Leveraging Digital Measuring, Reporting, and Verification: A Digital Technologies Perspective on Intra- And Inter-Organizational Decarbonization

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“Climate change is a result of the greatest market failure the world has seen.”

Nicholas Stern

Acknowledgments

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Abstract

The mitigation of climate change necessitates the rapid reduction of Greenhouse Gas (GHG) emissions, particularly CO_2 (hereafter: carbon), across all economic sectors. Achieving this goal requires not only robust decarbonization strategies but also accurate and scalable mechanisms for the Measuring, Reporting, and Verification (MRV) of GHG emissions data. As regulatory pressure, investor scrutiny, and societal expectations increase in scope, stringency, and enforcement, organizations face increasing demands for transparent and effective GHG emissions management within their own organizational boundaries, throughout their supply chains, and within (carbon) markets. Current carbon accounting practices are often constrained by fragmented data collection, reliance on estimates or industry averages, and manual, error-prone processes, especially for indirect emissions. These limitations undermine decarbonization efforts' effectiveness and impede the transition to data-driven GHG emissions management.

In this cumulative dissertation, I adopt a digital technologies perspective to investigate how digital MRV can transform GHG emissions management at both the intra- and inter-organizational level. Integrating insights from eight research articles, it systematically explores the potential of digital technologies and concepts such as Artificial Intelligence (AI), data spaces, digital identities, and Distributed Ledger Technologies (DLTs) to enhance MRV processes with the objective of enabling an end-to-end digitalized MRV (i.e., digital measuring, reporting, and verification processes at all stages in a value chain on the basis of interlinked Information Systems (IS)). To do so, this dissertation identifies key characteristics of digital MRV as well as digital carbon accounting architectures, develops frameworks for carbon accounting and trading, and examines the practical challenges to and opportunities of deploying digital technologies for decarbonization in diverse intra- and inter-organizational contexts.

By bridging the gap between theoretical frameworks and real-world implementation, this dissertation demonstrates how digital MRV can provide the data foundation required by different stakeholders not only for regulatory compliance and market transparency but also for CO_2-adaptive decision-making and the effective internalization of environmental costs. It highlights the necessity of strengthening internal carbon emissions management as well as fostering reliable data sharing within and between organizations to close the carbon accounting gap that is particularly evident regarding indirect emissions along and across supply chains. Ultimately, this dissertation contributes to both the Digital Decarbonization and Green IS fields by offering actionable guidance for researchers, organizations, and policymakers seeking to leverage digital MRV for effective, scalable, and trustworthy decarbonization.

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Copyright Statement

The following chapters are partly comprised of content taken from the research articles in this thesis. To improve the readability of the text, I have omitted the standard labeling of these citations.

1 Introduction

1.1 Motivation

The imperative to rapidly and substantially reduce GHG emissions, particularly CO_2, has reached unprecedented urgency. With global emissions continuing to rise and the window for limiting global warming to 2°C compared to pre-industrial levels rapidly closing, achieving deep decarbonization has become the defining challenge of our time. The Paris Agreement's ambitious targets require not merely incremental improvements but fundamental changes in how organizations measure and reduce their emissions across all economic sectors on a global scale. As noted by Nicholas Stern, this challenge can be seen as the result of the "greatest market failure the world has seen" (Benjamin, 2007), requiring a fundamental transformation of how environmental costs are internalized in global markets.

Central to this change is the critical role of transparency requirements: Organizations face increasing pressure from multiple stakeholders who are demanding comprehensive information about their environmental impact: First, the introduction of regulations such as the Corporate Sustainability Reporting Directive (CSRD) in the EU illustrates the increasing policy-driven pressure on organizations. Second, investors increasingly consider Environmental, Social, and Governance (ESG)-criteria, making GHG emissions, among others, a relevant metric for organizations to receive financing. Third, consumers are increasingly demanding transparency regarding their "carbon footprint" (i.e., the total GHG emissions emitted caused by a specific product or service) (Research Paper P1).

Current practices in carbon accounting and emissions management are subject to significant limitations that fundamentally undermine their effectiveness. As a telling example of the "market failure" described by Stern, investigative reports have revealed that more than 90% of rainforest carbon offsets (i.e., ways to reduce or avoid GHG emissions, for instance, through afforestation or reforestation) certified by Verra, a leading global standard setter, did not represent actual carbon reductions (Greenfield, 2023). This "trust deficit" highlights a systemic failure: current MRV processes are largely manual and lack the granularity needed for true accountability (Research Paper P1). Organizations predominantly rely on fragmented and cost-intensive data collection and reporting processes as well as on estimates or industry averages (e.g., if the collection of primary data is prohibitively expensive). These practices create substantial information asymmetries (i.e., conditions where relevant information about GHG emissions is unevenly distributed between parties) that limit the accuracy required for effective decarbonization strategies. Most critically, the accounting of indirect emissions (which often represents the majority of an organization's total carbon footprint, for instance, in manufacturing industry companies (Huang et al., 2009)), remains severely constrained by inadequate data collection and sharing mechanisms within and between organizations (Research Paper P5).

The existing data (sharing) challenges of current practices in organizations extend beyond mere accounting issues and create significant barriers to effective climate action: Without accurate, timely, and verifiable emissions data, organizations cannot take CO_2-adaptive decisions that are necessary for a deep decarbonization. In particular, the use of industry-average emission factors and proxy estimates impedes incentives for organizations to reduce their emissions to (or below) these values. Thus, the lack of accurate, timely, and verifiable emissions data undermines trust in corporate climate commitments (Research Paper P3). Beyond organizations' own boundaries, the reliance on estimates and average values prevents them from identifying "hotspots" in their supply chains (i.e., raw materials, (pre-)products, or processes that are associated with considerable emissions), often leading to unintended greenwashing where reported emissions (reductions) do not reflect physical reality. Thus, supply chains remain opaque, preventing the identification of decarbonization opportunities, the accurate allocation of environmental costs to their sources, and, ultimately, the development of effective market mechanisms for carbon management (Research Papers P7 and P8).

Advances in digital technologies and concepts such as AI, data spaces, digital identity management, DLTs, or Privacy Enhancing Technologies (PETs) present promising opportunities to address these fundamental challenges. They offer potentials to transform MRV processes from largely manual, estimate-based activities into end-to-end digitalized, automated processes capable of collecting and sharing verifiable emissions data within and beyond organizations' boundaries. These digital technologies have the potential to allow organizations to share sensitive, competitively relevant, emissions data in a secure, efficient, and self-sovereign way. In particular, a combination of digital technologies allows for practical applications such as a Digital Product Passport (DPP), which provides a transparent and trustworthy record of a product's environmental impact across its entire life cycle and acts as an enabler of sustainable business models as well as market mechanisms (Research Paper P1).

Realizing digital technologies' potentials for decarbonization within and beyond organizations' boundaries requires more than simply applying digital tools to existing processes: It demands a fundamental reconceptualization of MRV as integrated, end-to-end digital processes that can bridge organizational boundaries and enable seamless, trustworthy data sharing throughout complex supply chains (Research Paper P1). This reconceptualization must address not only technical challenges, such as interoperability between different ISs, but also fundamental questions about data quality, data governance, and data flows (Research Papers P2 and P5), thereby addressing concerns about aspects, such as privacy, standardization, and trust, which are essential for widespread adoption.

The urgency of climate action, combined with the limitations of current practices and digital technologies' transformative potentials, creates both opportunities and imperatives for comprehensive research into digital MRV for decarbonization. This dissertation addresses this critical need by taking a systematic approach to understanding how digital technologies can enhance MRV processes and can enable the transparent, efficient, and trustworthy emissions management required for effective decarbonization at both the intra- and inter-organizational level.

This dissertation is particularly timely given the convergence of several trends: the implementation of increasingly stringent emissions reporting requirements, the advancing capabilities of digital technologies to address current MRV limitations, and the recognition that effective climate action requires system-level approaches that exceed individual organizational boundaries. By bridging the gap between theoretical potential and practical implementation, this dissertation seeks to provide the foundational knowledge necessary to enable CO_2-adaptive decision-making, to effectively internalize GHG emissions environmental costs, and - ultimately - to accelerate the transition toward digital decarbonization strategies that can deliver the scale and speed of emissions reductions that global climate change requires.

1.2 Research Aim

This dissertation is situated in the interdisciplinary field of Green IS, a domain dedicated to examining, designing, and modeling digital solutions that foster a sustainable future (Melville, 2010; vom Brocke et al., 2013). As sustainability efforts rise and the climate crisis intensifies, this field has increasingly pivoted toward Digital Decarbonization - the targeted use of digital technologies to accelerate the reduction of GHG emissions (Heeß et al., 2024; Zampou et al., 2022). Traditionally, Green IS has focused on intra-organizational processes across different sectors such as logistics (Qu & Liu, 2022), mobility (Ketter et al., 2023), and energy (Watson et al., 2010). This dissertation identifies and guides a shift from such a purely intra-organizational focus toward a more supply chain- and ecosystem-oriented view, encompassing, for instance, digital carbon credits (Chakraborty et al., 2022), automated trading via smart contracts (G. Li & Li, 2021), and fine-granular proofs of origin for energy (da Cruz et al., 2020).

Against this background, this dissertation addresses a pressing challenge in current sustainability practices: organizations and value chains are struggling to measure, report, and verify carbon emissions in ways that are accurate, timely, and trustworthy. Drawing on recent advances in both Green IS and Digital Decarbonization, and building on digital technologies such as AI, DLTs, Internet of Things (IoT), data spaces, and PETs, it investigates how digital MRV can transform fragmented, largely manual carbon accounting practices into integrated, automated carbon management ecosystems. In particular, in this dissertation I explore three interconnected themes. First, I establish an understanding of digital MRV with the objective of an end-to-end digitalized MRV and an architectural foundation for digital carbon accounting architectures. Second, I provide an intra-organizational view on digital decarbonization, illustrating how a digital MRV perspective may help organizations to collect and manage their carbon data. Third, I develop conceptual frameworks to structure diverse approaches of carbon accounting and trading, clarifying pathways and options available to researchers and practitioners at the inter-organizational level.

By shifting the focus from an isolated, intra-organizational focus to collaborative, inter-organizational data ecosystems, this dissertation contributes to both theory and practice. It extends Green IS by establishing *Digital Measuring, Reporting, and Verification for Decarbonization* as a relevant research stream and provides conceptual foundations in this stream that provides various avenues for future research. For practitioners, it provides organizations with an overview over architectural design options relating to digital MRV in different contexts, thereby indicating paths for them to assess and improve current practices. It also provides policymakers and standard-setting bodies with evidence on how digital innovations can enhance regulatory frameworks, such as the EU's CSRD, by increasing market transparency and verifiability.

To do so, this dissertation draws mainly on qualitative empirical research and design science methodology, building frameworks and artifacts such as taxonomies based on guidance from Nickerson et al. (2013) and Kundisch et al. (2022) or maturity models following Becker et al. (2009). To do so, it uses different empirical foundations such as scientific literature (following Webster and Watson (2002)), gray literature (following Garousi et al. (2019)), and semi-structured expert interviews (following Myers and Newman (2007)). Iteratively refining and evaluating these frameworks and artifacts as recommended by the respective methodological background literature ensures that this dissertation's contributions are both scientifically rigorous and relevant. In doing so, it seeks to accelerate global decarbonization by leveraging digital technologies' transformative potentials for making GHG emissions data more accessible, reliable, and actionable, thereby enabling more informed decision-making and fostering rapid and effective climate action.

1.3 Structure of the Dissertation and Embedding of the Research Papers

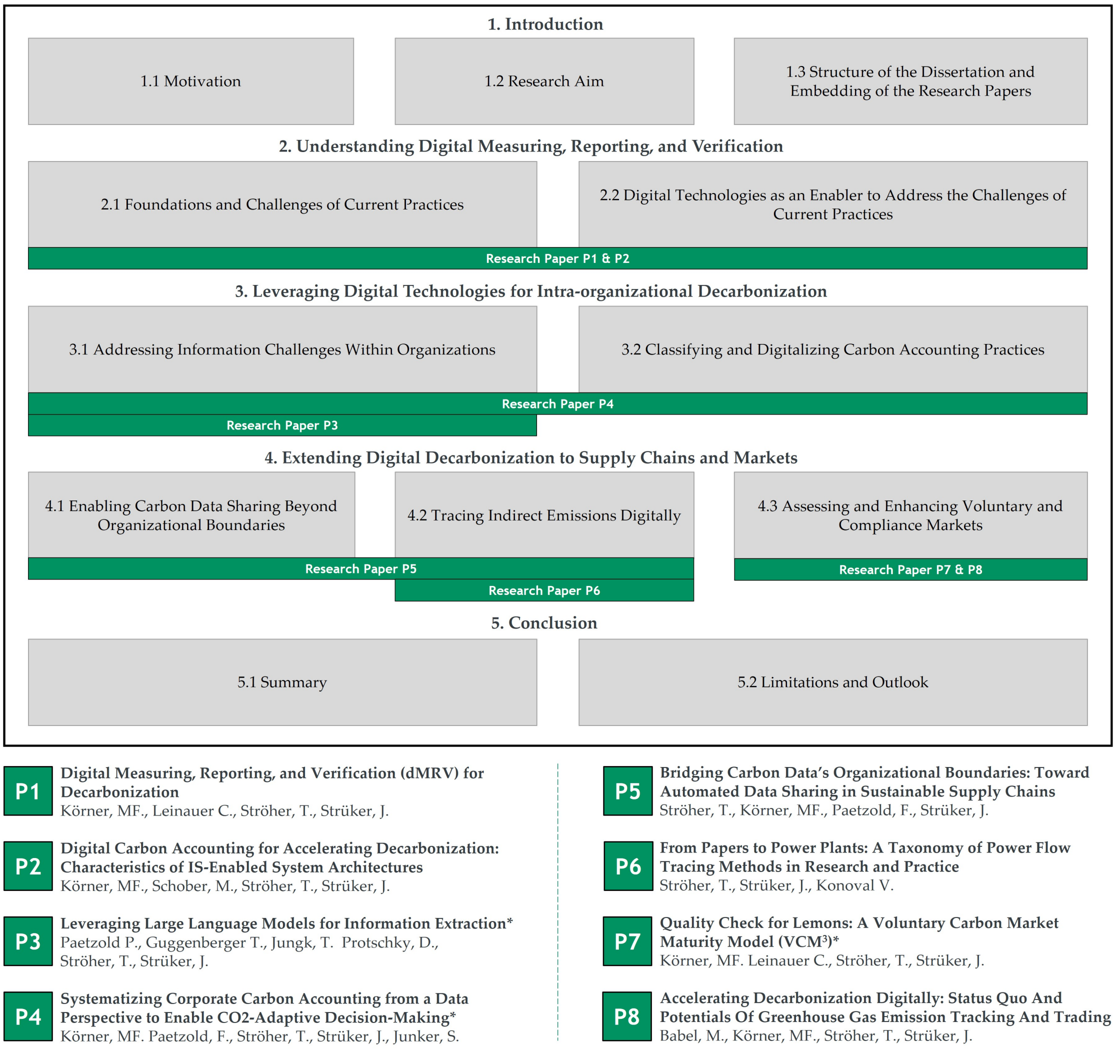
This cumulative dissertation is organized into five chapters and integrates eight essays that jointly address the understanding, design, and application of digital MRV for intra- and inter-organizational decarbonization. Figure 1.1 illustrates the overall dissertation's structure and the placement of each embedded paper. Chapter 1 introduces the dissertation's motivation, scope, and objectives.

