred for the provision of these products. Therefore, these emissions should be added to the emissions of the output c^u_{output}, and these are passed on to the next supply chain partner as Scope 3 emissions c^u_{input} for that supply chain partner.

2.4.2.2. The relationship between Scope 1, 2, and 3 emissions and inherent carbon

Implicit in the input-output equations above is the transformation from inherent carbon to Scope 1 emissions, which occurs by releasing carbon atoms that are part of input material flows to emit CO_2. We start with an input m with inherent carbon c^p, of which a fraction x is released into the atmosphere and the rest $(1-x)$ stays an inherent part of the product and waste. This

[8] Intuitively, superscript p refers to the potential CO_2 emissions from the carbon in the chemical composition of the materials which is inherent in the material but has not been emitted until now.

means, we have a transfer of a fraction x from the inherent carbon c^p to the focal company's Scope 1 emissions, which are then added to its output emissions c^u.

For the focal company, all incoming inherent carbon has either become Scope 1 emissions (through burning or another emission of CO_2), or they remain as inherent carbon within the material inventory or outputs. A graphical overview of the framework is given in Figure 2.1. It visualizes that the Scope 1 emissions can be calculated as follows: $Scope\ 1\ emissions = c^p_{input} + c^p_{start} - c^p_{final} - c^p_{waste} - c^p_{output}$. Importantly, these data are measurable because inherent carbon is a property of the material used, establishing a connection between Scope 1 CO_2 emissions and the material flow analysis. Furthermore, any inconsistencies in the emissions data are always apparent. This extension, therefore, provides MFCA with its intended input-output balances of total emissions (including inherent carbon, Scope 1, 2, and 3 emissions) and thereby creates validation through balances for the CO_2 emission layer of the analysis.

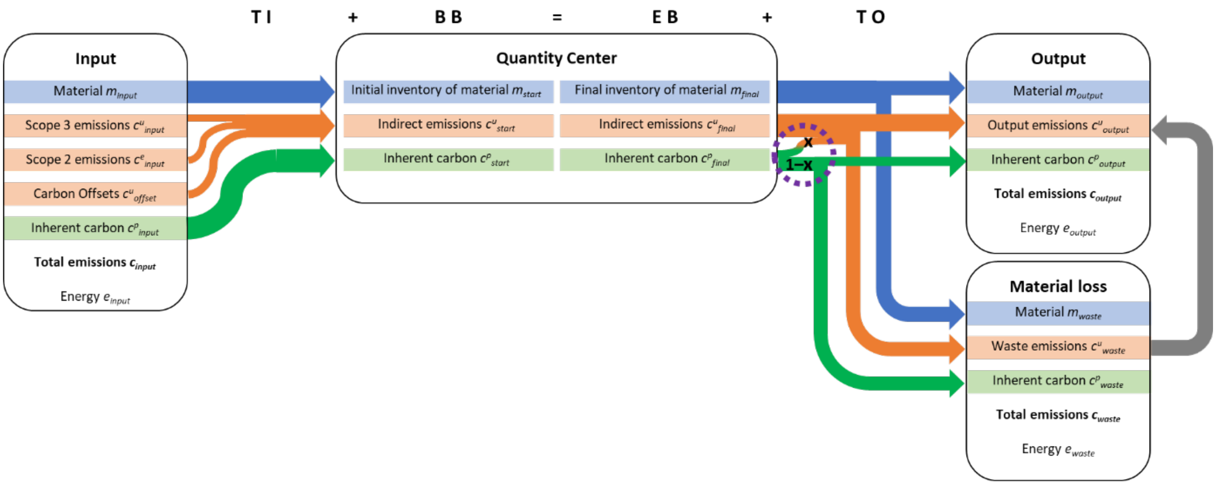


Figure 2.1: *Framework for calculating emission flows, based on the logic that transferred in (TI) + beginning balance (BB) equals ending balance (EB) + transferred out (TO). The blue arrows indicate the flow of material, the orange arrows emissions, and the green arrows inherent carbon. The purple, dotted circle highlights the origin of Scope 1 emissions: fraction x of the inherent carbon of the input and inventory becomes Scope 1 emissions. These are included in the output emissions. The gray arrow indicates that emissions from waste can be allocated to output.*

2.4.2.3. Carbon offsets

The extension can also be applied to processes that involve carbon offsetting. Carbon offsetting can be defined as a "measurable avoidance, reduction or sequestration of carbon dioxide (CO_2)" (Ramseur, 2009, p. 1). Carbon offsetting is a possibility for companies and individuals to mitigate their impact on climate change and will need to be part of the global effort to stop emissions, as not all production processes can be done without emitting CO_2 (Calel et al., 2025; Kaplan et al., 2023). Carbon offsetting is also part of the GHG Protocol as a tool to compensate for emissions by an organization (GHG Protocol, 2004).

We address carbon sequestration (for example through an engineered sequestration in a mineralized form of carbon capturing and storage (CCS) or through natural sequestration such as planting trees) as these are carbon offsets with actual atmospheric changes. CCS is an emerging technology that is currently under development. It directly captures CO_2 from the atmosphere and stores carbon in a solid form (Gibbins and Chalmers, 2008; Rubin et al., 2012). It is a transition between inherent carbon and CO_2 in the atmosphere as well, but in the opposite direction than discussed previously. If a CCS company or any other company, such as a forest owner growing trees (Alice-Guier et al., 2020; Kayo et al., 2011), takes CO_2 out of the atmosphere, the amount of output emissions c^u is reduced. Specifically, there will be an output m_{output} in Equation I that contains carbon atoms collected from the atmosphere. Due to this atmospheric change, we have a negative value for waste m_{waste} in Equation I, as emissions that happened previously have been taken back as inherent carbon into the company's output. Therefore, the Scope 3 emissions c^u of the CCS company will be lower by the amount of CO_2 taken out of the atmosphere (as negative Scope 1 emissions). The inherent carbon c^p of the output will be higher by the same amount as the carbon is now in a solid state (e.g., mineralized carbon, wood).

The CO_2 impact of the CCS company (more specifically their negative Scope 1 emissions) is typically transferred to other companies. The CCS company and the customer company sell and buy emission certificates. In the production process of the customer company, the output emissions c^u_{output} are reduced by the amount of negative Scope 1 emissions of the carbon offset c^u_{offset} (with a negative sign) bought from the CCS company. This reduces the output emissions by the offset.

2.4.3. Numerical example

We pick up our example of the furniture manufacturer and add a value of inherent carbon to the materials, as shown in Table 2.4. The sum of the total inherent carbon, Scope 1, 2, and 3 emissions are the total emissions. The totals are calculated for the sum of inputs and initial inventories, and for the sum of outputs and final inventories.

The inherent carbon of the timber input must ultimately either remain embodied in finished tables or inventories or be converted into atmospheric emissions. Once the scrap from the timber is burned, its inherent carbon can no longer remain in the balance as if it were still only waste. Under conventional MFCA, waste handling and its associated costs could draw attention to such a flow. In this case, however, the scrap is directly burned, so no separate waste handling costs arise that might trigger further investigation. If the combustion of the scrap is omitted, total output emissions plus remaining inherent carbon will fall short of total input-related carbon emissions, thereby violating the emission balance. This violation of balances will come up while the MFCA analysis is conducted and will directly trigger the preparer to investigate this issue further. This investigation reveals that the CO_2 data are incomplete and the results of the MFCA analysis are revised. Also accounting for inherent carbon adds the constraint that input-output must also be balanced for CO_2, which forces preparers to look into issues that, in contrast, might remain undetected if input-output does not necessarily need to be balanced for CO_2. In this way, the extension strengthens internal control over Scope 1 emission data through an additional validation. Table 2.4 shows the correct balances of total emissions (3,730 kg CO_2) with the extended MFCA. Table 2.A1 in the appendix demonstrates how the error of the not considered wood scrap becomes apparent with the extension.