Chapter 2 establishes the foundations of digital MRV for decarbonization, embedding Research Paper P1 (M.–F. Körner et al., "Digital Measuring, Reporting, and Verification for Decarbonization") and Research Paper P2 (Körner et al., "Digital Carbon Accounting for Accelerating Decarbonization: Characteristics of IS-Enabled System Architectures"). To do so, this chapter provides a definition and an understanding of the MRV concept, including the exploration of its interrelationship with the carbon accounting concept. Chapter 2 further highlights challenges in current MRV practices and illustrates that digital technologies can serve as a critical enabler to address these challenges. It then provides a general understanding of digital carbon accounting system architectures by presenting key characteristics.

Chapter 3 examines intra-organizational applications of digital technologies for MRV and digital carbon accounting. It starts by considering advances in natural language processing, particularly regarding Large Language Models (LLMs), for exemplifying the application of digital technologies to transform unstructured data into actionable information, which is an important prerequisite for digital MRV. To do so, it draws insights from Research Paper P3 (Paetzold et al., “Leveraging Large Language Models for Information Extraction”). Further, via Research Paper P4 (Körner et al., “Systematizing Corporate Carbon Accounting from a Data Perspective to Enable CO2-Adaptive Decision-Making”), it analyzes current carbon accounting and reporting architectures and provides a digital technologies perspective for single organizations to assess and improve their current practices.

Chapter 4 extends the digital MRV perspective from the intra-organization view of Chapter 3 to supply chains and markets. Research Paper P5 (Ströher et al., “Bridging Carbon Data’s Organizational Boundaries: Toward Automated Data Sharing in Sustainable Supply Chains”) demonstrates the pathway toward this broader view by analyzing digital technologies’ potentials to enable carbon data sharing beyond organizational boundaries to achieve supply chain automation and more efficient markets. Then, Research Paper P6 (Ströher et al., “From Papers to Power Plants: A Taxonomy of Power Flow Tracing Methods in Research and Practice”) illustrates the concrete capabilities of applying an inter-organizational digital MRV perspective by focusing on the example of the electricity supply chain and Scope 2 emissions accounting. Research Paper P7 (Körner et al., “Quality Check for Lemons: A Voluntary Carbon Market Maturity Model (VCM^3)”) and Research Paper P8 (Babel et al., “Accelerating Decarbonization Digitally: Status Quo And Potentials Of Greenhouse Gas Emission Tracking And Trading”) further extend the inter-organizational perspective from supply chains to markets by illustrating the application of a digital MRV perspective in voluntary and mandatory carbon markets. This enables the classification, assessment, and, ultimately, the improvement of various approaches for GHG tracking and trading from a systemic perspective.

Chapter 5 concludes the dissertation by summarizing the core contributions, reflecting on theoretical and practical implications, outlining limitations as well as opportunities for future research. The bibliography and the appendix follow. Together, these chapters and papers support the advancement of Green IS and Digital Decarbonization by demonstrating how digital MRV can accelerate decarbonization within and across organizational boundaries.



P1 **Digital Measuring, Reporting, and Verification (dMRV) for Decarbonization**
Körner, MF., Leinauer C., Ströher, T., Strüker, J.

P2 **Digital Carbon Accounting for Accelerating Decarbonization: Characteristics of IS-Enabled System Architectures**
Körner, MF., Schober, M., Ströher, T., Strüker, J.

P3 **Leveraging Large Language Models for Information Extraction***
Paetzold P., Guggenberger T., Jungk, T. Protschky, D., Ströher, T., Strüker, J.

P4 **Systematizing Corporate Carbon Accounting from a Data Perspective to Enable CO2-Adaptive Decision-Making***
Körner, MF. Paetzold, F., Ströher, T., Strüker, J., Junker, S.

P5 **Bridging Carbon Data's Organizational Boundaries: Toward Automated Data Sharing in Sustainable Supply Chains**
Ströher, T., Körner, MF., Paetzold, F., Strüker, J.

P6 **From Papers to Power Plants: A Taxonomy of Power Flow Tracing Methods in Research and Practice**
Ströher, T., Strüker, J., Konoval V.

P7 **Quality Check for Lemons: A Voluntary Carbon Market Maturity Model (VCM^3)***
Körner, MF. Leinauer C., Ströher, T., Strüker, J.

P8 **Accelerating Decarbonization Digitally: Status Quo And Potentials Of Greenhouse Gas Emission Tracking And Trading**
Babel, M., Körner, MF., Ströher, T., Strüker, J.

*Working titles and author teams at the time of writing for unpublished Research Papers P3, P4, and P7

Figure 1.1: Structure of This Dissertation and Embedding of the Research Papers

2 Understanding Digital Measuring, Reporting, and Verification

The increasing urgency of climate change mitigation has driven both regulatory mandates and voluntary commitments to decarbonization across multiple sectors. Central to the credibility and effectiveness of these efforts are robust MRV processes, which underpin the collection, assessment, and communication of GHG emissions data. Recent analyses have exposed fundamental shortcomings in traditional MRV processes. For instance, investigative research by journalists of the Guardian, Die Zeit, and SourceMaterial discovered that more than 90% of rainforest carbon offset credits approved by the established certifier Verra did not correspond with de facto emissions reductions, undermining the legitimacy and value of Voluntary Carbon Markets (VCMs) and broader sustainability claims (cf. Chapter 1).

In this chapter, based on Research Paper P1 and P2, I will position MRV for decarbonization within the broader concept of carbon accounting, outline challenges of current MRV practices, and present the concept of an end-to-end digital MRV that can serve as the foundation for leveraging digital technologies to addressing these challenges.

2.1 Foundations and Challenges of Current Practices

To contextualize the role of MRV for decarbonization, it is first necessary to distinguish it from carbon accounting. While closely related, MRV and carbon accounting are distinct: while carbon accounting provides a broad conceptual framework for monitoring and evaluating emissions as well as the resulting climate impact, MRV provides a more procedural view on the collection, sharing, and validation of data:

Stechemesser and Guenther (2012) define **carbon accounting** as the "recognition, the non-monetary and monetary evaluation and the monitoring of GHG emissions on all levels of the value chain". Carbon accounting operates across distinct scales, each governed by different standards and objectives (Research Paper P4):

Territorial Scale focuses on all emissions within a specific geographic area, such as a country, and typically adheres to the guidelines for national GHG inventories established by the Intergovernmental Panel on Climate Change (IPCC).

Entity Scale carbon accounting refers to emissions associated with specific entities such as companies (i.e., corporate carbon accounting) or other organizations. ISO 14064 offers a generic standard for quantifying and reporting GHG emissions and removals on this scale. With its corporate standard, the GHG Protocol provides the most widely used standard for carbon accounting on this scale, offering more specific tools and guidance on setting organizational boundaries than the generic ISO 14064 (Damsø et al., 2016; WRI and WBCSD, 2004). While these standards focus exclusively on climate impacts, a Life Cycle Assessment (LCA) perspective can also be applied at the entity level via ISO 14072. Such a perspective utilizes a multi-criteria logic, aggregating climate and other environmental impacts across an entire organization's activities. For entity-scale carbon accounting, the GHG protocol distinguishes between three scopes to help delineate direct and indirect emission sources:

- **Scope 1** includes direct emissions from sources owned or controlled by the organization (e.g., its own facilities).
- **Scope 2** includes indirect emissions from purchased energy (i.e., electricity, steam, heating, and cooling).
- **Scope 3** includes all other indirect emissions from the upstream and downstream value chain.

The *Installation Scale* offers finer granularity than the entity scale by focusing on specific units of organizations, such as factories or facilities (Gu et al., 2023; Wegener et al., 2019).

Project Scale concerns emissions relating to specific activities, such as reforestation or carbon capture projects. In compliance markets, these are often governed by mechanisms like the Clean Development Mechanism (CDM), while voluntary carbon markets utilize various independent standards to certify credits.

Product Scale carbon accounting is typically conducted via an LCA (Kennelly et al., 2019) according to ISO 14040/14044. Similar to the entity scale, product-level LCA addresses multiple environmental impacts throughout a product's entire life cycle, from raw material acquisition through production, use, and disposal. When focusing solely on GHG emissions, this is referred to as a Product Carbon Footprint (PCF) (Balduf et al., 2024; Bausch et al., 2023). PCFs are particularly influential in sustainability-based decision-making, because they represent a function of a product's entire life cycle (Meinrenken et al., 2020). Thus, PCFs serve as the primary data building blocks for Scope 3 accounting, as they provide the granular, unit-based information required from the supply chain.

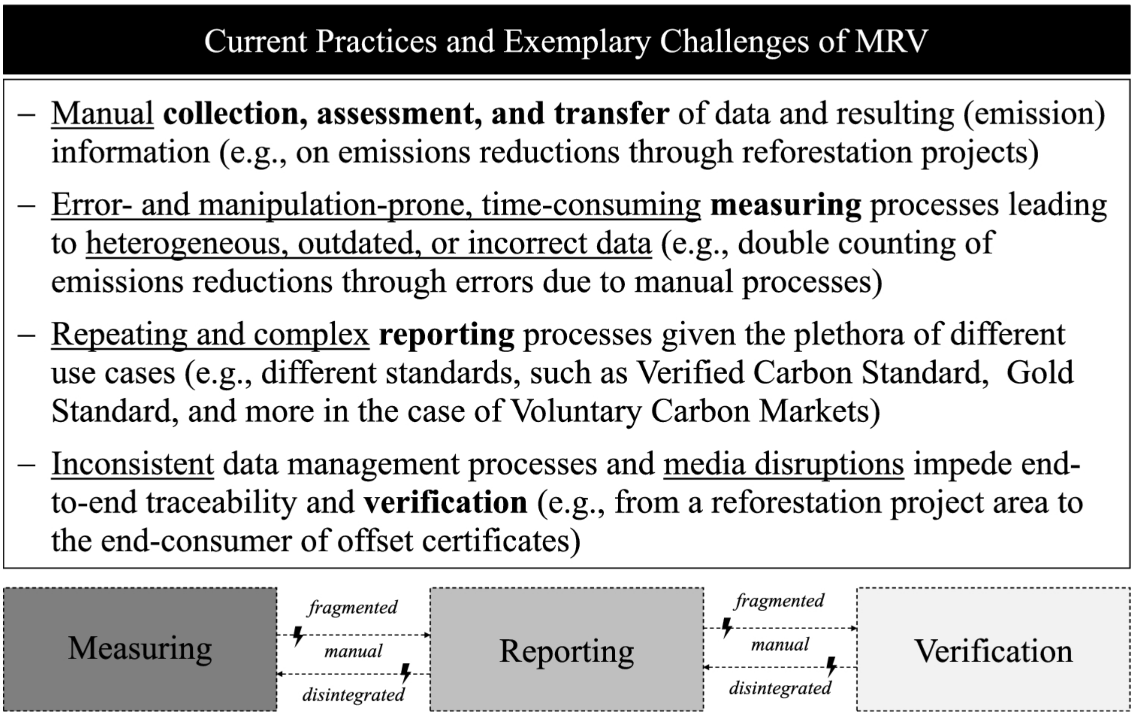
To understand the challenges inherent in the measurement of indirect emissions requires the analysis of the processual foundations of current carbon accounting practices on entity scale, i.e., traditional **MRV** processes within and across organizations. In contrast to carbon accounting, MRV provides the procedural mechanism for the collection, sharing, and validation of data. MRV processes encompass three distinct, yet interconnected stages: (1) measuring and monitoring of data, (2) reporting it to a specific system, and (3) verifying the reported data's accuracy (Research Paper P1).

Measuring refers to the systematic collection of data to assess the carbon emissions or other relevant climate impacts of projects, companies, or activities. Measuring processes include direct physical measurement of carbon emissions or calculations based on primary data and emission factors. The underlying methodology of environmental measuring is often LCA (cf. above), which incorporates directly measured primary data, such as kilograms of raw materials used, and emission factors indicating the amount of carbon emissions that one kilogram of this material causes, and secondary data from other sources to calculate allocated carbon emission equivalents (Bellassen & Stephan, 2015). Gathering and converting primary data from different sources - particularly regarding emission factors - can be complex, time-consuming, and lead to errors or manipulation. Thus, current MRV practices often rely on secondary data or average values that lack accuracy and limit incentives for reducing emissions to (or below) these average values.

Reporting involves aggregating the data obtained during measuring processes into inventories and other standardized formats, followed by communicating the resulting information to relevant authorities such as regulators. Reporting processes serve two purposes: disclosing measurement and assessment information for subsequent verification and making information accessible to diverse stakeholders. Reporting faces substantial challenges owing to the multitude of mandatory and voluntary reporting standards, each with their own reporting requirements (Research Paper P1).

Verification is typically conducted by third parties not involved in the measuring and reporting processes and entails reviewing the compliance of reported data and their collection processes with relevant guidelines. During verification processes, reported data and assessment information undergo (independent) analysis to ensure their completeness and reliability, while also identifying errors and deficiencies. This process may include assessing evidence that emissions reductions from projects are legitimate and is crucial for ensuring the accuracy and credibility of reported data and the resulting key figures (Bellassen & Stephan, 2015). Current verification can be time-consuming, because it requires independent experts. Further, inconsistent data management as well as media disruptions impede end-to-end traceability and verification.

As summarized in Figure 2.1, traditional MRV systems typically involve manual and fragmented processes: Measuring currently often relies on estimates or average values that are often error-prone. Reporting aggregates and communicates this measuring data using diverse and evolving standards, leading to a lack of traceability and comparability. Verification is commonly conducted by third parties through manual document review and audits, which are time-consuming and infrequent, potentially reducing overall trust and confidence in sustainability assessments.