Input	Quantity Center		Output
	Initial inventory	**Final inventory**	
Material (Timber): • 1,800 € • 900 kg timber • 450 kg CO_2 (Scope 3) • 1,620 kg CO_2 (inherent)	Material (Timber): • 400 € • 200 kg timber • 100 kg CO_2 (Scope 3) • 360 kg CO_2 (inherent)	Material (Timber): • 200 € • 100 kg timber • 50 kg CO_2 (Scope 3) • 180 kg CO_2 (inherent)	Product: • 1,600 € • 800 kg tables • 400 kg CO_2 (Scope 3) • 1,440 kg CO_2 (inherent)
Fuel (Wood Chips): • 150 € • 200 kg wood chips • 40 kg CO_2 (Scope 3) • 360 kg CO_2 (inherent)	Fuel (Wood Chips): • 300 € • 400 kg wood chips • 80 kg CO_2 (Scope 3) • 720 kg CO_2 (inherent)	Fuel (Wood Chips): • 225 € • 300 kg wood chips • 60 kg CO_2 (Scope 3) • 540 kg CO_2 (inherent)	Material losses (Waste): • 225 € • 300 kg wood chips • 540 kg CO_2 (Scope 1) • 60 kg CO_2 (Scope 3) • 400 € • 200 kg wood scrap • 360 kg CO_2 (Scope 1) • 100 kg CO_2 (Scope 3)

Σ	Σ

• 2,650 €
• 600 kg wood chips
• 1,100 kg timber
• 3,730 kg CO_2
  ○ 670 kg CO_2 (Scope 3)
  ○ 3,060 kg CO_2 (inherent)
	• 2,650 €
	• 600 kg wood chips
	• 1,100 kg timber
	  ○ 100 kg timber
	  ○ 800 kg tables
	  ○ 200 kg wood scrap
	• 3,730 kg CO_2
	  ○ 900 kg CO_2 (Scope 1)
	  ○ 670 kg CO_2 (Scope 3)
	  ○ 2,160 kg CO_2 (inherent)

Table 2.4: *Consistent input-output balances of total CO_2 of the furniture manufacturing example with the proposed extension of MFCA with inherent carbon.*

2.5. Discussion and conclusion

2.5.1. Information validation through the introduction of inherent carbon

The essential idea introduced in this paper is to account for all CO_2 emissions related to material flows by extending MFCA with inherent carbon, and therefore embedding an internal validity check to strengthen internal control over Scope 1 CO_2 emission information. This provides a decision-relevant and physically grounded information base on material usage and process CO_2 emissions across all processes of a focal company. Previous extensions of MFCA included CO_2

emissions as an additional layer to MFCA (Schmidt, 2015; Viere et al., 2010). These methods can show which processes inside single companies and in supply chains emit CO_2 and where reduction measures will have the greatest impact, such as through process optimization, product development choices, and capital investments. However, these MFCA extensions with CO_2 emissions do not yet offer a mechanism to validate whether Scope 1 CO_2 emissions are complete. The extension of MFCA presented in this paper addresses this methodological gap by ensuring that CO_2 emissions data used for managerial decisions are consistent with both the physical reality of carbon flows and their accounting representation. MFCA's condition that total input emissions equal total output emissions provides a built-in validation mechanism that helps detect whether all carbon released within processes is accounted for. Consequently, this balance exposes omissions or calculation errors, reinforcing internal control over CO_2 data and improving confidence in numbers used for decision-making. The specific decisions enabled by this extended MFCA method depend on a company's internal goals and external regulatory context. For companies pursuing CO_2 reduction targets, the extended method provides a robust informational foundation.

The extended approach aligns MFCA (a standardized method) with internal control frameworks such as ISO 14064, which defines controls in carbon accounting as procedures ensuring that data are free from material misstatements (ISO, 2018). At the same time, with the proposed extension, MFCA is even more able to achieve the purpose of the ISO 14051 standard for MFCA, which requires accuracy, completeness and comparability of physical data through physical balances (ISO, 2011). Incorporating inherent carbon into MFCA therefore further develops the MFCA method towards a management accounting instrument for monitoring and controlling CO_2 emissions. It enables companies to track real changes in atmospheric CO_2, creating a stronger basis for decision-making.

2.5.2. Interpretation of inherent carbon

Whereas thus far, inherent carbon was discussed primarily as a basis for validation of Scope 1 CO_2 emissions data, this information on inherent carbon also has information value on its own. The interpretation of inherent carbon depends on how responsibility for emissions is allocated along the supply chain. We draw on the classification of carbon responsibility introduced by Tukker et al. (2020), which distinguishes three approaches: the *extraction-based approach*, the *polluter-pays principle*, and the *user-pays principle*.

The *extraction-based approach* assigns responsibility to extractors that transfer material flows containing carbon from nature into supply chains, thereby enabling future CO_2 emissions.

Typical extractors are timber, oil, or mining companies. Following the extraction-based approach, they are responsible for the inherent carbon that is transferred into the supply chain from the natural environment, regardless of whether the carbon is released into the atmosphere by them or further down the supply chain, forming CO_2. With the *polluter-pays principle*, each entity of the supply chain is responsible for the CO_2 it actually emits into the atmosphere through its own processes. The logic aligns with our perspective on inherent carbon: as long as carbon remains bound in the material (inherent), it does not negatively impact the environment; the negative impact arises only when the carbon is released and forms CO_2 in the atmosphere. Large inventories or transfers of inherent carbon are therefore neutral under this regime. Finally, the *user-pays principle* solely places the responsibility of all supply-chain emissions on the consumer of a final product. Hence, the companies in the supply chain do not face any responsibility for either their Scope 1, 2, and 3 emissions or their inherent carbon.

To illustrate these regimes, we present a supply chain with an extractor, producers and sellers, and a customer. Figure 2.2 summarizes the stylized example. The extractor consumes electricity (Scope 2), its suppliers have emitted CO_2 (Scope 3) and it releases a small amount (+) of carbon during the extraction process as CO_2 in the atmosphere (Scope 1). The essential characteristic of the company is transferring a large quantity of inherent carbon from nature to the producer. Then, producers and sellers use the material for production, distribution and sales, emitting the inherent carbon from the input in the process (7+). When the product is purchased by the customer, the product and its Scope 3 emissions are transferred to the customer.[9] Finally, the customer uses the product without emitting any additional carbon in this example.

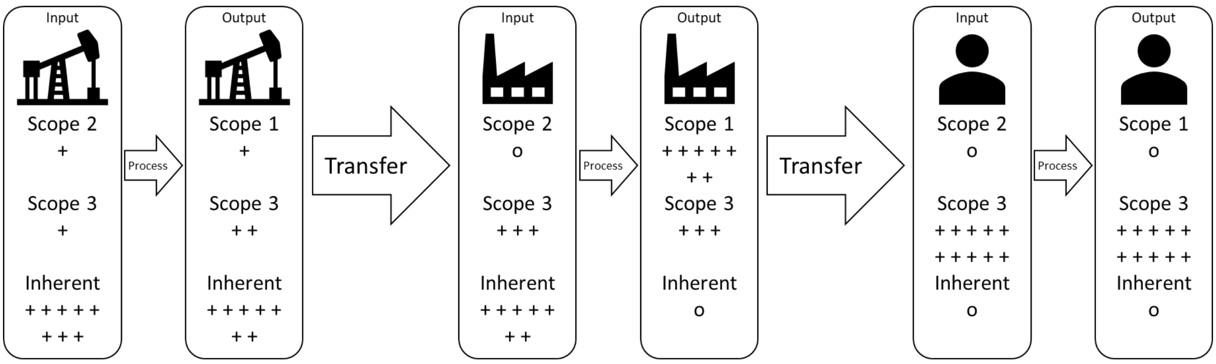


Figure 2.2: *Illustration of Scope 1, 2, and 3 and inherent carbon with the example of a supply chain comprising the extractor, the producers & sellers, and the final consumer of the product. Each "+" represents one unit of emissions and "o" represents no emissions.*

[9] In these cases, a company's Scope 1 output emissions become Scope 3 emissions for the customer. However, for an energy provider that sells electricity, steam, heat, or cooling, its Scope 1 output emissions become Scope 2 emissions for the customer.