Current Practices and Exemplary Challenges of MRV

- Manual **collection, assessment, and transfer** of data and resulting (emission) information (e.g., on emissions reductions through reforestation projects)
- Error- and manipulation-prone, time-consuming **measuring** processes leading to heterogeneous, outdated, or incorrect data (e.g., double counting of emissions reductions through errors due to manual processes)
- Repeating and complex **reporting** processes given the plethora of different use cases (e.g., different standards, such as Verified Carbon Standard, Gold Standard, and more in the case of Voluntary Carbon Markets)
- Inconsistent data management processes and media disruptions impede end-to-end traceability and **verification** (e.g., from a reforestation project area to the end-consumer of offset certificates)

Figure 2.1: Current Practices and Challenges of MRV (Based on Research Paper P1)

2.2 Digital Technologies as an Enabler to Address the Challenges of Current Practices

Many organizations aim to transition from traditional MRV processes to more digital approaches, driven by three primary factors (Research Paper P5):

1. **Regulatory Mandates**: New EU regulations such as the CSRD require companies to detail their sustainability impacts, for instance on the basis of "double materiality" (i.e., how environmental factors impact their finances and how their operations affect the environment). Further, political instruments to deal with GHG emissions from imported goods (e.g., the Carbon Border Adjustment Mechanism) necessitate the fine-granular tracking of emissions.
2. **Capital Markets**: Investors increasingly use ESG criteria to assess risks, demanding trustworthy and auditable carbon data to avoid "greenwashing".
3. **Consumer Demand**: A growing segment of consumers is requiring transparency regarding the "carbon footprint" of individual products and services.

Digital technologies can serve as an essential enabler for addressing the structural deficits of traditional, manual MRV, as outlined in the previous section. As I will point out in the subsequent chapters of this dissertation, digital technologies can reduce information asymmetries and enable a level of transparency and trust previously unattainable in fragmented carbon accounting and reporting environments, for instance by offering efficient and fine-granular collection, automated processing, and verifiability of data. Ultimately, digital technologies can enhance MRV to transform carbon accounting from an error-prone, retrospective, and administrative task into a trustworthy foundation for proactive, CO_2-adaptive decision-making. In this light, Research Paper P2 identifies five overarching characteristics of digital system architectures for carbon accounting that build the foundation for the subsequent chapters and are explained below: (1) integration and interoperability, (2) automation of data flows, (3) digital MRV of emissions data, (4) identity and user management, and (5) governance. Table 2.1 summarizes the key aspects of each characteristic.

Integration and interoperability ensure that digital carbon accounting systems can seamlessly connect to existing infrastructures such as emission trading systems, enterprise resource planning tools, or supply chain registries while also maintaining compatibility with emerging digital tools and ecosystems. This characteristic is crucial for embedding digital carbon accounting into broader decarbonization frameworks and for avoiding data silos. *Automation of data flows* enables real-time acquisition and verification of emissions data through IoT sensors, smart meters, and distributed networks, thereby reducing manual errors and transaction costs. *Digital MRV of emissions data* as an architectural component seeks to ensure accurate measurement, immutable recording, and trustworthy verification of carbon-related transactions, thereby reinforcing trustworthy and auditable processes. Further, the inclusion of a meaningful *digital identity and user management* (e.g., through Self-Sovereign Identity (SSI) frameworks) can, for example, enable secure and privacy-preserving authentication of persons, organizations, and/or machines. Finally, governance mechanisms in digital carbon accounting architectures determine how decisions are taken about data access, validation, and use.

Table 2.1: Key characteristics of digital carbon accounting system architectures (based on Research Paper P2)

#	Characteristic	Description	Exemplary sources
1	Integration and Interoperability	Integration in existing infrastructure and interoperability with other new and legacy systems.	Ito et al. (2022), Khaqqi et al. (2018), Schletz et al. (2020)
2	Automation of Data Flows	Gathering and processing of emissions data and communication between peers (without the need of intermediaries).	Babel et al. (2022), Sipthorpe et al. (2022), Yang et al. (2021)
3	Measurement, Reporting, and Verification of Emissions Data	Precise, secure, and transparent measuring, reporting, and verification of emissions data.	Khaqqi et al. (2018), Kim and Huh (2020), Woo et al. (2020)
4	Identity and User Management	Easy and secure identification of the architecture's machines, companies, and individuals. Derived directly from this are meaningful channels, applications, and services for users.	Chakraborty et al. (2022), Rosado da Cruz et al. (2020), Woo et al. (2020)
5	Governance	Decision-making power within the architecture to control the processes to a certain extent.	Al Sadawi et al. (2021), Babel et al. (2022), Kim and Huh (2020)

These architectural characteristics illustrate that digital carbon accounting constitutes not merely an accounting enhancement but a socio-technical infrastructure for verifiable and efficient decarbonization. As Research Paper P2 emphasizes, establishing interoperable data registries and trustworthy identity mechanisms will be crucial to enabling precise and verifiable accounting of carbon emissions, especially within complex global supply chains. The characteristics also illustrate that digital carbon accounting is a broader concept that builds on and complements the procedural perspective of digital MRV by providing an architectural layer that ensures that carbon data can be reliably collected, processed, and exchanged across systems, organizations, and jurisdictions.

Against this background, particularly the digitalization of MRV has emerged as a promising approach to address the challenges outlined in Section 2.1. Following Research Paper P1, digital MRV for decarbonization can be defined as "a research stream that addresses the interrelation of IS with Measuring, Reporting, and Verification processes as well as the MRV concept as a whole". This research stream encompasses both the digitalization of individual MRV processes and the development of integrated, end-to-end digitalized MRV systems that transform isolated, manual activities into coherent, automated frameworks leveraging digital artifacts and concepts (Research Paper P1). To do so, digital MRV leverages IS as well as emerging digital technologies and concepts, including AI, DLT, IoT and SSI to automate and integrate MRV processes: Digital measuring enables automated, fine-granular data collection in (near) real-time (e.g., based on IoT devices), which significantly enhances emissions data's reliability and enables, for instance, steering measures in real-time. Digital reporting benefits from standardized formats, the seamless integration of environmental with other (e.g., financial) information, and automated processing (e.g., based on leveraging AI). Digital verification utilizes technologies and concepts (e.g., DLTs and SSI) to increase transparency, traceability, and trust while seeking to reduce transaction costs and reliance on institutional intermediaries.

To realize the objective of end-to-end digital MRV, several emerging digital technologies and concepts may be integrated. Based on Research Paper P5, Table 2.2 provides an overview over the digital technologies I primarily discuss in this dissertation as well as their roles in the context of digital MRV and carbon accounting.

Table 2.2: Digital Concepts and Technologies That Are Discussed in This Dissertation (based on Research Paper P5)

Digital Concept or Technology	**Description and Application within the Context of digital MRV and carbon accounting**	**Exemplary References**
Artificial Intelligence (AI)	Computational systems capable of performing tasks requiring human intelligence, such as learning, reasoning, and problem-solving. In the context of carbon accounting, AI can enable automated data analysis, validation of emissions data, and optimization of data collection processes across organizations.	Tsolakis et al. (2023)
Distributed Ledger Technology (DLT)	A system that maintains an immutable record of transactions across a distributed network of participating nodes. DLT like blockchains can, among others, create transparent and verifiable audit trails for carbon data.	Diniz et al. (2021)
Data Space	A federated data infrastructure that enables sovereign data sharing between participating organizations in digital ecosystems. In carbon accounting, data spaces can facilitate the controlled exchange of emissions data while preserving data sovereignty, enabling organizations to share carbon-related information without losing control over their data.	Ito et al. (2022)
Privacy Enhancing Technology (PET)	Technology designed to protect data privacy while allowing processing and analysis. PETs, such as Zero-Knowledge Proofs (ZKPs) or Homomorphic Encryption, allow organizations to share and analyze sensitive emissions data while maintaining confidentiality.	Babel et al. (2022)
Self-Sovereign Identity (SSI)	A digital identity paradigm where users and organizations maintain sovereignty over their identity data and credentials. SSI can enable organizations to selectively share verifiable emissions data while maintaining data sovereignty.	Mandaroux et al. (2021)
Smart Contract	Self-executing software programs that automatically enforce predefined rules and agreements. In carbon accounting, smart contracts can automate the verification and reporting of emissions data between supply chain partners, reducing the need for intermediaries while ensuring compliance.	Sadawi et al. (2021)
Token	A digital unit that can represent any form of value or asset, primarily used on blockchain systems. Fungible tokens (i.e., tokens representing interchangeable units) can represent assets, such as equal emission allowances, while non-fungible tokens (i.e., tokens representing non-interchangeable units) can be used to distinguish the origin of emissions.	Babel et al. (2022)

Digital MRV for decarbonization seeks to transform MRV from isolated, manual activities into an end-to-end digitalized MRV (cf. Figure 2.2). Thus, the adoption of digital MRV not only supports compliance with new regulatory requirements (e.g., the EU's CSRD) but also fosters greater transparency, seamless data sharing, and enhanced decision support within and across organizational boundaries. Holistic digital MRV approaches can enable new business models, support credible participation in carbon markets, and foster investments in verifiable sustainability measures.

Characteristics and Exemplary Opportunities of End-to-End Digitalized MRV

- Automated data **collection, assessment, and transfer** of data and resulting (emission) information within and beyond organizational boundaries (e.g., verifiable end-to-end data flows from project areas to end-consumers)
- Increasing data quality through digital **measuring** processes (e.g., regarding granularity, accuracy, immutability of emissions reductions data based on IoT sensor data)
- Reduction of information asymmetries through seamless digital **reporting** processes (e.g., prevention of prohibitively high MRV costs for carbon offsets)
- Digital (bilateral) **verification** processes with seamless process interfaces and digital consistency (e.g., more credible auditing mechanisms in emissions offset projects to enhance trust in Voluntary Carbon Markets)
- Close integration of the three MRV processes at all relevant stakeholders to a **cohesive system** reducing the risks of media disruptions, errors, and manipulation while simultaneously increasing efficiency

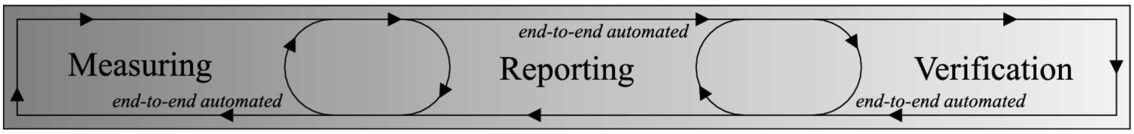


Figure 2.2: Characteristics and Opportunities of End-To-End Digitalized MRV (based on Research Paper P1)

3 Leveraging Digital Technologies for Intra-organizational Decarbonization

This chapter examines how digital technologies, particularly AI and data-centric frameworks, can transform intra-organizational MRV from fragmented, manual activities into comprehensive and auditable digital processes. By leveraging digital MRV within their boundaries, organizations can move beyond retrospective reporting toward CO_2-adaptive decision-making in real time. This chapter synthesizes research contributions that address intra-organizational MRV from the (automated) extraction of information to the architectural design of integrated carbon accounting systems.

This chapter is organized as follows: Section 3.1 addresses the foundational challenge of information quality and availability in organizations for corporate carbon accounting. It introduces an LLM-based, multi-agent architecture designed to automate the extraction of structured information from heterogeneous and unstructured sources, thereby reducing manual effort and errors in the M(easurement) phase of MRV.

Section 3.2 builds on this information foundation by providing a comprehensive taxonomy of corporate carbon accounting practices, categorizing twelve distinct dimensions across the levels of counting, accounting, and accountability. This section specifically highlights how digital automation and standardized classification can empower resource-constrained Small and Medium-sized Enterprises (SMEs) to achieve regulatory compliance and transition toward CO_2-adaptive decision-making. The chapter concludes by highlighting the limitations of intra-organizational perspectives and motivates the need for inter-organizational data sharing, which is the focus of Chapter 4.

3.1 Addressing Information Challenges within Organizations

As established in Chapter 2, the primary challenge of current carbon accounting within organizations (i.e., corporate carbon accounting) relates to a lack of information about their GHG emissions, which is rarely caused by a total absence of data; rather, it stems from a lack of structured, reliable, and decision-relevant information provided in a timely way.

Intra-organizational carbon accounting efforts are often hampered by a plethora of organizational and technical hurdles, including manual data entry errors, the persistence of disconnected spreadsheets that act as data silos, and a lack of interoperability between (legacy) systems (e.g., Enterprise Resource Planning (ERP) systems) and specialized environmental management software (Research Papers P1, P4, and P5).

Digital technologies address these issues, for instance, based on interconnected IoT sensors that deliver fine-granular GHG data (Khatua et al., 2020). Regarding environmental disclosures under the CSRD, particularly for Scope 2 assessments involving purchased energy, data is already being collected digitally in near real-time. This data is often recorded at short time intervals (e.g., seconds) and provides high spatial accuracy by focusing on specific areas (e.g., single production lines) (Tranberg et al., 2019). Such improved collection methods, which often utilize IoT devices equipped with specialized sensors and software (Nižetić et al., 2020), create the necessary basis for reporting accurate PCFs (Körner, Paetzold, et al., 2026). By automatically providing timely data, these systems help organizations identify effective measures to reduce their GHG emissions impact. Thus, digital data collection supports compliance with CSRD mandates and enables CO_2-adaptive decision-making (Research Paper P8).

However, because a significant portion of valuable data is still not available in a machine-readable, digital way, it remains largely inaccessible for CO_2-adaptive decision-making: Relevant information relating to an organization's GHG emissions is often hidden in unstructured or semi-structured sources, such as scanned supplier invoices, unstructured logistics reports, or heterogeneous bills of materials which only exist as spreadsheets or PDF documents. Manually processing these documents is not only resource-intensive but also prone to errors as well as significant time lags, hindering the use of the information for CO_2-adaptive decision-making (Research Papers P1 and P4).

Thus, to advance digital MRV and transform carbon accounting from a labor-intensive compliance-oriented reporting process into a foundation for targeted management action, it is necessary to leverage this multitude of unstructured or semi-structured data in an efficient and auditable way. To address this prerequisite, Research Paper P3 develops and evaluates an LLM-based multi-agent architecture to automate the extraction of information based on unstructured data (exemplified on the use case of project risk management). By doing so, it illustrates how to conduct auditable and adaptable LLM-based information extraction in dynamic, context-rich domains such as MRV. Unlike traditional extraction systems, the proposed architecture enables the continuous ingestion of heterogeneous data and employs specialized agents that interpret source- and domain-specific context (e.g., document type, data provenance, and MRV-specific semantics) and that extract domain-specific information types. By transforming unstructured or semi-structured data into actionable information, this approach provides one possible source related to the M(easuring) step of digital MRV in contexts where unstructured data sources may otherwise remain untapped, thereby contributing to the data foundation upon which the subsequent architectural and market-based components of this dissertation (cf. Section 3.2 and Chapter 4) are built.