Under the *extraction-based approach*, the extractor that is extracting carbon from nature carries full responsibility for the inherent carbon extracted (8+), which is displayed in Table 2.5. Additionally, the whole upstream supply chain of the extractor is responsible for the inherent carbon they have extracted from nature (++). With the *polluter-pays principle*, each entity in the supply chain is responsible for its own Scope 1 emissions by emitting CO_2 into the atmosphere. That corresponds to the amount of CO_2 that is transformed from inherent carbon to Scope 1 emissions in processes. Hence, the companies in the supply chain upstream of the extractor carry some responsibility (++), the extractor carries some responsibility (+), the producers and sellers are responsible for the emissions during production, distribution and sales (7+), while the customer is not responsible for any emissions as they do not emit any CO_2 in their processes in this example. Finally, under the *user-pays principle*, the responsibility is solely placed on the consumer (10+).

	Responsibility for CO_2 emissions		
	Extraction-based approach	**Polluter-pays principle**	**User-pays principle**
Supply chain upstream of the extractor[a]	+ +	+ +	o
Extractor	+ + + + + + + +	+	o
Producers and sellers	o	+ + + + + + +	o
Customer	o	o	+ + + + + + + + + +

[a] The supply chain upstream of the extractor is shown in italics here, because it is outside the scope of this supply chain. This is included so that all CO_2 that ends up being accounted for in the user-pays principle can also be accounted for in the extraction-based approach and in the polluter-pays approach.

Table 2.5: *Placement of responsibility for CO_2 emissions on each entity according to the extraction-based approach, the polluter-pays principle, and the user-pays principle. Each "+" represents one unit of emissions and "o" represents no emissions.*

2.5.3. Future research and limitations

Future research could further develop our MFCA extension to also include other chemical elements included in input and output material flows that could be converted to other greenhouse gases, such as nitrogen that reacts with oxygen to form nitrous oxide (N_2O). Additionally, future research could address the technical issues of information transfer of inherent carbon information between organizations. Blockchain integration has been suggested for a traceable presentation of supply chain sustainability information (Hu et al., 2019; Wang et al., 2020). Future research should extend this to carry Scope 1, 2, and 3 and inherent information through the supply chain for all materials and products. Finally, it seems a promising avenue to develop the concept of inherent inputs and outputs to other variables that are important for sustainability as well, such as energy and water.

To conclude, we show how extending MFCA with information on CO_2 emissions of Scope 1, 2, and 3 and inherent carbon serves as a thorough method with a validation of the produced information on CO_2 emissions to guide the information through the processes following material flows. By establishing balances of total input and output emissions, this method provides an additional validation check of the emission data. This is achieved through the addition of inherent carbon with the requirement of balances of these through the law of conservation of mass. The model is elaborated through a numerical example, which demonstrates the model’s ease of application and advantages. Additionally, the example demonstrates the interpretation of inherent carbon, based on the placement of responsibility. The extension of MFCA input-output balances helps to generate validated CO_2 emission information. This information can help to identify emission-intensive parts of the production, as the basis for internal control to reduce and optimize internal emission management. In sum, the proposed extension integrates the principles of industrial ecology by ensuring mass conservation and closed-system consistency across material and emission flows.

2.6. Appendix

Table 2.A1 shows how not considering the wood scraps leads to unfulfilled balances with the extension of MFCA with inherent carbon. The total input-related emissions are 3,730 kg CO_2, while the output-related emissions are only 3,370 kg CO_2. Because input-output must also be balanced for total CO_2, the failed validation triggers an investigation into the error. This investigation provides another opportunity to correct the mistake and report the correct result, as shown in Table 2.4.

Input	**Quantity Center**		**Output**
	Initial inventory	**Final inventory**	
Material (Timber): • 1,800 € • 900 kg timber • 450 kg CO_2 (Scope 3) • 1,620 kg CO_2 (inherent)	Material (Timber): • 400 € • 200 kg timber • 100 kg CO_2 (Scope 3) • 360 kg CO_2 (inherent)	Material (Timber): • 200 € • 100 kg timber • 50 kg CO_2 (Scope 3) • 180 kg CO_2 (inherent)	Product: • 1,600 € • 800 kg tables • 400 kg CO_2 (Scope 3) • 1,440 kg CO_2 (inherent)
Fuel (Wood Chips): • 150 € • 200 kg wood chips • 40 kg CO_2 (Scope 3) • 360 kg CO_2 (inherent)	Fuel (Wood Chips): • 300 € • 400 kg wood chips • 80 kg CO_2 (Scope 3) • 720 kg CO_2 (inherent)	Fuel (Wood Chips): • 225 € • 300 kg wood chips • 60 kg CO_2 (Scope 3) • 540 kg CO_2 (inherent)	Material losses (Waste): • 225 € • 300 kg wood chips • 540 kg CO_2 (Scope 1) • 60 kg CO_2 (Scope 3) • 400 € • 200 kg wood scrap • 100 kg CO_2 (Scope 3)

Σ	Σ

• 2,650 €
• 600 kg wood chips
• 1,100 kg timber
• 3,730 kg CO_2
  ○ 670 kg CO_2 (Scope 3)
  ○ 3,060 kg CO_2 (inherent)
	• 2,650 €
	• 600 kg wood chips
	• 1,100 kg timber
	  ○ 100 kg timber
	  ○ 800 kg tables
	  ○ 200 kg wood scrap
	• 3,370 kg CO_2
	  ○ 540 kg CO_2 (Scope 1)
	  ○ 670 kg CO_2 (Scope 3)
	  ○ 2,160 kg CO_2 (inherent)

Table 2.A1: *Incorrect input-output balances of the furniture manufacturing example with the proposed extension of MFCA with inherent carbon. The validation of the balance fails, triggering further investigation into the error.*

3. Show Me the Carbon: Accounting for Inherent Emissions

Abstract

Carbon accounting systems record emissions flows but lack mechanisms that enable the detection of errors 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 as a physical stock 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 by numerical examples that show how inherent emissions can help to identify inconsistencies in carbon data and to support comprehensive carbon audits. Hence, inherent emissions accounting aims to improve error detection and to provide a tangible connection between carbon accounting and real-world emission quantities through physical stocks, promoting carbon accounting practices that are more accurate and trustworthy than they currently are.

Keywords: *carbon accounting, carbon emissions, inherent emissions, carbon auditing, carbon reporting, carbon verification*

3.1. 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 and 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; Clarkson et al., 2015; Cohen et al., 2023; Datt et al., 2025b; Millar et al., 2025). Furthermore, by issuing high-quality sustainability reports, companies credibly signal their dedication to transparency and to the reduction 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 of carbon accounting and disclosure (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 verifiability of reported emissions data are becoming increasingly critical for preventing misrepresentation and greenwashing practices, an issue exacerbated by the inability to physically examine emissions and compare them to reported emission quantities after they have been emitted.

Several scandals of underreported Scope 1 emissions have been subject to public scrutiny, highlighting the need for verifiable carbon information. Among these are cases of misreports in the energy sector in different parts of the world such as Bulgaria (EPPO, 2023), China (Phillips, 2015; Stanway and Chen, 2016), the UK (UK, 2022), and Colorado, USA (Fassler, 2024). However, this is not limited to energy companies, even though they draw high attention due to their large absolute quantity of emissions. An analysis of Scope 1 emissions disclosures of the S&P 500 shows that over half of originally reported Scope 1 emissions are later corrected (Cohen et al., 2026). Additionally, Scope 1 restatements rise significantly if stricter rules for Scope 1 emission reporting are enforced (Aobdia et al., 2025).

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 to 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., 2025). Therefore, it is sensible to be skeptical of the reported information and to request third-party sustainability assurance. Sustainability assurance is a new market that differs from financial assurance although it is often conducted by the same assurance teams (Dal Nial et al., 2025; 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 assurance providers have to work with as often being 'diverse', 'vague', and 'disconnected'. In sum, while financial reporting freedom is restricted by limited discretion in accruals due to future corresponding cash flows, carbon accounting lacks an equivalent verification mechanism (Gipper et al., 2025b).

Recently, there have been several advancements in corporate carbon accounting systems. 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). However, these systems remain susceptible to errors and intentional misreporting. They 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, defined as emissions released 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., 2025) 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; Gipper et al., 2025b).