The proposed multi-agent architecture for proactive and adaptable information extraction in Research Paper P3 follows a modular, four-layered design consisting of the Input Layer, the Extraction Layer, the Storage Layer, and the Output Layer. This structure is governed by two distinct flows: an Information Flow that converts unstructured or semi-structured data into structured information, and an Extraction Control Flow that allows for the versioned governance of extraction logic. By explicitly separating these flows and making extraction logic transparent and traceable, the architecture addresses key MRV requirements relating to data credibility and auditability (cf. Chapter 2). I illustrate the architecture in Figure 3.1 and describe each key component in more detail in the subsequent paragraphs.

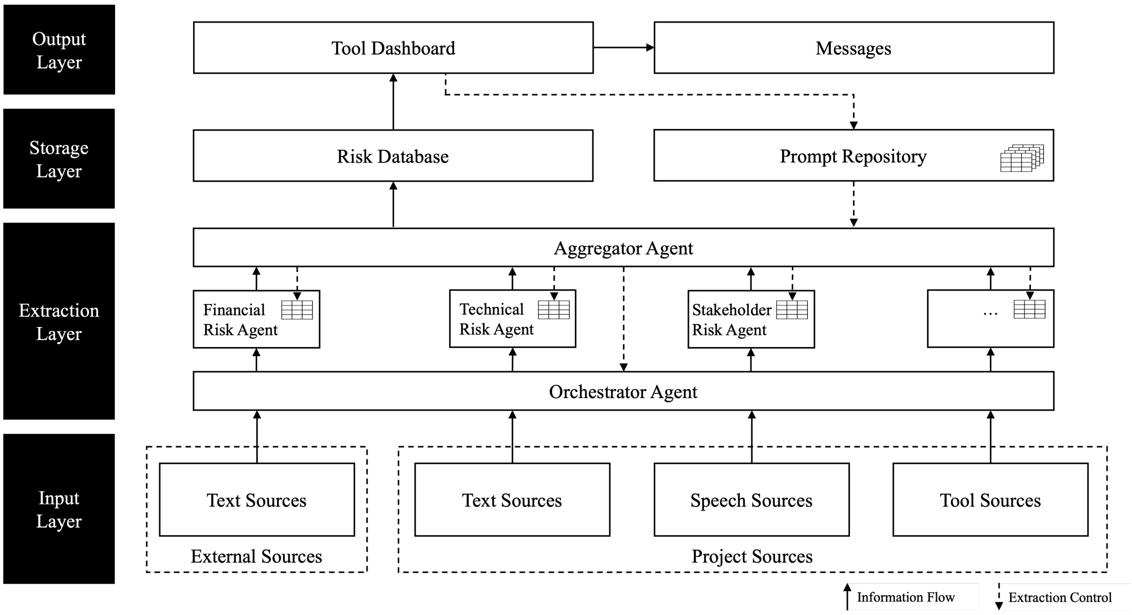


Figure 3.1: Architecture for LLM-Based Information Extraction (based on Research Paper P3)

The system's operation is defined by two complementary pathways. The *Information Flow* is responsible for converting varied, heterogeneous data into structured, evidence-backed information. Conversely, the *Extraction Control Flow* manages the externalization, versioning, and governance of the extraction logic in evolving environments. Specifically, this control flow handles project- and agent-specific configurations, such as active specialized prompts, schema definitions, and detection thresholds. By linking every extracted information to its specific generation configuration, the architecture supports rigorous auditability and prevents drift from unstructured, ad-hoc prompt changes.

The **Input Layer** functions as the architecture's gateway, designed to capture information that is often hidden in unstructured or informal communication channels (Afzal et al., 2021; Okudan et al., 2021). To build a dependable analytical base, this layer collects and standardizes data from diverse environments. This includes *internal sources* such as textual documents (emails, meeting notes), audio recordings (transcribed meetings), and technical tool data (issue trackers, version control), as well as *external sources* such as industry trends or security reports. From the moment of ingestion, the Input Layer tracks provenance metadata (including IDs, timestamps, and origin) to ensure both verifiability and traceability (Sambasivan et al., 2021). Following normalization and deduplication, a refined document stream is passed to the Extraction Layer.

The **Extraction Layer** serves as the analytical engine where unstructured inputs are transformed into structured information. Research Paper P3 implements the Extraction Layer as a collaborative network of AI agents that work in collaboration to perceive, reason, and execute context-aware cognitive tasks (Allmendinger et al., 2026; Guo et al., 2024; Wooldridge, 2009), facilitating a high degree of coordinated domain specialization. By leveraging a multi-agent AI configuration, the architecture also overcomes the constraints of monolithic LLM designs, which often struggle with the conflicting semantic requirements of diverse categories (Wooldridge, 2009): Rather than relying on one general-purpose agent, Research Paper P3 employs a group of specialized agents. This approach strikes a balance between domain-specific depth and the overhead of orchestration, ensuring that the agent graph remains manageable for purposes of provenance and explanation. Each agent is independently configurable via its own prompts and schemas, allowing the architecture to adapt to specific needs or changing organizational standards without requiring a total overhaul. Our architecture utilizes agent types:

- The *Orchestrator Agent* handles the initial document reception. Utilizing an LLM that evaluates both the content and the current project settings, it categorizes and routes data to the most relevant specialized agent.
- The *Specialized Agents* conduct the primary semantic investigation. Each agent focuses on a specific area (in the paper's example, different risk types) and operates based on specific settings and individualized prompts from a central repository. This design decouples specific task logic from the broader capabilities of the underlying foundation model (Allmendinger et al., 2026) and enables adaptability across diverse MRV contexts, allowing the same architecture to accommodate different data types, reporting frameworks, and organizational boundaries. By using a prompt-based method, sustainability managers can translate their tacit knowledge into operational logic without the high costs associated with fine-tuning models for every project. The resulting output is a structured indicator containing the information (i.e., risk type in the exemplary use case of Research Paper P3), supporting evidence, source links, and metadata. To maintain verifiability, which is essential for MRV, agents also generate a brief natural-language explanation for their findings.
- The *Aggregator Agent* collects these structured outputs to produce a unified set of structured information. It is responsible for deduplicating entries and resolving any discrepancies between agents. The Aggregator Agent is designed to utilize a rule-based prioritization system that weighs factors such as the volume of evidence, source reliability, and the agent's self-reported confidence. If significant ambiguity remains, the Aggregator can initiate a more detailed follow-up analysis. Finally, it links related indicators across different sources and timeframes, facilitating the detection of emerging risks from scattered weak signals. Before passing the data to the Storage Layer, the Aggregator attaches detailed process provenance (e.g., including model versions and prompt configurations) so as to ensure full traceability.

The **Storage Layer** provides a permanent repository for the data generated by both the Information Flow and the Extraction Control Flow. In this layer, the *Database* archives structured information alongside a comprehensive provenance trail, allowing for ensuring verifiability and traceability. Complementing this, a *Prompt Repository* manages the versioned prompts and extraction configurations that dictate the AI agents' behaviors. This setup is fundamental to the system's adaptability, because it allows sustainability managers to embed tacit knowledge and refine extraction logic to suit specific environments. It also maintains an explicit historical record of all configuration adjustments over time.

The **Output Layer** serves as the primary user interface and the main entry point for managing the Extraction Control Flow. It displays each consolidated information together with its associated evidence and rationale, empowering users to validate the system's findings and trace them back to their original sources and specific system configurations. Beyond visualization, the Output Layer provides specialized interfaces for sustainability manager feedback and the adaptation of prompts and settings, ensuring that the system remains aligned with shifting contexts. To support proactive decision-making without requiring manual queries, this layer includes an interactive analysis dashboard and generates automated alerts for information flagged as high priority.

The development of the architecture results in design knowledge that exceeds the exemplary use case and illustrates how to conduct auditable and adaptable LLM-based information extraction in dynamic, context-rich domains such as MRV: Applying such AI-driven architectures can help organizations to efficiently build their MRV processes on a more comprehensive and timely information foundation, if parts of the necessary data are only available in an unstructured or semi-structured way, thereby supporting CO_2-adaptive decision-making. Further, automated ingestion, which we also illustrate with our architecture, builds the foundation for further automation, enabling to move toward end-to-end digitalized MRV systems, as described in Chapter 2.

The presented architecture demonstrates how digital technologies can provide access to previously unavailable (emission-relevant) data and can ensure that it is structured for auditable reporting. Building on this foundation, in the next section, I expand the perspective from information extraction toward the design of organization-wide carbon accounting frameworks that govern how this data (and the respective information based on this data) is processed, reported, and verified.

3.2 Classifying and Digitalizing Carbon Accounting Practices

Section 3.1 illustrated how heterogeneous and unstructured data can be converted into actionable information that enables CO_2-adaptive decision-making within organizations. However, even high-quality information on GHG emissions only realizes its full potential when it is embedded into a comprehensive carbon accounting architecture that governs the organization-wide carbon data collection and processing as well as how the organization reports and verifies respective information based on this data. Hence, building on the informational foundation from Section 3.1, Section 3.2 adopts a holistic perspective to conceptualize how organizations can design coherent carbon accounting architectures that integrate the collection, processing, and reporting of data. This perspective enables organizations to compare alternative system designs and provides a starting point for improving current carbon accounting practices.

Drawing on Research Paper P4, this section identifies twelve dimensions that shape intra-organizational carbon accounting frameworks from a data perspective. The dimensions are grouped into three levels, as carbon accounting is often used as an umbrella term (cf. Chapter 2): *Counting*, for the collection of underlying GHG emissions data, *Accounting* for the respective calculations to account for GHG emissions based on these data, and *Accountability*, referring to the reporting of information based on this accounting (Baehr et al., 2024). I will now explain the corresponding dimensions and characteristics and illustrate them in Figure 3.2.

	Dimension	Characteristics							Exclusive (Yes/No)
Counting	Type of Emission	CO_2	CH_4	N_2O	HFCs	PFCs	SF_6	NF_3	No
	Sector	Agriculture	Building	Energy	Industry	Transportation	Other		No
	Data Foundation	Primary Data	Secondary Data	Primary & Secondary Data					Yes
	Data Collection	Dynamic	Static	Hybrid					Yes
Accounting	Frequency	Triggered by Event	Periodic	Real-Time					Yes
	Level of Analysis	Organization	Installation	Product					No
	Scope of Emissions	Scope 1	Scope 2	Scope 3					No
	Quantification Method	Economic Input-Output	Process-Based	Hybrid					Yes
Accountability	Commitment	Mandatory	Voluntary						Yes
	Targeted Stakeholders	Internal Decision-Makers	Regulatory Bodies	Financial Institutions	Other Organizations	Individuals			No
	Compensation	Excluded	Not Excluded						Yes
	Audit	None	Internal	External	Internal & External				Yes

Figure 3.2: Design Criteria for Carbon Accounting Frameworks (based on Research Paper P4)

Counting

Our four Counting dimensions define how organizations generate their base emission data and determine their capacity for accuracy, timeliness, and automation. The first dimension in our taxonomy, *Type of Emission*, identifies the specific GHG emissions an organization intends to track and for which it gathers data during the Carbon Accounting (CA) process. Our classification is built on the six primary GHGs defined by the Kyoto Protocol (Carbon Dioxide (CO2), Methane (CH4), Nitrous Oxide (N2O), Hydrofluorocarbons (HFCs), Perfluorocarbons (PFCs), and Sulfur Hexafluoride (SF6)), with the addition of Nitrogen Trifluoride (NF3) as a potent GHG.

The *Sector* dimension denotes the specific area of economic activity in which an organization is engaged. This classification is vital for corporate CA frameworks because data needs, regulatory obligations, and market expectations vary significantly across different industries (Kazemian et al., 2022). We categorize this dimension into six distinct characteristics: Agriculture (e.g., Alromaizan et al. (2023)), buildings (e.g., Klymenko et al. (2021)), energy (e.g., Babel et al. (2022)), industry (e.g., Xiang et al. (2024)), transportation (e.g., Luo et al. (2024)), and "other." The "other" category represents sectors that may not be emission-intensive in their direct operations - such as financial services but where indirect emissions remain significant. Because organizations often span multiple industries, this dimension is treated as non-exclusive.

Our *Data Foundation* dimension classifies carbon data based on whether it stems from primary, secondary, or hybrid sources. Primary data consists of direct measurements (e.g., via sensors or smart meters) (Babel et al., 2022), offering superior transparency and precision (Comello et al., 2023; He et al., 2022). However, using primary data often necessitates complex digital systems to manage various data streams (Bausch et al., 2023; Xiang et al., 2024). Secondary data involves processed information or indirect estimates, such as industry benchmarks or emission factor databases (Gutwald et al., 2024). While secondary data is more practical when direct measurement is difficult, it typically results in reduced accuracy (Bausch et al., 2023; Gutwald et al., 2024). Organizations may adopt a hybrid model, mixing primary and secondary data to achieve a balance between data quality and operational feasibility (Comello et al., 2023).

The *Data Collection* dimension describes the temporal frequency and method of gathering carbon data (Kazemian et al., 2022). We distinguish between static, dynamic, and hybrid approaches. Static collection relies on manual gathering at fixed intervals, such as yearly reporting cycles (Gutwald et al., 2024). Dynamic collection uses automated systems such as sensor networks to provide continuous data streams, reducing the latency between emission events and accounting (Eleftheriadis & Anagnostopoulou, 2024; Heiss et al., 2023). A hybrid approach uses static methods for certain sources while integrating dynamic data where feasible (Gutwald et al., 2024).

Accounting

The Accounting dimensions specify how emission data is processed into actionable metrics, balancing granularity with computational feasibility. The *Frequency* dimension describes the specific triggers that initiate the processing of collected emission data. We identify three main types: event-triggered, periodic, and real-time. Event-triggered accounting is reactive, and occurs in response to specific needs such as supplier data requests (Baehr et al., 2024; Kazemian et al., 2022). Periodic accounting happens at set intervals, most commonly for annual disclosures (Reichelstein, 2024). Real-time accounting involves constant monitoring, facilitating immediate reporting and analysis (Bausch et al., 2023; Heiss et al., 2023).

Our *Level of Analysis* dimension specifies the primary unit of the CA framework. We categorize these into the organizational, installation, and product levels. The organizational level captures emissions from the entire entity's operations across all its sites (e.g., Carrión et al. (2024) and Klymenko et al. (2021)). The installation level offers higher granularity by focusing on specific units such as individual factories (Gu et al., 2023; Wegener et al., 2019). The product level tracks emissions throughout the lifecycle of specific goods to calculate individual PCFs, as discussed in Section 2.1 (Bausch et al., 2023; He et al., 2022; Xiang et al., 2024). This dimension is non-exclusive, as product-level data can be combined to support organizational-level reporting.

The *Scope of Emissions* dimension follows the established GHG Protocol: Scope 1 covers direct emissions from owned or controlled sources; Scope 2 involves indirect emissions from purchased energy (e.g., electricity); and Scope 3 includes all other value chain emissions, from procurement to product end-of-life (e.g., Klaaßen and Stoll (2021)). While most firms report Scope 1 and 2 effectively, Scope 3 remains hard to quantify owing to data gaps and measurement complexity (Carrión et al., 2024; Comello et al., 2023).

Our *Quantification Method* dimension addresses the underlying logic used to calculate emissions. We categorize these into economic input-output (a top-down method using financial data), process-based (a bottom-up method analyzing specific activities), and hybrid methods (Gutwald et al., 2024; Kazemian et al., 2022; Reichelstein, 2024; Xiang et al., 2024). A hybrid approach uses process-based analysis for primary activities while filling data gaps with economic input-output calculations (Klaaßen & Stoll, 2021).

Accountability

Finally, the Accountability dimensions govern how calculated emissions are verified, reported, and used for strategic decision-making. The *Commitment* dimension explores the motivation behind GHG reporting (Research Paper P8), distinguishing between mandatory and voluntary actions. Mandatory reporting is driven by regulations such as the CSRD (Reichelstein, 2024). Voluntary reporting is often guided by private standards such as the Global Reporting Initiative (Carrión et al., 2024). Notably, research suggests that voluntary disclosures may lack the same reliability level as those required by law (Wegener et al., 2019).

The *Targeted Stakeholders* dimension identifies who receives the CA information. Key recipients include internal management, regulators, financial institutions (investors/lenders), business partners, and the general public.

The *Compensation* dimension evaluates whether an organization uses offset mechanisms to balance its emissions on paper (Carrión et al., 2024). We distinguish between removal offsets (active atmospheric GHG extraction such as afforestation) and avoidance offsets (preventing planned emissions such as forest conservation) (Baehr et al., 2024). Due to concerns over standardization and the "additionality" of such projects, some frameworks entirely exclude offset data entirely (Comello et al., 2023; Gutwald et al., 2024; Reichelstein, 2024).

Finally, the *Audit* dimension examines the verification of the CA process to ensure data integrity (Bakarich et al., 2020). We categorize audits as none, internal, external, or a combination of the latter two. Some organizations perform no formal validation (Hoogerbrugge et al., 2023; Kazemian et al., 2022). Internal audits are conducted in-house (Gu et al., 2023), while external audits involve independent third parties such as consulting firms (Hoogerbrugge et al., 2023; Xiang et al., 2024). Combining both types can significantly enhance the reported data's credibility (Kazemian et al., 2022).

Digital technologies can not only mitigate resource constraints by automating the most labor-intensive parts of these dimensions (e.g., through novel approaches for leveraging unstructured or semi-structured data in an efficient way as illustrated in 3.1), but also improve existing carbon accounting approaches along the above-mentioned dimensions. For instance, regarding the *Data Foundation*, digital technologies can be used to address data quality and availability issues, which constitute a major challenge in current practices (Research Paper P4): Organizations currently often rely on indirect measurements and assumptions due to limited collection of primary data. Rather than gathering carbon data directly through sensors or monitoring systems, many organizations rely on secondary data (Comello et al. (2023) and Reichelstein (2024)). Implementing IoT devices, such as digital sensors, enables the accurate and real-time collection of primary data, providing the necessary data foundation for enabling more accurate and timely carbon accounting (Eleftheriadis & Anagnostopoulou, 2024). Further, instead of manually handling this primary data, an organization could implement automated modules to reuse it for different purposes, as indicated in Sturm et al. (2025), enabling efficient and timely carbon accounting. Also, by shifting the focus from vague commitments to CO_2-adaptive decisions based on verifiable primary data (e.g., enabled by digital signatures), organizations can establish a high-integrity baseline for their internal decarbonization strategies and can report credible sustainability metrics.

The technologies and frameworks discussed in this chapter primarily allow an organization to achieve a high degree of internal transparency regarding its own emissions: As organizations seek to account for their full environmental impact, they need precise and trustworthy data relating to their indirect (i.e., Scope 2 and Scope 3) emissions, which often represent the majority of an organization's carbon footprint (Huang et al., 2009; Meinrenken et al., 2020). Indirect emissions emerge outside the organization's direct control, residing in the IS of suppliers and partners. Intra-organizational digitalization provides necessary yet insufficient foundations for systemic decarbonization. Even advanced internal systems remain constrained by supply chain data access (Research Paper P5). Against this background, there is a need for a conceptual foundation for bridging organizations' boundaries to enable secure and automated data sharing of carbon data. Chapter 4 discusses such a foundation.

4 Extending Digital Decarbonization to Supply Chains and Markets

This chapter extends the intra-organizational lens of digital MRV to inter-organizational supply chains and market infrastructures. While the previous chapter focused on intra-organizational foundations, this chapter examines the transition to sharing carbon data beyond organizational boundaries to better account for indirect emissions and to enable efficient carbon markets.

It synthesizes contributions from four papers (i.e., Research Papers P5, P6, P7, and P8) that progressively address enabling inter-organizational data sharing, improving the accuracy of indirect emissions tracing, and designing market infrastructures that can internalize emission costs more effectively based on fine-granular carbon data. Together, these papers illustrate how digital architectures can transform intra-organizational carbon accounting into an inter-organizational ecosystem for global decarbonization, supporting verifiability while respecting data sovereignty and privacy.

4.1 Enabling Carbon Data Sharing Beyond Organizational Boundaries

The transition from intra-organizational carbon accounting to a comprehensive and systemic view of climate impacts requires overcoming organizational boundaries. While Scope 1 emissions are within an organization's direct control, Scopes 2 and 3 represent indirect emissions and, therefore, require data that resides with their external partners. For instance, upstream Scope 3 emissions can account for up to 80% of total GHG emissions for most manufacturing industries. Against this background and regarding today's complex global supply chains, there is a need for a large number of organizations to share their carbon data. Due to the vast amount of data to be shared as well as the granularity and timeliness needed, this sharing of carbon data should be digital and automated. However, the current use of digital technologies in carbon accounting practices is often limited to an intra-organizational perspective (cf. Chapter 3). Thus, extending the application of digital technologies for automated data sharing beyond organizational boundaries appears promising for addressing supply chain emissions accounting and potentially closing the accounting gap relating to indirect emissions. Further, automated data sharing beyond organizational boundaries can provide the necessary foundation for fostering automation in supply chain management based on sustainability metrics. Against this background, Research Paper P5 provides a comprehensive framework for automated data sharing in supply chains to support carbon accounting within and beyond organizational boundaries. By doing so, it serves as the conceptual and technical bridge for the transition from intra- toward inter-organizational decarbonization. Our developed framework (cf. Figure 4.1) identifies four main categories for automated data sharing: Data Quality, Integration and Interoperability, Data Flows, and Data Governance.

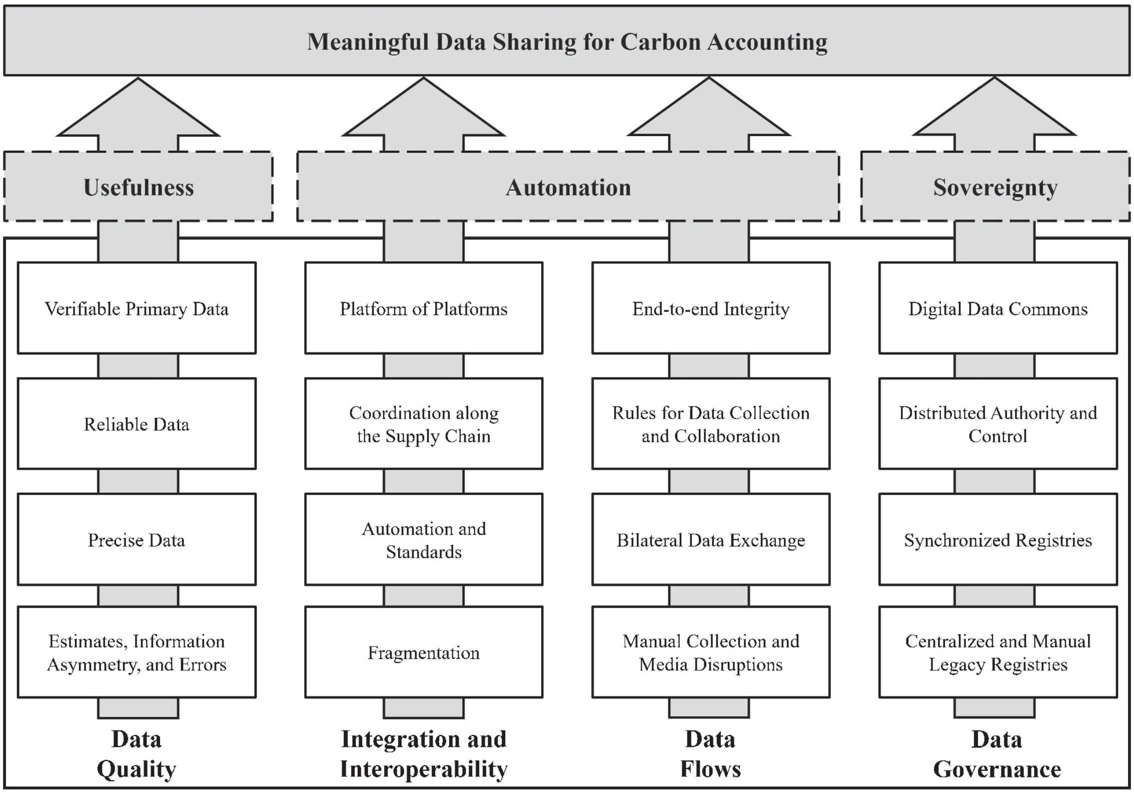


Figure 4.1: Framework for Meaningful Data Sharing in Supply Chains to Support Carbon Accounting Within and Beyond Organizations' Boundaries (based on Research Paper P5)

Our framework provides four sub-categories for each of these categories. We sort these sub-categories in ascending order according to the level of digitalization: From manual processes, to the use of legacy systems, to the integration of emerging digital concepts and technologies to enable meaningful data sharing for carbon accounting. By doing so, our developed framework allows organizations to assess their current level of digitalization and provides steps toward enabling automated inter-organizational data sharing. I will now present each category and sub-category.

Data Quality

The first category of our framework focuses on data quality, which is fundamentally defined as data that fulfills the specific requirements of its users (Strong et al., 1997). Based on this perspective, data quality is classified into four dimensions: intrinsic (such as accuracy), accessibility (including security of access), contextual (such as completeness), and representational (ensuring consistent formatting) (Strong et al., 1997). Achieving high-quality GHG emission data is often complicated by the fact that traditional IS in supply chain management, including ERP or logistics routing systems, often lack dedicated fields for carbon data (Zampou et al., 2022).

Our first sub-category, *Estimates, Information Asymmetry, and Errors*, examines current limitations. In many legacy systems, MRV is conducted manually, which often fails to meet high standards for rigor, consistency, and precision (Lorenzo-Sáez et al., 2022; Schletz et al., 2020; J. Yan et al., 2022). These systemic weaknesses can lead to significant issues, including double counting, fraud, poor source traceability, and prolonged confirmation timelines, while also imposing high administrative costs and offering few incentives for actual emission reductions (Ju et al., 2022; Mandaroux et al., 2021; Sun et al., 2023; Tang et al., 2018). Furthermore, these deficiencies can prevent entire industries from effectively entering carbon markets (Woo et al., 2021). Verification remains a particularly burdensome manual process, occasionally hindered by a shortage of specialized experts, especially for complex tasks such as methane accounting (Olczak et al., 2022; Schletz et al., 2023). Ultimately, the MRV data in older systems is often untrustworthy, particularly when tracking various inputs across different supply chain tiers (Shou & Domenech, 2022; Tóth et al., 2021; A. Zhang et al., 2020).

The sub-category *Precise Data* highlights the shift toward automated collection, enabling the efficient gathering of more data. Recent studies emphasize that digital MRV is essential for improving data accuracy (Körner et al., 2023; Müller et al., 2023; Zampou et al., 2022). Z. Liu et al. (2022) describe a system for near real-time calculation of global emissions using sectoral activity data, though they note that such systems can be expensive and complex to implement. To address these scalability challenges, Schletz et al. (2023) suggest that merging deep learning with remote sensing can drastically improve accuracy. Similarly, M. Wang et al. (2020) advocate for the use of automated sensors to enhance data integrity. In specific contexts like gas stream monitoring, continuous emission monitoring systems are already being used to provide precise, certified data (Sun et al., 2023), while others propose the use of digital twins and the IoT for infrastructure monitoring (J. Yan et al., 2022).

Under our third sub-category, *Reliable Data*, we find technologies that ensure that information remains immutable. Blockchain and tokenization are often suggested as means to prevent double counting and manipulation in carbon trading and tracking (Diniz et al., 2021; Franke et al., 2020; Muzumdar et al., 2022; Sadawi et al., 2021; M. Wang et al., 2020). Using DLTs can ensure that records are almost immutable once stored (Ju et al., 2022). Further, smart contracts can automate MRV enforcement, which lowers collection costs and further elevates data quality (Schletz et al., 2020). To solve the "oracle problem" (i.e., ensuring that the real-world data entering the DLT is accurate), Babel et al. (2022) suggest using smart meters in the energy sector to record and transmit real-time electricity data. These devices are assigned unique digital identities, verified by trusted third parties and stored via public keys in a registry. This approach, supported by G. Li and Li (2021), uses blockchain-based identity certificates to increase the transparency and efficiency of the verification process.