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 and 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 accurately assesses the total changes in emissions, and that offers the possibility to audit changes in carbon offsets over time in order to adjust the numbers correctly (Brander et al., 2021).

The aforementioned shortcomings lead to the central research question guiding the investigation:

How can carbon accounting information and carbon accounting systems become physically auditable?

To address this research question, 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, i.e. they represent possible *future emissions*. In contrast, the carbon accounting systems proposed by Kaplan and Ramanna (2021), Penman (2024), and Reichelstein (2024) 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 (direct emissions) that are already in the atmosphere in the form of CO_2 and other greenhouse gases. Other greenhouse gases are discussed in detail in the appendix, along with a description of how this can be integrated into regulations. Accounting for inherent emissions creates a tangible link between physical assets and carbon accounting systems, allowing verification through physical examination, similar 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 (that is enriched by including the quantity of carbon in the materials) with observable carbon stored in a company's materials and products. A physical examination of substances that contain inherent emissions can be executed through visual inspection, weighing, or other kinds of material inspection. Furthermore, inherent emissions can also be physically observed for carbon capturing, rendering it auditable. Therefore, inherent emissions accounting significantly improves the reliability of reported emissions data and enhances auditability, thereby counteracting any misreporting and greenwashing practices. This paper 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. Using illustrative numerical examples, this paper shows how the extension of these carbon accounting frameworks with inherent emissions can address critical verification gaps.

The remainder of this paper is structured as follows. Section 3.2 describes current advances in carbon accounting, the relevant theory behind them, and their improvement opportunities. Section 3.3 introduces inherent emissions into these carbon accounting systems. Section 3.4 discusses the implications of this addition, answers the research question, and concludes with directions for future research. Finally, the appendix (section 3.5) shows how the extension is used for multiple greenhouse gases with a corresponding policy recommendation.

3.2. Background

3.2.1. Carbon accounting: definitions, users, and current advances

Companies are being increasingly pressured to measure and report their environmental impacts and emissions at 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 and Cohen, 1997; Millar et al., 2025; Tang and 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, 2026), 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 labelling 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 that 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. Naturally, Scope 3 emissions are often the largest share of a company's emissions as they include upstream and downstream emissions of the whole supply chain. However, Scope 3 emissions are the Scope 1 emissions of the supply chain partners. Hence, correct reporting of Scope 1 emissions can help to improve total data quality. Extending the financially and disclosure focused point of view of carbon accounting (Bebbington et al., 2023; Bebbington and Larrinaga-González, 2008) and the GHG Protocol (2004), 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 and Ramanna, 2021).
- Reichelstein (2024) proposed an accrual carbon accounting system that incorporates emissions into traditional accounting structures, creating carbon emission statements that track emissions 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 toward 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. These approaches emphasize the measuring and managing of emissions at the firm level, offering frameworks to track and report a company's transition toward net-zero emissions.

Efforts to reduce CO_2 in the atmosphere, known as carbon offsets, are also addressed in the aforementioned 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 and Ramanna, 2021), to offset past 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. However, 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.

3.2.2. 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 these practices has increased significantly over the last decade (Gipper et al., 2025a). Furthermore, it is associated with higher-quality carbon accounting data and improvements in the carbon performance of companies (Berg et al., 2024; Gipper et al., 2026; Lee et al., 2026; Steinmeier and Stich, 2019). Also, it addresses frequent issues of misstatements and false claims (Luo et al., 2023). Interdisciplinary teams of accountants, engineers, and specialists are crucial, however, team biases necessitate improved team training and structured processes (Ekasingh et al., 2019; Kim et al., 2016). Technological innovations can enhance data integrity (Boedijanto and Delina, 2024; Li et al., 2024).

Much of the generated carbon information is difficult to audit; it may be incomplete or include double counting of emissions (Glenk, 2023; Kaplan and 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 (Gipper et al., 2025b). Despite the already discussed new carbon accounting systems that include more holistic accounting for carbon emissions of companies' activities and carbon offsets (Kaplan and Ramanna, 2021; Penman, 2024; Reichelstein, 2024), the information provided by these systems is not physically verifiable. Furthermore, 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 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 emissions accounts), representing the same data twice. Within these accounting systems, emissions simply appear without any traceable source or balancing mechanism.

3.2.3. The example of an aluminum can producer

To illustrate the shortcomings, namely the difficulty of physically detecting 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. For this example, the assumption is that the incoming data is correct, even though it cannot be verified. The company then uses the gas to power 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. An overview of the transactions is shown in Table 3.1. 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. 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 and the emissions entering 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.

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 3.1: *Carbon accounting transactions in the illustrative example of the aluminum can producer.*

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 in Table 3.2 of the aluminum can producer builds on the carbon balance sheet and transaction tableau of Reichelstein (2024).

Table 3.2 shows the transactions within the transaction tableau. For simplicity, most accounts start with an opening balance of zero, 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 3.2 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 3.2: *Transaction tableau for the purchase of materials and production of aluminum cans, using the carbon emission balance of Reichelstein (2024). Abbreviations: CE = Carbon Emissions; 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. Cells where the transactions would show a change of zero are left empty.*

Table 3.3 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 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 3.3 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 3.3 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 3.3: *Transaction tableau for the purchase of materials and production of aluminum cans, using the carbon emission balance of Reichelstein (2024) with unrecorded Scope 1 emissions. Abbreviations: CE = Carbon Emissions; 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. Cells where the transactions would show a change of zero are left empty.*

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 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 not measurable after their occurrence[10]. 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 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

[10] Satellite imaging can identify large quantities of carbon emissions (Carbon Mapper, 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, requiring constant monitoring.

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 toward 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 and Koonce, 1997). Even intangible assets can be traced to a company and their value can be recorded (Barker et al., 2022). Consequently, the stated financial numbers can be verified by an auditor (Gipper et al., 2025b), even after the period has ended. Without auditor needing 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.

3.3. Extension

3.3.1. Extended carbon emission statements: inherent emissions accounting

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 and Ramanna, 2021; Penman, 2024; Reichelstein, 2024). Inherent emissions, in the paper at hand, are defined as the quantity of CO_2 that can be released from the material of the physical assets through combustion or other chemical processes due to the reaction of carbon atoms within the materials or fuels with oxygen atoms from the air[11]. 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 emissions. Unlike in financial accounting, where recognition is tied to realization, the recording of inherent emissions captures a physical stock under the company's control. This stock can be directly observed and verified with the materials and assets on hand.

From an accounting perspective, inherent emissions represent a *physical stock* of carbon atoms embedded in fuels, materials, and products. When these carbon atoms react with oxygen through combustion or other chemical processes, the stored carbon is converted into CO_2 and released into the atmosphere. This release constitutes a *physical flow* of emissions. Although the stock-flow terminology is frequently used in the accounting profession, it needs careful differentiation in the context of carbon accounting. In the accrual carbon accounting system, Reichelstein (2024) uses emission stocks and emission flows to denote accounting balances and period flows on carbon emission statements. The extension of inherent emissions gives an additional *physical* perspective on stocks and flows, describing tangible phenomena: the quantity of carbon physically stored in materials and the actual release of that carbon as CO_2. Clearly distinguishing between these physical processes and accounting constructs avoids confusion and ensures that the proposed inherent emissions accounting is consistent with, yet distinct from, Reichelstein's stock-flow terminology. Accordingly, inherent emissions represent the emission quantities to be expected if the asset is combusted in the respective processes.

[11] While carbon emissions within the United States make up 79.7% of the warming potential (GWP-100) of industrial greenhouse gases, other gases such as methane (11.1%) and nitrous oxide (6.1%) are covered in the Appendix (US EPA, 2015).

All past emissions have been inherent in materials as carbon atoms at some point in time before reacting and combining with two oxygen atoms to form CO_2. 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 quantity of inherent emissions still in the material by the quantity of CO_2 emitted during these processes, i.e., inherent emissions become past 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 and Chalmers, 2008). In this case, CO_2 is taken out of the air (negative emissions) and an equal quantity of 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 Scope 2 and upstream Scope 3 emissions that were assigned to incoming goods bought by the company from suppliers. Direct emissions are Scope 1 emissions that are released 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 on direct emissions in the accounting systems becomes verifiable through a comparison of inherent emissions in the accounting system and the inherent emissions that are physically present, indicating errors if the numbers do not align. 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 quantity 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 most fuels and gases in emission factor databases. For other materials, the information on the quantity of carbon can be provided by the supplier, 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 emission factors or through an analysis of the chemical composition of materials, depending on the knowledge of the material's composition.