Our final sub-category is *Verifiable Primary Data*. This refers to information gathered directly through measurement, such as sensor data, which allows for independent verification. Several scholars have introduced blockchain frameworks for carbon accounting that utilize cryptography to ensure that all transactions are verifiable (e.g., Chakraborty et al. (2022), Ju et al. (2022), or Sadawi et al. (2021)). Sharing verifiable primary data not only guarantees authenticity but also prevents the loss of quality that often occurs when data is aggregated into different formats across a supply chain. For instance, in the electricity industry, Babel et al. (2022) demonstrate how verifiable primary data can be traced back to a specific power plant, providing end-users with trustworthy and highly granular emission insights.

Integration and Interoperability

The second category in our framework focuses on the integration and interoperability of systems (Babel et al., 2022; Guzman et al., 2019; Mandaroux et al., 2021; Schletz et al., 2022). As H. M. Kim and Baumann (2022) highlight, the spread of consistent standards and methodologies is a central challenge in climate mitigation. They argue that a digital MRV system must be flexible enough to support various methodologies while ensuring interoperability between systems that use similar standards. Furthermore, embedding carbon accounting into climate policies, broader IS, and carbon markets is vital for effective digital carbon management (Körner et al., 2023). This requires seamless interoperability among all participants and their respective technical infrastructures to ensure that data sources are accessible and that all the actors remain accountable (Schletz et al., 2022). Researchers therefore stress the need for carbon accounting architectures that can integrate smoothly with existing legacy systems (Mandaroux et al., 2021; Schletz et al., 2022).

Our first sub-category, *Fragmentation*, identifies the challenges posed by data silos and highly varied data formats (Guzman et al., 2019; Ju et al., 2022; Sun et al., 2023). These silos can exist within and beyond organizational boundaries, and they prevent effective collaboration and communication. Meanwhile, heterogeneous data formats complicate the technical landscape, making it hard to analyze and integrate data across different platforms. Current carbon accounting tools within organizational ERP systems are often disconnected, leading to a lack of end-to-end verifiability (Babel et al., 2022). Similarly, existing tracking technologies such as barcodes and Radio Frequency Identification (RFID) are often fragmented, serving limited functions with rigid data structures (M. Wang et al., 2020).

The second sub-category, *Automation and Standards*, focuses on digital carbon accounting approaches where internal processes are automated to boost efficiency (Tang et al., 2018; Tóth et al., 2021; A. Zhang et al., 2020). This involves integrating digital technologies directly into the carbon accounting processes. For instance, in the construction and infrastructure sector, J. Yan et al. (2022) suggest integrating building information modeling into carbon accounting tools to better manage asset complexity and automate boundary definitions. In transportation, Ajufo and Bekaroo (2021) demonstrate how location tagging, GPS, and specific algorithms can autonomously calculate individual carbon footprints by identifying travel distances and modes of transport, thereby removing the need for manual data entry. Standardization is essential for making different datasets comparable and allowing for data aggregation (Schletz et al., 2023). Universal standards enable digital carbon accounting systems to communicate with one another and with older legacy systems (Mandaroux et al., 2021). To this end, Tang et al. (2018) propose standardized file specifications for an integrated compliance cycle that includes monitoring plans and multi-stakeholder access. Similarly, Lorenzo-Sáez et al. (2022) developed a monitoring system for GHG emissions based on IPCC standards to ensure global coherence. Organizations can further improve automation by using IoT sensors or visual scanners to capture data in standardized units, automatically calculating key metrics and populating reports (Ito et al., 2022; A. Zhang et al., 2022).

Coordination along the Supply Chain centers around industry-wide standards for data exchange (Schletz et al., 2022). This level of coordination improves transparency and efficiency compared to isolated efforts. In infrastructure, adapting building information modeling allows for better data sharing for LCAs, which enhances technical interoperability (J. Yan et al., 2022). Researchers often explore combining multiple technologies, such as blockchain, AI, big data, and IoT, to facilitate this coordination (e.g., Franke et al. (2020), or M. Wang et al. (2020)). Sadawi et al. (2021) suggest connecting sensors directly to a blockchain to address security and privacy vulnerabilities in wireless sensor networks. Likewise, Chakraborty et al. (2022) and Woo et al. (2021) advocate for sharing sensor or smart meter data directly via blockchain for trading and accounting. This decentralized approach ensures data verification through a network of nodes, resulting in a tamper-proof ledger of all transactions. Smart contracts can further automate these processes such as by calculating carbon budgets without human intervention (Sadawi et al., 2021)), ensuring that transactions are secure, replicable, and auditable (Schletz et al., 2023). Finally, "smart standards" and Semantic Web ontologies can help harmonize different quantification methodologies, allowing smart contracts to function across multiple different blockchain networks (H. M. Kim & Baumann, 2022).

A *Platform of Platforms* is achieved when carbon data is referenceable and comparable across different systems. A "nested" accounting approach allows for the collection and aggregation of data from various actors using IoT devices, often managed through a central platform hub (Schletz et al., 2020, 2022). To address privacy concerns, PETs such as ZKPs can provide anonymization while maintaining cryptographic verifiability and traceability. Finally, as Sadawi et al. (2021) note, the future likely involves a network of multiple blockchains working in tandem rather than a single, universal chain.

Data Flows

To facilitate inter-organizational data sharing, many digital carbon accounting strategies utilize IS to optimize the movement of information between supply chain partners (Babel et al., 2022; Heiss et al., 2023; Zampou et al., 2022). Our framework organizes these flows into four sub-categories: manual collection and media disruptions, bilateral data exchange, rules for data collection and collaboration, and end-to-end integrity.

In traditional legacy systems, data management is defined by *Manual Collection and Media Disruptions*. Such data management typically relies on fragmented data trails, static reporting, and disconnected spreadsheets (Schletz et al., 2020).

Such reliance on manual entry makes it hard to trace data back to its origin, resulting in a lack of transparency and creating information asymmetries that hamper applications such as carbon markets (Franke et al., 2020; Sadawi et al., 2021; Tang et al., 2018).

Our second sub-category is *Bilateral Data Exchange*. As noted by J. Yan et al. (2022), the increasing requirement for multi-stakeholder collaboration and access to cloud-based services is pushing organizations away from stand-alone software toward more advanced digital tools. However, current collaboration is often restricted by concerns about data confidentiality and a lack of mutual trust. Organizations are often hesitant to share carbon data due to fears that suppliers may use environmental metrics as leverage in selection processes or that a poor sustainability profile relative to competitors could harm their reputation (Olczak et al., 2022; Zampou et al., 2022). Thus, many entities currently limit their information sharing to bilateral exchanges based on established relationships and specific agreements, which prevents the comprehensive data flow needed across the entire supply chain.

Standardizing the *Rules for Data Collection and Collaboration* can significantly ease the sharing of carbon data throughout the value chain (Zampou et al., 2022). It is often hard to develop these rules owing to the sensitive nature of the data involved (Müller et al., 2023), highlighting the critical need for privacy-preserving mechanisms to encourage participation (Franke et al., 2020). Blockchain technology is often suggested as a solution approach to ensure a more dependable data flow, mitigate supply chain disruptions, increase transparency, and reduce information asymmetry (Franke et al., 2020; M. Wang et al., 2020). For instance, da Cruz et al. (2020) introduce a smart contract-based platform designed to track the carbon footprint of both products and organizations by facilitating the registration and sharing of data between businesses and consumers. Similarly, Shou and Domenech (2022) as well as A. Zhang et al. (2020) propose blockchain frameworks specifically aimed at improving traceability and collaborative data sharing.

Our final sub-category, *End-to-end Integrity*, focuses on ensuring that data remains unaltered as it moves through various sources in the supply chain, even when shared selectively (Heiss et al., 2023). To prevent data manipulation, a comprehensive system must offer robust security, authenticity, and privacy for both data storage and transmission (Sadawi et al., 2021). In this context, Babel et al. (2022) present a concept for an end-to-end tracking system that allows end consumers to verify emission claims. This concept integrates several emerging digital technologies, including fractional non-fungible tokens to achieve high data granularity, alongside PETs, specifically ZKPs, to resolve privacy conflicts. ZKPs allow one party to prove the truth of a statement without revealing any underlying sensitive information. In blockchain contexts, this allows participants to conduct computations off-chain and only record the results and a "proof of correctness" on-chain, effectively solving common privacy and scalability hurdles (Babel et al., 2022; Franke et al., 2020; Ju et al., 2022). Further, ZKPs facilitate trustworthy pre-processing, ensuring that data from primary sources such as sensors is handled accurately before being shared, which greatly strengthens the original data source's integrity (Heiss et al., 2023).

Data Governance

This category in our framework examines how decision-making authority is distributed regarding the utilization and sharing of carbon data. Distributing this power is essential for maintaining process control and is a prerequisite for the broad participation envisioned by the Paris Agreement (Schletz et al., 2020). Thus, in this context, while accounting for authority and inclusivity, data governance seeks to establish data sovereignty. This allows actors to retain control over their specific data contributions while supporting the system, aligning with the Agreement's focus on decentralized and collaborative climate initiatives (Franke et al., 2020).

Current practices are largely defined by *Centralized and Manual Legacy Registries*, where decision-making power is often concentrated in specific entities, such as the United Nations Framework Convention on Climate Change (UNFCCC) (Schletz et al., 2020). Such centralized models are vulnerable to becoming single points of failure, which can significantly hinder both scalability and operational efficiency (Schletz et al., 2020). Further, these systems raise concerns regarding data security and availability, as control is restricted to one or a few dominant organizations (Babel et al., 2022). A major hurdle in these legacy environments is the difficulty of synchronizing disparate registries, reflecting a persistent tension between centralized oversight and sovereignty, a conflict clearly seen at the international level in the implementation of the CDM under the Kyoto Protocol (Schletz et al., 2023). Additionally, Franke et al. (2020) note that reliance on these registries results in high transaction costs due to bureaucratic bottlenecks, illustrating the inherent inefficiencies of current data-sharing governance.

Our second sub-category, *Synchronized Registries*, addresses the limitations of isolated data silos by integrating and interconnecting these systems. Much of the literature advocates for a unified "meta-registry" platform to bridge these gaps (Diniz et al., 2021; Franke et al., 2020; Schletz et al., 2020, 2022). Initiatives such as the World Bank's Climate Warehouse seek to link national registries to ensure environmental transparency on a single interface (Schletz et al., 2020). However, the extreme heterogeneity of various registries presents substantial barriers to integration, similar to the organizational challenges discussed previously (Schletz et al., 2020). Blockchain-based solutions are often cited as a way to aggregate diverse emissions systems into a unified platform (Diniz et al., 2021; Schletz et al., 2020). By leveraging decentralized storage and governance, blockchain enables collective participation, allowing all network nodes to contribute to and audit the data. This can empower individual actors to participate in global climate efforts without relying on central intermediaries (Franke et al., 2020; H. M. Kim & Baumann, 2022). Nevertheless, the specific architecture of the blockchain is central: simply bridging silos with a blockchain network without careful design could actually increase fragmentation (Babel et al., 2022). Moreover, a poorly designed unified platform may inadvertently centralize power with the network owner, recreating the very problems of isolated registries it is meant to solve (Babel et al., 2022; Schletz et al., 2023; M. Wang et al., 2020).

The third sub-category is *Distributed Authority and Control*. Franke et al. (2020) suggest that blockchain technology reflects the democratic spirit of the Paris Agreement by enabling decentralized governance. Regarding specific network types, some researchers advocate for permissionless blockchains where anyone can participate in auditing and verification without a central gatekeeper (e.g., Schletz et al. (2023) or M. Wang et al. (2020)). Conversely, Mandaroux et al. (2021) propose permissioned blockchains, in which only verified and trusted institutions participate, because this can reduce technical overhead and improve transaction efficiency. In both cases, smart contracts are seen as essential for increasing transparency: by automating audits and the enforcement of rules, they streamline administrative tasks and remove the inefficiencies common in manual legacy systems (Franke et al., 2020).

Finally, the transition toward a *Digital Data Commons* represents a fundamental shift toward inclusive and sovereign data practices by decentralizing both storage and governance. This can ensure that all participants have access to high-quality data while maintaining their own data sovereignty (Franke et al., 2020; Ito et al., 2022). Such decentralized, verifiable data can support digital MRV processes that foster trust and enable new financing models (Schletz et al., 2023). In this context, Mandaroux et al. (2021) emphasize the role of SSI in protecting individual sovereignty. By using decentralized identity standards, participants can manage their own credentials, allowing emission data to be shared as verifiable credentials while retaining full control over their personal information.

The findings of Research Paper P5 indicate that the implementation of a combination of digital technologies has the potential to enhance the efficacy of carbon accounting practices within organizations and their supply chains. Further, this integration can contribute to the development of digital supply chain ecosystems, thereby facilitating the automated sharing of data for a multitude of applications. By moving from an intra-organizational perspective to a data ecosystem perspective as outlined in Research Paper P5, organizations can utilize accurate and verifiable primary data across entire supply chains to enable CO_2-adaptive decision-making while maintaining data sovereignty and privacy. However, the value of such inter-organizational data ecosystems ultimately depends on how this shared data is collected and how it is used to derive physically meaningful emissions information, particularly for indirect emissions that cannot be captured accurately through aggregated averages or certificates.

4.2 Tracing Indirect Emissions Digitally

Building on the inter-organizational data sharing foundations outlined in the Research Paper P5, specific attention must be paid to how shared carbon data can be derived in a physically meaningful way in the first place, particularly regarding Scope 2 emissions: Scope 2 emissions are indirect GHG emissions that arise, among others, due to purchased electricity (cf. Chapter 1). The physical complexity of the electricity grid, where electrons follow complex paths governed by Kirchhoff's laws, leads to inaccurate emissions statements. For instance, Bjørn et al. (2022) illustrate that current Scope 2 standards lead to an inflated estimate of mitigation progress: There are two approaches to Scope 2 emissions accounting, each with severe downsides. First, *location-based* Scope 2 emissions accounting is based on the average emissions intensity of the grid supplying the consumption location, using standardized regional or grid-specific emission factors and, hence, limited by its reliance on generic grid averages that reflect regional or national changes rather than specific organizational actions. Second, the *market-based* approach includes emissions tied to a company's procurement choices, such as Renewable Energy Credits (RECs), which often lead to inflated emissions reductions numbers due to a lack of additionality. The combination of the two accounting approaches (i.e., dual reporting as recommended by the GHG protocol further introduces a risk of double counting, as the renewable attributes claimed by one entity via market-based instruments simultaneously lower the grid-average emission factors that organizations use for their location-based reporting (Bjørn et al., 2022).