Inherent emissions 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 physical examination can be used to quantify the inherent emissions in the materials of the assets, i.e., the quantity of emissions that could potentially be emitted through the consumption of the assets under the control of the company when their carbon content fully reacts with oxygen.

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 the carbon balance sheet and extra columns in the transaction tableau. For direct emissions (Scope 1 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 recorded physical flow from inherent emissions to past emissions. Table 3.4 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 bookkeeping system in financial accounting and allows time-independent verification of emissions data. 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, direct removals, and in the equity account. Consequently, mathematically, this can be expressed as

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

Hence, this enables an assessment of the total Scope 1 emissions of a company. Moreover, the values of inherent emissions in each account also provide a tangible reference to physically audit the correctness of the carbon information. In this vein, accounting for both past emissions and inherent emissions enables physical audits of carbon accounting information due to the observable inventory of assets and the respective asset-inherent emissions accounted for.

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

Table 3.4: *Carbon Emission Balance Sheet of the extended model with inherent emissions. Based on Reichelstein* (2024). *Note that BLD and MAC are later combined to Plant, Property, and Equipment (PPE).*

Following this, an auditor can enter a company at any given time with the request 'Show me the carbon!'. If the accounting is correct, *the physically examined carbon will have the same value as the inherent emissions in the balance sheet.* Any differences 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 the auditor to decline confirmation of correct disclosure with (potential) corresponding consequences such as fines or the need to restate the correct emission quantities.

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 quantity of CO_2 taken out of the atmosphere and stored in material form. This material can be physically examined and audited to assess the quantity 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 capture and storage. The carbon accounting for carbon capture and storage is demonstrated in section 3.3.2.2. 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.

3.3.2. Numerical examples

3.3.2.1. Aluminum Can Producer

We return to the numerical example of the aluminum can producer from section 3.2.3 to demonstrate how accounting for inherent emissions helps to detect errors. To demonstrate this, the same five transactions as in Table 3.1 are used.

As in section 3.2.3, Table 3.5 shows the situation where the Scope 1 emissions of the company are not (or falsely) reported as 0 kg CO_2. This leads to finished goods with 1,500 kg CO_2 of past emissions and 3,050 kg CO_2 of inherent emissions. However, Scope 1 emissions are actually much higher and, therefore, far fewer inherent emissions are "left" in the physical inventory of finished goods. It is known (and can physically be examined) 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 physically 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. Note that values for inherent emissions can be negative in the DE and EQ accounts to enable tracking, while the total quantity of inherent emissions cannot be negative. Table 3.6 shows the correct values in the transaction tableau with the correct quantity of both past and inherent emissions. Specifically, in Transaction IV, when the gas is burned, which leads to 3,000 kg of CO_2 emissions because MAT_{Gas} inherent emissions are transformed into past emissions and recorded in the DE account. Hence, the Scope 1 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, representing the physical flow of emissions between the material and the atmosphere. The differences between Table 3.5 and Table 3.6 are highlighted in bold font in transactions IV. and V. of Table 3.6.

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	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 3.5: *Transaction tableau for the purchase of materials and production of aluminum cans using the extended carbon emission statement with inherent emissions. Direct emissions (3,000 kg) are not recorded in Transaction IV. As a result, too many inherent emissions are recorded in the FG inventory. The falsely recorded amount of 3,050 kg can be compared with the actual amount of inherent carbon that is part of the available inventory through physical inspection, leading to a detection of the error through inventory taking. Abbreviations: CE = Carbon Emissions; 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. Cells where the transactions would show a change of zero are left empty.*

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	**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 3.6: *Correct transaction tableau for the purchase of materials and production of aluminum cans using the extended carbon emission statement with inherent emissions. The previously unrecorded direct emissions (3,000 kg) are now recorded in Transaction IV. Now, the correct amount of inherent emissions is recorded in the FG inventory. The recorded amount of 50 kg can be compared with the actual amount of inherent carbon that is part of the available inventory through physical inspection. The difference in the last two transactions is highlighted in bold font. Abbreviations: CE = Carbon Emissions; 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. Cells where the transactions would show a change of zero are left empty.*

3.3.2.2. Carbon Offsetting

Carbon offsetting can also be accounted for and becomes physically verifiable with the introduction of inherent emissions into carbon accounting systems. The quantity of carbon captured 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 the example company engaging in carbon offsetting that captures carbon from the atmosphere by using electricity and employing a carbon capture and storage system. The opening balances of assets are the ending balances from Table 3.6. In this carbon capture example, the following transactions occur to demonstrate the case of carbon capturing, as shown in Table 3.7 (note that some columns that have no values are hidden for clarity):

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 a certificate for 2,000 kg of carbon offset while keeping the carbon within the company. The total quantity 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 yield the total number of inherent emissions in the form of captured carbon in the 'CO_2 Captured inherent' account. Note that the quantity of carbon certificates sold should not exceed the inherent emissions 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 quantity of inherent emissions should be examined regularly and possibly reassessed. When part of the captured carbon is re-emitted into the atmosphere, the offsetting company needs to compensate for this change. Hence, the total volume of sold certificates should not exceed the positive value of the equity of the company.

Accounts	CE in Assets							CE in Liabilities							
	PPE	**PPE inherent**	**FG**	**FG 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**	**4,500**	**50**	**0**	**0**	**=**	**21,500**	**8,050**	**3,000**	**-3,000**	**0**	**0**	**0**	**0**
Transactions															
I.					1,500		=	1,500							
II.					-8,000	8,000	=					-8,000	8,000		
III.					2,000		=							2,000	
Closing Balance	**20,000**	**5,000**	**4,500**	**50**	**-4,500**	**8,000**	**=**	**23,000**	**8,050**	**3,000**	**-3,000**	**-8,000**	**8,000**	**2,000**	**0**
				Sum	Past	20,000							Sum	Past	20,000
					Inherent	13,050								Inherent	13,050
					Total	33,050								Total	33,050

Table 3.7: *Transaction tableau for the carbon offsetting example using the extended carbon emission statement with inherent emissions. Abbreviations: CE = Carbon Emissions; PPE = Plant Property and Equipment; FG = Finished Goods; ETI = Emissions Transferred In; DE = Direct Emissions; DR = Direct Removals; EQ = Equity. Cells where the transactions would show a change of zero are left empty.*

3.3.3. 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 and 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, 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 different processes, such as receiving, storage, and selling.

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.

3.4. 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 verifiable 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 materials, 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, the emissions are released into the atmosphere, leading to a part or all of the previously inherent emissions becoming past emissions. This enables 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 carbon accounting information and carbon accounting systems become physically auditable?*), this paper shows how 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 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. Furthermore, even when fuel efficiency or material efficiency varies over time, accounting for inherent emissions provides an additional control as changes of materials and their composition will mirror these differences. 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 relevant assets via emission factors, analyses of their chemical composition, or other methods. If the quantity of physically observed inherent emissions in the assets is different from the quantity provided by the carbon accounting system extended with inherent emissions, there are either emissions that are not accounted for, or the labelling of incoming and outgoing emissions is false. Moreover, the total quantity of carbon certificates sold needs to correspond to the quantity of CO_2 taken from the atmosphere and stored within the control of the offsetting company. The quantity of captured carbon can be verified (Murugan et al., 2020) as it needs to correspond to the quantity of inherent emissions in the accounting system. Such controls can be applied for different types of offsets. For photosynthesis-based offsets (e.g., planting trees), the resulting inherent emissions are bound in organic materials like wood. The carbon stock can be estimated from the mapped area, species composition, stand density, age structure, and observed damage or losses, enabling reasonably accurate inventories. For carbon capture and storage offsets, the resulting materials are stored in underground formations and mineralized into stable carbonates. These reservoirs can be monitored and audited to estimate and track the sequestered carbon (and the quantity of inherent emissions) over time. This systematic approach 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 the inherent emissions captured from the atmosphere show, the interpretation of inherent emissions is neutral in itself. Inherent emissions describe a physical stock of emissions bound in material. They can become emission flows into the atmosphere (Scope 1 emissions) but do not necessarily do so. Examples of diamonds, carbonate minerals generated from carbon capture and storage, and recycled plastic illustrate this. Under normal circumstances, diamonds do not react with oxygen to form CO_2, unless the carbon crystal is heated to high temperatures in an oxygen-rich environment, in which it transforms into CO_2. Hence, diamonds have inherent emissions. However, as they can be physically observed over time, these inherent emissions do not need to be interpreted negatively but as a physical stock of stable carbon. The same is true for materials that are formed through carbon capture and storage facilities which are often also very stable, carbon-rich materials such as graphite. Finally, plastics contain inherent emissions. Assuming that the weight and chemical composition of recycled plastic is not significantly different than the virgin plastic entering the process, after the recycling process the inherent emissions in the material will still be the same. Consequently, the inherent emissions are not emitted into the atmosphere. However, if it is burned, all inherent emissions are released. When disposed of in landfills, the inherent emissions of plastics can be bound in material for many years. However, even if it is not combusted in the traditional sense, it will be released by natural processes at some point, despite taking many years (Blank, 2024). Hence, inherent emissions are passed through supply chains alongside materials, supplies, and products and contain information about possible future emissions.