Against this background, Research Paper P6 analyzes Power Flow Tracing (PFT) as a more accurate location-based approach and identifies digital technologies as a critical enabler for accurate and timely Scope 2 emissions data sharing by providing the necessary data foundation. The provided taxonomy (cf. Figure 4.2) structures PFT methods across six distinct dimensions: data foundation, temporal resolution, tracing approach, level of analysis, topology model, and application area.

<table>
<tr><th>Dimension</th><th colspan="6">Characteristics</th><th>Exclusive (Yes/No)</th></tr>
<tr><td>Input</td><td colspan="2">Historic</td><td colspan="2">Real-Time</td><td colspan="2">Simulation</td><td>No</td></tr>
<tr><td>Output</td><td colspan="3">Static</td><td colspan="3">Dynamic</td><td>Yes</td></tr>
<tr><td>Tracing Approach</td><td>Circuit Theory</td><td>Electrical Distance</td><td>Game Theory</td><td>Graph Theory</td><td>Linear Equation</td><td>Optimization</td><td>Yes</td></tr>
<tr><td>Application Area</td><td colspan="2">Electricity Pricing</td><td colspan="2">Grid Stability</td><td colspan="2">Tracing of Origin and Emissions</td><td>No</td></tr>
<tr><td>Topology Model</td><td colspan="2">AC</td><td colspan="2">DC</td><td colspan="2">Hybrid</td><td>Yes</td></tr>
<tr><td>Level of Analysis</td><td colspan="2">Transmission Grid</td><td colspan="2">Distribution Grid</td><td colspan="2">Microgrid</td><td>No</td></tr>
</table>

Figure 4.2: Taxonomy of Power Flow Tracing Methods (based on Research Paper P6)

Input

The input dimension captures the temporal and contextual origin of system data and solved power flows (i.e., the results of a power flow analysis in electrical power systems) that act as inputs for the tracing stage. It differentiates whether a given method operates on archived historical data, depends on real-time system inputs, or uses simulated values. Approaches using a *historical* data foundation apply stored system information to retrospectively allocate power flows. For instance, Bai and Crisostomi (2020) reconstruct line losses from previous days based on recorded current and bus injection data. Similarly, ex-post approaches such as Tranberg et al. (2019) rely on dispatch data that, while dated, allow for a detailed understanding of energy consumption and origin over a specific period without direct system access. Such ex-post analyses help assign responsibility more accurately, for instance, by providing a physically consistent perspective on transmission cost allocation.

Real-time methods, in contrast, utilize (near) real-time data streams from the studied system to perform PFT. Dudkina et al. (2022), for instance, employ real-time flow information to attribute renewable electricity used in hydrogen production. Likewise, Z. Yan et al. (2021) introduce a real-time carbon flow algorithm for emissions tracking, while Hofmann (2020) apply tracing to hourly, time-resolved data across the European energy system. Real-time approaches depend on continuous data acquisition (e.g., through sensor networks) and make it possible to monitor changing hotspots, supporting immediate operational interventions such as redispatch or curtailment.

Simulation-based PFT techniques employ synthetic rather than measured data. D. Li et al. (2023), for instance, use simulated power flows to explore carbon allocation strategies under coupled sectoral scenarios. Similarly, Lu et al. (2024) analyze market power behavior under varying network topologies with simulated input data using PFT. This enables experimentation with policy, infrastructure, and market configurations even when real-world measurements are unavailable. Simulated results can also be complemented by estimates when measurement data are missing or delayed, as shown in Electricity Maps (2025). Consequently, this dimension is non-exclusive.

Output

The output dimension defines the temporality of the system state analyzed through PFT, distinguishing between methods applied to a single solved snapshot and those covering a time series of operating points. This distinction determines how suitable PFT is for dynamic grid operations or planning scenarios. We distinguish between two main characteristics: static and dynamic.

Static approaches perform tracing on a single steady-state snapshot of the grid, assuming that system variables (such as generation, load, and topology) remain constant during analysis. For instance, Lou et al. (2024) present a static tracing model to calculate allocation costs in a Peer-to-Peer (P2P) electricity market. This model, based on fixed injections and withdrawals, offers precise but temporally limited insights into energy use and contributions. Likewise, Zhao et al. (2023) develop a virtual contribution-based loss allocation method using a single time step. Although they address broader network dynamics, their main PFT approach relies on static conditions and predefined operating points. Static methods are computationally efficient and thus particularly well-suited for regulation, cost allocation, and billing contexts characterized by stable operations.

Conversely, *dynamic* methods extend tracing across varying operating points (e.g., multiple solved power flows) or explicitly integrate system dynamics prior to the tracing step. These models capture how flows and related quantities—such as emissions or costs—evolve over time in response to system variations. For instance, Y. Liu et al. (2020) introduce a ‘dynamized’ PFT method that applies differential transformation to directly embed dynamic behavior into tracing instead of solving sequential static points. Similarly, Qing and Xiang (2024) propose a dynamic carbon emission factor model that enables accurate temporal tracking of emission flows.

Tracing Approach

This dimension describes the theoretical foundation used to allocate contributions based on a solved system state. As illustrated in Figure 4.2, we identify six main groups of tracing approaches: circuit theory, electrical distance, game theory, graph theory, linear equation, and optimization.

Circuit-theoretic approaches apply electrical fundamentals such as Ohm's and Kirchhoff's laws to represent and allocate power flows. They treat the grid as an electrical circuit and trace active or reactive flows based on quantities such as current, voltage, and impedance. For instance, Y. C. Chen and Dhople (2020) develop an analytical formulation that leverages these basic laws to map power movement from sources to sinks.

Electrical distance-based metrics measure the relative distance between nodes in electrical terms. Originating from Visakha et al. (2004), this technique uses a network matrix to quantify the position of loads relative to generators. However, the original approach focuses on cost allocation against a desired schedule rather than tracing physical power contributions, which is why it may not strictly qualify as a PFT method. We include it for completeness. While simpler electrical distance models are less common today, advanced implementations - such as Vlaisavljevic et al. (2019) - combine the concept with additional analytical features.

Game-theoretic frameworks model tracing as a (non-)cooperative game, emphasizing equity and actor strategy. These formulations are particularly relevant for dividing costs or emissions among participants in ways that reflect their marginal contributions and fairness principles. For instance, Zuo et al. (2024) use cooperative game theory to apportion carbon emissions among participants in hybrid electricity markets, applying a Shapley value-inspired approach. While these models do not alter physical system conditions, they bridge fairness with the physical grid structure.

Graph-theoretic methods conceptualize the power network as a collection of nodes and edges, using flow and topology properties to identify power paths. Such approaches typically rely on the proportional sharing principle, assuming that input flows at a node are proportionally distributed across outgoing lines (Ströher & Strüker, 2024). Bhand and Debbarma (2021), for instance, build transaction-specific graph models for unbalanced distribution systems, while X. Yu (2022) use a similar foundation for network analytics.

Linear equation-based techniques express tracing relationships algebraically, solving systems of linear equations derived from simplified power flow representations or approximate energy constraints. Lu et al. (2024), for instance, integrate linear distribution factors into a market-clearing model to link generation to load allocations and trace carbon flows in multi-market systems. Theoretical analyses indicate that linear equation- and graph-based variants of the proportional sharing approach are fundamentally equivalent. Ansyari et al. (2007) compare these methods, while Achayuthakan et al. (2010) formally prove their mathematical equivalence.

Optimization-based approaches formulate tracing as a constrained optimization problem, balancing accuracy with computational efficiency. These methods often require simplifying assumptions, such as neglecting loop flows or assuming convexity, to remain tractable. Similar to game-theoretic techniques, they seek to respect physical grid limitations while embedding fairness or efficiency objectives (Ströher & Strüker, 2024). Optimization approaches can be deterministic, producing consistent results for given inputs, or non-deterministic, potentially yielding different solutions under the same conditions. Deterministic variants follow classical mathematical programming (linear or nonlinear), while non-deterministic or hybrid optimization techniques, such as particle swarm optimization, have been introduced to improve global exploration capabilities (Tijani et al., 2019).

Application Area

PFT approaches play an important role in analyzing and optimizing modern energy systems, providing physically grounded insights that conventional accounting often overlooks. While PFT builds on power flow analysis, it extends it by assigning shares of usage, losses, emissions, or attributes to network participants. We distinguish between three principal application areas: electricity pricing, grid stability, and proofs of origin.

In *electricity pricing*, PFT serves as a physically consistent basis for equitable cost allocation. One major use case is the attribution of transmission and distribution losses, especially in networks with Distributed Energy Resources (DERs) and bidirectional flows. Existing allocation schemes such as pro rata, MW-mile, or contract path differ in fairness and precision, but PFT directly reflects physical causation by tracing losses back to generators and loads. It is also used to allocate network operation and investment costs by quantifying individual participants' grid use (Shuai et al., 2021). These mechanisms extend to cross-border networks, where PFT supports equitable cost sharing among multiple regions based on actual power exchanges (Schäfer et al., 2019). Concepts such as "price tracing" extend this physical approach to locational marginal prices, enabling transparent, usage-based tariff designs. Integrated frameworks also combine energy and carbon prices into unified, node-specific price signals, such as the nodal energy-carbon scheme by S. Ma et al. (2022).

Regarding *grid stability*, PFT supports analysis and operational planning by identifying how active and reactive power flows influence stability indicators. Voltage stability, for instance, benefits from the tracing of reactive power flows to detect critical nodes or weak connections. Modified methods target specific issues, such as voltage control in local markets (Angaphiwatchawal et al., 2024), frequency stability (Y.-X. Chen et al., 2019), or overload management (Jiandong et al., 2019). Further, PFT provides valuable information for congestion management by identifying which generators or consumers drive line congestion (Lawal et al., 2019). Such analysis is particularly relevant in cross-border contexts, although the precise tracing formulation has limited impacts on overall cost outcomes (Stavropoulos et al., 2025). Tracing-based insights can also guide load curtailment decisions during system restoration by mapping critical flow linkages (Wu et al., 2019).

PFT is further applied to *tracing origin and emissions*, linking electricity flows to environmental attributes such as carbon intensity or renewable content. This is increasingly relevant for carbon footprinting, where emissions are treated as a virtual flow parallel to physical electricity movement (Qing & Xiang, 2024; P. Wang et al., 2023). Studies by Hu et al. (2024) and Eleks (2025) illustrate this in both academic and practical implementations. PFT-based emission tracing provides an alternative to marginal emission metrics in market models (Lu et al., 2024) and can also support forward-looking emission estimates using historical data (Liang et al., 2023). Also, PFT is used to verify renewable electricity transfers in green power markets (Aarhus University, 2023), enabling high physical correspondence between renewable sources and designated consumers, such as electrolyzers for green hydrogen. Thus, it ensures the principle of "additionality" (Dudkina et al., 2022, 2024).

Topology Model

PFT methods can vary substantially based on the network topology representation used to derive the underlying power flow solution. The corresponding model may adopt an Alternating Current (AC), a simplified Direct Current (DC), or a hybrid formulation that integrates the two.

AC-based approaches build directly on the outcomes of AC power flow calculations. Circuit-theoretic methods commonly fall into this group, using network matrices such as admittance (Y) (Y. C. Chen & Dhople, 2020) or impedance (Z) (C. Wang et al., 2022) to trace complex power flows. Nonetheless, proportional sharing-based methods, including graph-based variants, can also be extended to complex power analysis (e.g., F. Ma et al. (2023)).

DC-based variants apply a simplified DC power flow model that focuses on active power and neglects losses (Purchala et al., 2005). Historically, this approach suits transmission-level analyses where reactive power effects are minimal. Examples include H. Zhang et al. (2023), Yang et al. (2023), and Ren et al. (2023), who use active-flow tracing for transmission carbon allocation. However, reactive power remains essential for maintaining voltage balance and enhancing transfer capabilities (Enshaee & Yousefi, 2019). As distribution networks integrate growing shares of DERs, tracing reactive power has drawn increasing attention (Jiang & Zhang, 2021).

Our *hybrid* category comprises methods combining AC- and DC-based models, typically solving AC flows for some areas and DC approximations for others (S. Kim & Overbye, 2011). This hybridization offers a trade-off between numerical efficiency and electrical accuracy. Other approaches start from an AC base model and subsequently add components such as losses ex post, for instance as demonstrated by Vlaisavljevic et al. (2019).

Level of Analysis

The level of analysis dimension distinguishes PFT studies by the grid type they investigate. This distinction is essential since tracing objectives, operational characteristics, and data granularity vary markedly among transmission, distribution, and microgrid systems. Although some methods are theoretically scale-neutral, actual implementations often adapt to the practical constraints of each grid type, for instance, the greater relevance of reactive flow in distribution networks (cf. above).

In *transmission grids*, PFT is primarily used in (ultra) high-voltage systems operated by transmission system operators. These backbones of national and regional grids rely on PFT for large-scale loss and emission attribution as well as flow decomposition across regions. Examples include Deacon et al. (2021), who trace zonal carbon intensities in Great Britain's transmission system, highlighting its policy relevance for emission pricing and border adjustments, and M. Yu et al.

(2023), who analyze interprovincial energy transfers in China. Similarly, Schäfer et al. (2019) identify temporal and spatial trade patterns in European cross-border flows.

In *distribution grids*, which include medium- and low-voltage networks, PFT supports decentralized configurations marked by P2P trading, renewable integration, and flexible loads. These settings require methods capable of dealing with bidirectional flows and incomplete datasets. Hofmann and Schlott (2022) present a linear equation-based tracing framework for quantifying flexibility at this level, while Fei and Moses (2019) propose a decentralized scheme with privacy-preserving data exchange, which is crucial given that detailed distribution-level data can reveal individual consumption patterns. D. Wang et al. (2024) focus on identifying critical nodes to improve monitoring reliability and transparency.

Finally, *microgrid*-level tracing relates to localized systems operating autonomously or semi-independently from the main grid. Their scale, self-sufficiency, and diverse mix of assets make them ideal test environments for novel tracing concepts. Budi et al. (2020) design a P2P trading scheme using PFT to allocate transactional losses and ensure equitable settlement, while Pease et al. (2023) investigate tracing in a solar-based community microgrid to enhance transparency and accountability.

While Research Paper P6 finds PFT methodologies to be technically mature, the primary barrier to wider adoption is the lack of temporally and locally fine-grained, timely data. This particularly applies to the tracing at the distribution grid level, which is increasingly relevant due to the presence of renewable integration, P2P energy trading, and flexible loads: These grids are more decentralized and often data-constrained, necessitating approaches that can handle incomplete data (cf. Section 4.1). Also, privacy is a bigger concern in distribution grids, as fine-granular energy data on this level may allow for concluding consumers' behaviors.