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 labelled 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.

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 related to 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 and Reichelstein, 2019) and can, therefore, have a large quantity of past emissions in the supply chain, which can be reduced by purchasing green hydrogen instead of grey hydrogen (Oliveira et al., 2021), 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 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. Inherent emissions can help to estimate future emissions both within the company and for downstream Scope 3 emissions. Internally, this can help companies to calculate their own downstream Scope 3 emissions. Externally, stakeholders can obtain an idea of a company's (possible) future emissions for forecasts and risk assessments. Evaluating a company's emission intensity requires a comparison of the 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 corporate environmental impacts. Additionally, such condensed information can help to quantify 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 emission 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 some 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. Enterprise resource planning (ERP) systems should allow a sufficient differentiation between different materials that include inherent emissions to enable a consistent tracking of both past and inherent emissions. 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., 2025) but also for inherent emissions. Additionally, data exchange between companies should be possible to pass information about past and inherent emissions through the supply chain. However, for companies that already have transactional carbon information available, the additional information needed is only a single value for inherent emissions since existing data can be used. As a result, the added complexity of this approach is low. 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 emissions under their control. Standardization of incorporating this information into ERP and accounting systems could be achieved through the introduction of new standards. This has the additional benefit of introducing comparability across companies, sectors, and jurisdictions. Standard setters and policymakers could amend existing standards such as the GHG Protocol or introduce entirely novel, comprehensive standards to make this approach accessible.

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., 2025), the opportunity for fraud can be reduced substantially. Furthermore, accounting for inherent emissions should not replace internal controls, material flow analyses, continuous checks of records, and other governance mechanisms, but rather extend them to further facilitate auditing and assurance of carbon accounting data. Additionally, future research can uncover how fraudulent behavior could be detected when applying inherent emissions accounting in combination with other internal controls 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 engineers or natural scientists, 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 additional 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. 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 help determine the actual costs and benefits of implementing inherent emissions accounting. In summary, recognizing inherent emissions as a *physical stock* of carbon, and their transformation into past emissions as a *physical flow*, enables the physical verification of emissions recorded in accounting systems while remaining consistent with and extending established carbon accounting systems.

3.5. Appendix

3.5.1. Extending inherent emissions beyond CO_2

The appendix generalizes the concept of inherent emissions from CO_2 to other greenhouse gases. Extending the concept of inherent emissions from CO_2 to other greenhouse gases requires accounting for all relevant greenhouse gases simultaneously, along with their global warming potential. The global warming potential (GWP) mirrors the warming effect that one ton of a greenhouse gas has compared to CO_2, which has a GWP of 1 by definition (Lashof and Ahuja, 1990; Rodhe, 1990). Usually, the warming effect is expressed over a specific time horizon, GWP-20, GWP-100, and GWP-500 have a time horizon of the warming over 20, 100, and 500 years, respectively. In climate policy, the 100-year global warming potentials are regularly used (Forster et al., 2021). Table 3.A1 gives an overview of the GWPs for several greenhouse gas emissions.

Greenhouse Gas	Lifetime in the atmosphere	GWP-20	GWP-100	GWP-500
CO_2	Multiple	1	1	1
CH_4-fossil	11.8 ± 1.8	82.5 ± 25.8	29.8 ± 11	10.0 ± 3.8
CH_4-non fossil	11.8 ± 1.8	79.7 ± 25.8	27.0 ± 11	7.2 ± 3.8
N_2O	109 ± 10	273 ± 118	273 ± 130	130 ± 64

Table 3.A1: *Global warming potential for the most important greenhouse gases and GWP according to the IPCC (Forster et al., 2021). The ± notation reflects the uncertainty of the GWP. For example, for the GWP-100 of one ton of CH_4-fossil, the global warming potential is between 18.8 and 40.8 times that of one ton of CO_2.*

3.5.2. Representing inherent emissions as a vector

With multiple gases considered, the inherent emissions of a material can be represented as a vector *I,* where each element corresponds to an upper bound of a specific greenhouse gas. For material m, the vector $I(m) = \left(I_{CO_2}, I_{CH_4}, I_{N_2O}, I_{HFCs}, I_{PFCs}, I_{SF_6}, \dots\right)$ lists the maximum possible formation of CO_2, CH_4, N_2O, SF_6, etc. from the atoms contained in m (plus freely available atmospheric reactants, like oxygen, where appropriate). The vector does not constitute a forecast; instead, it provides mutually exclusive maxima per greenhouse gas to support audit tests. To facilitate comparability, each component can be expressed in CO_2-equivalent terms using the relevant GWP, as in the vector I^{CO_2e} below. It is important to note that it is not meaningful to sum the vector elements because the underlying atoms cannot be oxidized into more than one gas at a time. As described in the main text of this article, bookkeeping continues to follow the double-entry structure with distinct past versus inherent columns. The vector expands the inherent column to multiple gases. While the values cannot be considered as forecasts, some of its informational value *can* be used to anticipate potential future emissions and for risk assessments. For inter-greenhouse gas comparability, the CO_2 equivalents of each inherent emission can be expressed as

$$I^{CO_2e}\,(m) = \left(I_{CO_2} \times 1, I_{CH_4} \times GWP_{CH_4}, I_{N_2O} \times GWP_{N_2O}, \ldots\right)$$

using a specified GWP time-horizon depending on the local rules and regulations (e.g., 100-year GWP).

3.5.3. Deriving gas-specific upper bounds

Upper bounds for each gas can be calculated from the elemental composition of each of the materials. For the inherent emissions of a material, the masses (in kg) of different elements (carbon, hydrogen and nitrogen) in the material are denoted by m_C, m_H, and m_N. This leads to the gas-specific inherent emissions CO_2, CH_4, N_2O, and fluorinated gases. For the case of fluorinated gases SF_6 is taken as an example, as it is the most potent fluorinated gas, measured by its GWP (US EPA, 2025).

CO_2 is formed and emitted through the reaction of carbon and oxygen. Oxygen is freely available in the air and reacts with carbon through processes like burning.

$$I_{CO_2} = m_C \times \frac{44}{12}$$

The fraction $\frac{44}{12}$ is derived from the atomic masses of carbon ($12\,u$) und oxygen ($16\,u$) when combined to CO_2 (Ball and Key, 2014). When one carbon atom reacts with two oxygen atoms the mass changes from originally $12\,u$ to $44\,u$ ($12\,u + 16\,u \times 2 = 44\,u$).

CH_4 is formed and emitted through the reaction of carbon and hydrogen. Hydrogen is not as available in the air as oxygen. Hence, the inherent CH_4 can be limited by the quantity of carbon or the quantity of hydrogen available in the reaction. Inherent CH_4 emissions can be calculated as:

$$I_{CH_4} = \min(m_C \times \frac{16}{12}, 4m_H)$$

The minimum formula is used as hydrogen is not freely available in the atmosphere to react with carbon (as opposed to oxygen with carbon). Again, the factors $\frac{16}{12}$ and 4 reflect the weights of carbon ($12\,u$) and hydrogen ($1\,u$). However, a more prudent approach assumes that hydrogen is readily available. This reduces the formula to:

$$I_{CH_4} = m_C \times \frac{16}{12}$$

N_2O is formed and emitted through the reaction of nitrogen and oxygen.

$$I_{N_2O} = m_N \times \frac{44}{28}$$

Here, the factor $\frac{44}{28}$ reflects the weights of Nitrogen ($14\,u$) and oxygen ($16\,u$) that combine as two nitrogen atoms and one oxygen atom ($16\,u\ +\ 14\,u\ \times 2 = 44\,u$).

Fluorinated gases have no significant natural source and are almost entirely emitted from human activities. This indicates that they are not simply formed through carelessness but are usually deliberately produced as refrigerants, as insulating gases, or in aluminum and semiconductor production (US EPA, 2025). Fluorinated gases are the most powerful greenhouse gases in terms of their GWP (US EPA, 2025). For example, the most potent greenhouse gas, SF_6 depends on the presence of sulfur and fluorine. Hence, chemical reactions to form SF_6 do not occur naturally but are deliberately caused in industrial processes. Otherwise, $I_{SF_6} = 0$.

The interpretation of inherent carbon is straightforward, as the focus is just on CO_2. However, for the interpretation of the multi-gas inherent emissions vector there are a few things that need to be considered.

- These are mutually exclusive upper bounds by gas (one cannot emit all maxima simultaneously).
- The vector can be used for scenario checks (e.g., 'all C to CO_2' vs 'all C+H to CH_4'), not to sum across rows.
- When using CO_2e, it is important to state the GWP horizon.
- The bookkeeping still follows the paper's double-entry approach with distinct 'past' vs 'inherent' columns. This appendix only defines how to calculate the inherent side of other gases while past emissions are recorded in CO_2e as the global warming potential of a greenhouse gas multiplied by the quantity of the respective greenhouse gas emitted.

3.5.4. Examples

This section demonstrates how the extension by several greenhouse gases can be operationalized for different materials. Additionally, it briefly elaborates on the consequences and interpretation of this information for companies and auditors.

First, this is demonstrated using the example of natural gas or methane. Methane (which is the main component of natural gas) is a commonly used gas for heating and industrial applications, which is combusted to generate heat and is the second most emitted greenhouse gas by GWP (US EPA, 2015). Table 3.A2 shows the vector of inherent emissions for 1 kg methane. Here, it becomes apparent that methane can be converted to CO_2 or stay in its current form (Cenci and Biffis, 2025). However, the lines 'N_2O' and 'HFCs/PFCs/SF_6' show that no other greenhouse gases can be formed from the chemical composition of methane. Multiplying the quantity of gases with their GWP-100 values yields the quantity of CO_2e per resulting gas.

Greenhouse Gas	Inherent Emissions (upper bound)	CO_2e adjusted by GWP-100
CO_2	$0.75 \times \frac{44}{12} = 2.75$ kg	2.75 kg
CH_4	1.00 kg	1.00 kg × 28 = 28 kg
N_2O	0 kg	0 kg
HFCs/PFCs/SF_6	0 kg	0 kg

Table 3.A2: *Vector of different inherent greenhouse gas emissions for one kg of methane (natural gas) (Ball and Key, 2014). The value of 28 kg is chosen as it is between the IPCC's values of CH_4-fossil and CH_4-non fossil.*

The example of methane illustrates the importance of keeping track of what happens to greenhouse gases in industrial and other processes. In a landfill waste facility, some material decomposes, emitting methane. Suppose the methane is emitted into the environment. In that case, it should be accounted for as 28 kg CO_2e per kilogram, but when it is burned (even without serving an additional purpose), it should be accounted for as 2.75 kg CO_2e per kilogram. Consequently, an auditor who observes that emitted gas is consistently burned can be confident that the emitted greenhouse gases are equivalent to their inherent emissions (2.75 kg per kg of methane). However, if the auditor observes that (part of) or all of the methane is emitted without being burned, it is sensible to expect the client to account for these emissions with a CO_2e of 28 kg per kilogram of gas. If there is a large uncertainty about which greenhouse gas is formed in the processes, the auditor should perform a prudent CO_2e assessment, avoiding costly scandals such as the US$2b decline of market value of Santos Limited due to its methane management (EDF, 2025). Hence, the auditor should assume that at least some or all of the greenhouse gases formed are of the more potent types of the vector.

For a more complex, yet economically and ecologically relevant combination of hydrocarbons, the following example considers one kilogram (1.35 L) of gasoline. Gasoline is not a greenhouse gas in itself, but it contains a combination of hydrocarbons. Table 3.A3 shows the vector of inherent emissions for gasoline. It shows that from the chemical composition of gasoline, both CO_2 and CH_4 can be formed (CH_4 only when sufficient hydrogen is available to react with) as it contains about 0.85 kg of carbon while the other greenhouse gases are not feasible.

Greenhouse Gas	Inherent Emissions (upper bound)	CO_2e adjusted by GWP-100
CO_2	$0.85 \times \frac{44}{12} = 3.11$ kg	3.11 kg
CH_4	$0.85 \times \frac{16}{12} = 1.13$ kg	1.13 kg × 28 = 31.64 kg
N_2O	0 kg	0 kg
HFCs/PFCs/SF_6	0 kg	0 kg

Table 3.A3: *Vector of different inherent greenhouse gas emissions for one kg of gasoline (Ball and Key, 2014; Natural Resources Canada, 2014).*

3.5.5. Economic and policy consequences

The question arises whether inherent multi-gas emissions accounting is too complex or costly. In practice, computing the inherent emissions vector requires the same fundamental information already used for conventional greenhouse gas inventories: the carbon content of inputs, standard emission factors and an understanding of process chemistry. For example, the combustion of one kilogram of methane produces approximately 2.75 kg of CO_2, while one kilogram of gasoline yields about 3.11 kg of CO_2; these factors are readily available and widely used in existing inventories. Furthermore, emissions from these factors already make up a large share of total carbon emissions. Firms that already perform accurate carbon accounting can therefore implement the inherent emissions vector with low additional effort. The only new step is *recording* the maximum potential emissions per gas. This recording enables physical audit tests and sends a strong signal of commitment to external stakeholders. Auditors will still need to inquire about processes that could emit greenhouse gases, but the inherent vector gives them an additional information base to verify the claims.

Policymakers and standard setters play a critical role in making this extension practicable by distinguishing between *baseline-based* and *pathway-specific* emissions. For materials that are converted to just CO_2 with high certainty, a baseline could be established. They should mandate the use of standard emission factors for carbon-based materials and other common inputs, such as fossil fuels, so that large portions of emissions are automatically determined from material quantities. For other materials where the emission of different greenhouse gases depends largely on the production processes in which different pathways exist, the policymakers and standard setters should also provide guidance for those materials by specifying when firms should report the highest inherent CO_2e value unless verifiable evidence demonstrates a different conversion pathway. For instance, as shown in Table 3.A2, if methane is combusted, emissions correspond to the CO_2 factor of 2.75 kg per kilogram; if it is released unburned, the GWP is about ten times as high (2.75 kg CO_2 vs. 28 kg CO_2e). Regulators could require firms to default to the higher value unless they can demonstrate that the gas is consistently combusted or otherwise managed.

For these cases, companies should be able to choose whether they want to disclose how materials react in their processes, to identify emission pathways (forming greenhouse gases other than CO_2) to show that their CO_2e emissions are lower than the calculated maxima, or whether they want to report the higher quantities. The respective decision tree of how to report inherent multi-gas emissions is shown in Figure 3.A1. This choice between lower complexity and more accurate emission reporting effectively makes accounting for multiple greenhouse gases more economical for companies, as they can always weigh the proprietary and calculation costs of disclosing their exact internal processes against the costs they incur when reporting the higher emission values. It is worth mentioning that, in this case, undisclosed processes can lead to some overreporting of emissions, while underreporting of emissions becomes unlikely. However, under regulations that intend consequences for emissions, companies will have more incentives to exert more effort to accurately report their emissions and disclose more details about their processes. Companies would only choose to report the higher emission quantities if the costs related to disclosing the processes to auditors are very high.

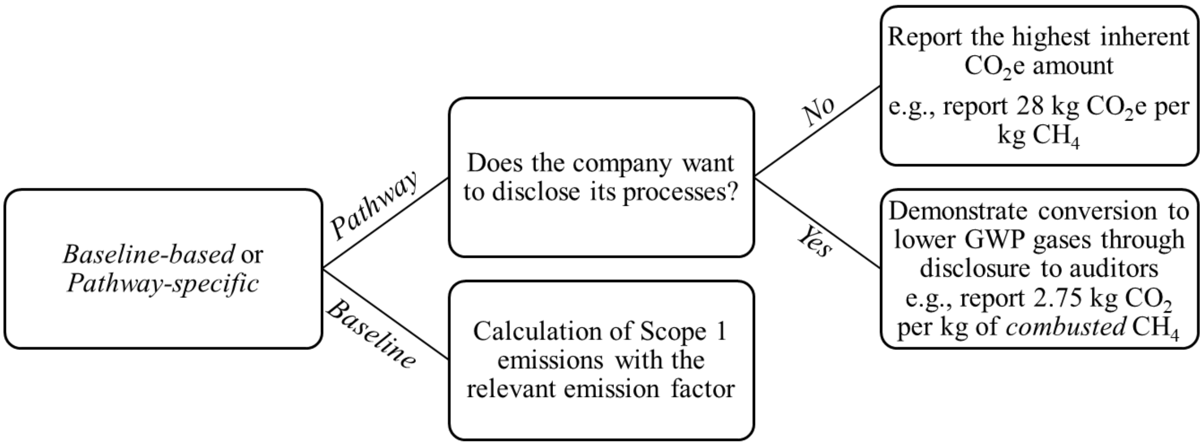


Figure 3.A1: *Decision tree of the proposed requirement to report inherent multi-gas emissions based on baseline-based or pathway-specific emissions.*

Other approaches might incorporate typical conversion pathways and rely on prudent assumptions for common materials, always keeping track of the physical composition. The level of prudence applied when assessing different gases will depend on the objectives of the standard and the auditor's judgement of the reliability of the firm's process information. Standardization is essential for comparability across firms and sectors and for preventing greenwashing. Clear rules on emission factors, GWP values, and acceptable documentation will ensure that the inherent emissions vector is applied consistently and give auditors a defined framework within which to exercise professional skepticism (Nelson, 2009).

Summary

This dissertation builds on the premise that the credibility problem in corporate carbon accounting is, at its core, a verifiability problem. Carbon information is increasingly used for internal decisions and external disclosure. Still, it is often produced in ways that are prone to errors and misstatements, which are hard to detect once emissions have occurred. Improving trust in carbon disclosures is therefore not only a matter of collecting more data, but also requires designing accounting systems so that (quantitative) information can be verified against independent evidence and a robust reconciliation logic.

The first chapter of the dissertation synthesizes a fragmented research landscape across disciplines into a structured view of how verifiability can be strengthened. The systematic literature review, using topic modeling, shows that proposed solutions span auditing and assurance research, governance and incentive-based perspectives, and technical innovations such as blockchain, satellite data, and artificial intelligence. The review's central contribution is to demonstrate that no single approach fits all settings, but that the approaches are suitable for different application areas, and have advantages and disadvantages. Overall, verifiable carbon information requires an interdisciplinary approach that combines standards and assurance practices, governance and enforcement mechanisms, and technological tools for data integrity and anomaly detection. The literature synthesis clarifies where current approaches are strong, where they remain limited, and why the next step should be to develop credible verification systems that integrate existing approaches and tools from different disciplines.

The second chapter develops a Material Flow Cost Accounting (MFCA)-based validation mechanism for Scope 1 emissions within a firm's internal information system. By extending MFCA to produce emission input-output balances consistently, this dissertation turns MFCA from a predominantly estimation-driven activity into one that enables internal validity checks. The extended input-output balances ensure that carbon in material flows is accounted for consistently, so that underestimation of emissions is not absorbed by the method but is validated with the proposed methodological extension. This enables managerial decisions about process changes, product design, and investments, relying on the integrity of emissions data. Therefore, the extension contributes a practical pathway for firms to strengthen internal control over emissions information and to increase confidence that reported emission quantities are complete and physically plausible.

The third chapter extends corporate carbon accounting by proposing a system design that enables time-independent verification through physical examination, similar to taking

inventory. By introducing inherent emissions as a physical emission stock related to assets under a company's control, the information recorded in the carbon accounting system gains an auditable element that remains observable in goods, inventories, and assets. This shifts the verification from relying solely on reconstructing past emissions flows toward a stock-flow structure in which auditors can physically inspect and estimate the carbon embedded in relevant assets and reconcile it with accounting records. If observed inherent emissions in assets do not match recorded inherent emissions, this indicates either unaccounted emissions or mislabeling of inflows and outflows. Importantly, this logic also offers a way to strengthen controls around carbon removals and offset claims by linking certificates and reported removals to physically stored carbon.

Collectively, the dissertation's contribution demonstrates that carbon accounting is not merely a passive recipient of emissions measurements but a discipline that can actively improve the reliability of carbon information through appropriate methods and system design. The central insight across the three chapters is that verifiability increases when carbon accounting strengthens validation systems, mechanisms, and accounts for physically auditable information. This provides clear implications for research and practice, such as that strengthening carbon accounting credibility requires not only better estimation techniques and more assurance engagements, but also accounting architectures and systems that make misstatements harder to hide and easier to detect. In that sense, the dissertation reframes the challenge from "measuring carbon better" to "building carbon accounts that can be verified," and it offers concrete conceptual and methodological building blocks to move carbon accounting closer to the evidence standards expected in accounting and assurance.

Several avenues for future research build on the contributions of this thesis. Empirical studies of firms applying the extended methods proposed here could examine how more verifiable carbon accounting, and therefore more trustworthy carbon information, affects managerial decision-making. Initial research could use case studies or field experiments to investigate effects on emissions management, investment decisions, production scheduling, and procurement. As these methods become more widely adopted, quantitative studies could then assess whether improved carbon information is associated with measurable changes in firm-level emissions. Future research should also address the development of standards for verifiable carbon accounting systems, carbon assurance practices, and emissions audits, since such standards are necessary to ensure comparability across firms.

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Summary of the dissertation

Verifiable Carbon Accounting: Systems, Methods, and Auditability

by

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In this dissertation, the verifiability of carbon information is analyzed and enhanced through the extension of carbon accounting methods. It shows that carbon accounting can actively improve the reliability of carbon information through appropriate methods and system design. While emissions measurement is an important element of carbon accounting, the accounting system also plays a central role in providing credible carbon information.

The three chapters of the thesis highlight different aspects of carbon information verification. Chapter one synthesizes the literature around verifiable and credible carbon information across different disciplines. It provides a framework of credible carbon information. Chapter two extends the Material Flow Cost Accounting (MFCA) method to validate carbon information by balancing input and output emissions across processes. This provides managers with a tool to generate internal carbon information for the management and control of carbon emissions. Finally, chapter three extends existing corporate carbon accounting systems to include physically observable evidence of carbon emissions. This enables internal and external audits of emissions to verify carbon information.

The central insight across the three chapters is that verifiability increases when carbon accounting strengthens validation systems, mechanisms, and accounts for physically auditable information. This provides clear implications, such as that strengthening carbon accounting credibility requires not only better estimation techniques and more standardized assurance engagements, but also accounting architectures and systems that make misstatements harder to hide and easier to detect. In that sense, the dissertation reframes the challenge from “measuring carbon better” to “building carbon accounts that can be verified,” and it offers concrete conceptual and methodological building blocks to move carbon accounting closer to the evidence standards expected in accounting and assurance.

This thesis was supervised by *Prof. Dr. Marc Wouters* at the Institute of Management. It is written in English. The pursued degree is *Dr. rer. pol.*