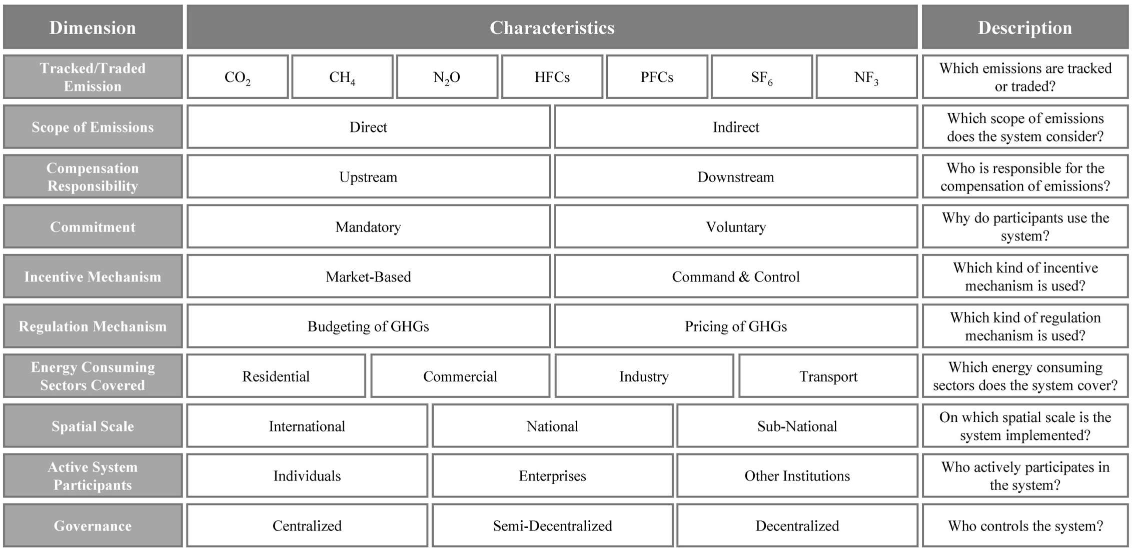
Digital technologies such as AI for grid mapping can be used to address these data gaps: for instance by using satellite data and evaluating it on the basis of image recognition enabled by AI that is trained on experts, power grids and relevant facilities (e.g., transformer stations) may be digitalized in an efficient way (Eleks, 2025). By applying PFT, organizations can move from Scope 2 emissions accounting based on grid averages toward a more precise, real-time approach. This enables not only more accurate location-based accounting of Scope 2 emissions but also allows for CO_2-adaptive decision-making based on real-time electricity emissions (e.g., by shifting electricity-intensive tasks to times when electricity causes fewer emissions). From a macroeconomic perspective, such physically grounded, fine-granular emissions information is a prerequisite for using electricity-related emissions as an economic market signal that is necessary for internalizing the external costs of climate change effectively.

4.3 Assessing and Enhancing Voluntary and Compliance Carbon Markets

Once emissions can be traced with sufficient accuracy (e.g., based on sophisticated accounting approaches for indirect emissions as well as the sharing of verifiable, fine-granular primary data outlined in the previous sections), they can be integrated into economic coordination and incentive mechanisms. For instance, in addition to RECs for market-based Scope 2 emissions accounting (cf. Section 4.2), organizations can voluntarily buy carbon credits (i.e., digital representations of GHG emission reductions or avoidance from projects such as reforestation) on Voluntary Carbon Markets (VCMs) to offset their emissions (independent of their scope). While reporting standards such as the GHG protocol do not allow for the inclusion of these offsets, organizations can, for instance, optionally note them in a separate part of their non-financial report (WRI and WBCSD, 2004) to use them for improving their reputation or for achieving their decarbonization targets. VCMs have emerged as a promising mechanism for offsetting residual emissions that cannot yet be eliminated through internal reductions or for occasions in which it is very expensive to do so. While VCMs represent a promising tool for organizations to reduce or completely negate their emissions impact, they currently suffer from persistent information asymmetries, a trust deficit, and fragmentation, ultimately leading to a market failure.

Research Paper P7 develops a maturity model to assess these VCMs and find potentials for improvements. By developing such a maturity model, we synthesize the body of research regarding the operation of VCMs, integrating both macroeconomic and microeconomic viewpoints. From a macroeconomic perspective, our maturity model offers insights into the fundamental mechanisms of carbon offset allocation, specifically aiming to mitigate current market failures in VCMs. From a microeconomic perspective, our findings yield two primary implications: first, both startups and established firms providing digital services or constructing VCM marketplaces can utilize the model to evaluate their specific environments. This allows them to intentionally design measures that elevate current market mechanisms toward a higher state of maturity. Second, organizations participating as buyers or sellers of carbon offsets can leverage the model to scrutinize existing marketplaces. This evaluation helps minimize the operational and reputational risks inherent in trading offsets on substandard or deficient platforms. Ultimately, our maturity model facilitates a comprehensive status-quo analysis and encourages critical reflection on the potential evolutionary trajectories of the VCM landscape.

While VCMs represent a "bottom-up" approach, they coexist with "top-down" compliance approaches such as Emissions Trading Systems (ETSs). To navigate this complex landscape and to coordinate different approaches in a way that they can meaningfully coexist, Research Paper P8 develops a first-of-its-kind taxonomy of GHG tracking and trading (cf. Figure 4.3, providing a structured framework for both enterprises and policymakers. I will now outline the framework's dimensions.



Dimension	Characteristics							Description
Tracked/Traded Emission	CO_2	CH_4	N_2O	HFCs	PFCs	SF_6	NF_3	Which emissions are tracked or traded?
Scope of Emissions	Direct	Indirect						Which scope of emissions does the system consider?
Compensation Responsibility	Upstream	Downstream						Who is responsible for the compensation of emissions?
Commitment	Mandatory	Voluntary						Why do participants use the system?
Incentive Mechanism	Market-Based	Command & Control						Which kind of incentive mechanism is used?
Regulation Mechanism	Budgeting of GHGs	Pricing of GHGs						Which kind of regulation mechanism is used?
Energy Consuming Sectors Covered	Residential	Commercial	Industry	Transport				Which energy consuming sectors does the system cover?
Spatial Scale	International	National	Sub-National					On which spatial scale is the system implemented?
Active System Participants	Individuals	Enterprises	Other Institutions					Who actively participates in the system?
Governance	Centralized	Semi-Decentralized	Decentralized					Who controls the system?

Figure 4.3: Taxonomy on the Design and Implementation of GHG Tracking and Trading Approaches (based on Research Paper P8)

The dimension *Tracked/Traded Emissions* identifies the specific types of GHG managed within the system. Similar to Research Paper P4, we align our characteristics with the six primary gases established by the UNFCCC in the Kyoto Protocol (UNFCCC, 1997), and include nitrogen trifluoride (NF_3). While CO_2 is universally covered in all identified systems, the inclusion of the other seven gases varies; for instance, the European Union (EU) ETS mandates CO_2, N_2O, and PFCs but allows member states to expand this list (Narassimhan et al., 2018). Thus, this dimension is non-exclusive.

Similarly, the *Scope of Emissions* is non-exclusive. It distinguishes between direct emissions produced by an entity's own activities, such as fuel combustion—and indirect emissions, which occur when an entity consumes services or goods that generated emissions elsewhere, such as purchased electricity (House of Commons, 2008).

The third, non-exclusive, dimension determines the *Compensation Responsibility*. Systems typically follow an upstream approach, targeting the initial polluters, or a downstream approach, targeting the end consumers (Kothe et al., 2021). Although downstream models often incur higher administrative overhead, they can facilitate much broader market participation due to the large volume of the stakeholders involved (Sonneborn, 1999; Starkey & Anderson, 2005).

Regarding *Commitment*, we distinguish between voluntary and mandatory approaches. While voluntary schemes often enjoy higher initial public popularity, mandatory frameworks demonstrate greater efficacy in achieving absolute emission reductions (Kothe et al., 2021). Some systems utilize a phased approach—starting as voluntary and transitioning to mandatory, as seen in the early stages of the Swiss ETS—or apply different commitment levels to different user groups, such as the New Zealand ETS (Narassimhan et al., 2018). This dimension is thus non-exclusive.

The *Incentive Mechanism* describes the logic used to motivate participants to achieve lower emissions. This exclusive dimension distinguishes between market-based mechanisms, which provide economic rewards or penalties, and command-and-control mechanisms, which rely on legal mandates. Similarly, the regulation mechanism governs the total volume of emissions. Regulation is achieved either through a quantity-based approach (e.g., an emissions cap or quota) or a price-based approach (e.g., carbon taxes or fixed allowance prices). As existing frameworks typically prioritize one over the other to avoid conflicting signals, this dimension is exclusive.

The non-exclusive dimension *Energy Consuming Sectors Covered* tracks which parts of the economy are subject to the system. Implementations often start with a subset of high-impact sectors, such as power generation, before gradually expanding to others (European Commission, 2012; Niizawa et al., 2020). The decision to include specific sectors involves balancing environmental effectiveness, economic efficiency, and administrative feasibility (European Commission, 2000).

The *Spatial Scale* of an approach is an exclusive dimension, ranging from international (e.g., EU ETS) and national (e.g., Switzerland) to sub-national levels such as the California Cap and Trade (Hintermann & Žarković, 2021; Narassimhan et al., 2018). Scale can also be expanded by linking distinct systems, such as California and Quebec, or by utilizing local pilot projects to test viability before a broader roll-out (Z. Zhang, 2015).

Regarding *Active System Participants*, this non-exclusive dimension identifies all parties directly interacting with the system, such as regulators, data providers, or entities with emission liabilities. We distinguish these from general stakeholders, who Freeman (1984) defines as any group affected by an organization's objectives. While the general public may be stakeholders due to climate concerns, only those with direct functional roles are considered active participants here.

The final exclusive dimension, *Governance*, identifies the decision-making authority (Alkawasmi et al., 2012). Centralized means that the authority rests with a single entity, usually a government agency while full decentralization means the power is distributed among all participants. In semi-decentralized options, responsibilities may be split; for instance, the EU ETS divides the duties for allowance assignment, enforcement, and financial reporting amongst individual member states (Alkawasmi et al., 2012). While traditional systems rely on centralized or semi-decentralized models, which can suffer from bureaucracy and single points of failure, current research increasingly advocates for a shift toward more decentralized architectures.

By structuring these design variations into a comprehensive taxonomy, we provide a holistic overview of the highly complex field of GHG tracking and trading. For enterprises seeking to transition toward cleaner production, this framework offers the uniform understanding necessary to navigate the diverse implementation options available in modern GHG tracking and trading. It also guides policymakers by enabling the comparison and coordination of different GHG tracking and trading policies that are being or will be implemented.

Collectively, my findings throughout this dissertation illustrate that taking a digital MRV perspective (Research Papers P1 and P2) facilitates CO_2-adaptive decision-making within organizations (Research Papers P3 and P4), enhances carbon data sharing between organizations (Research Papers P5 and P6), and ultimately builds the foundation for effective market structures that can internalize the external costs of GHG emissions (Research Papers P7 and P8). This transforms CO_2 adaptability from a technical possibility into a strategic economic necessity for organizations and is therefore an effective lever for a deep and rapid decarbonization.

5 Conclusion

5.1 Summary

This dissertation has examined how digital technologies can fundamentally transform MRV processes and thereby enable more effective and adaptive paths toward the deep and rapid decarbonization that the severity and pace of anthropogenic climate change increasingly require. Rather than treating carbon accounting as a static reporting task, my dissertation conceptualizes digital MRV as a socio-technical infrastructure that supports continuous, data-driven decision-making within and beyond organizational boundaries. By integrating eight research papers, this dissertation contributes to connecting technical system architectures with organizational practices as well as economic coordination and incentive mechanisms.

At the conceptual level, this dissertation has established *Digital MRV for Decarbonization* as a distinct Green IS research stream. It has identified key architectural characteristics of digital carbon accounting systems, including interoperability, automation, and decentralized governance, that distinguish digital MRV from traditional, manual approaches (Research Papers P1 and P2). In doing so, it demonstrates that leveraging digital technologies such as AI, DLTs, IoT, data spaces, and PETs not only allows for improvements to the efficiency or effectiveness of existing MRV processes, but also enables systematic restructuring of these processes (e.g., reporting based on verifiable carbon data instead of ex-post verification through third parties) as well as different process characteristics that are (almost) unattainable through manual approaches (e.g., the collection of fine-granular carbon data in real-time). These characteristics form the foundation for scalable, auditable, and adaptive carbon IS capable of supporting decision-making under increasing regulatory and market pressure.

Building on this foundation, my dissertation has demonstrated how digital MRV enables intra-organizational transparency and operationalization. It illustrates how LLM-based architectures can alleviate informational bottlenecks by extracting sustainability-relevant data from unstructured sources, and how domain-specific taxonomies can reduce complexity and resource constraints for SMEs engaging in carbon reporting (Research Papers P3 and P4). Together, these contributions illustrate how digital technologies can replace manual, fragmented, and error-prone processes with automated and reproducible workflows, thereby improving both the efficiency and credibility of corporate climate disclosures.

Extending beyond organizational boundaries, this dissertation conceptualizes and evaluates a "digital bridge" for inter-organizational carbon data sharing as a prerequisite for addressing the persistent indirect emissions accounting gap (Research Paper P5). By enabling the secure exchange of primary emissions data while preserving data sovereignty, such infrastructures allow organizations to move beyond industry averages and identify actual emissions hotspots in complex supply chains. The importance of physically meaningful and temporally resolved data is further demonstrated through the case of Scope 2 emissions, where PFT is identified as a mature yet data-intensive methodology whose practical applicability critically depends on the availability of high-resolution digital data (Research Paper P6).

Finally, my dissertation synthesizes these insights at the market level, illustrating how digital MRV infrastructures can reshape voluntary and compliance carbon markets and can support the emergence of more credible and coordinated economic instruments for climate mitigation (Research Papers P7 and P8). By proposing a unified taxonomy for GHG tracking and trading, the work responds directly to systemic shortcomings of existing market mechanisms, including opacity, fragmentation, and credibility crises such as those revealed by the Verra scandal (Greenfield, 2023). Collectively, this dissertation's contributions demonstrate how digital MRV can enable a transition from retrospective, estimate-based reporting toward an automated, high-trust digital ecosystem in which emissions information functions as reliable operational and economic signals.

5.2 Limitations and Outlook

This dissertation has limitations, which open important directions for future research. Many of the proposed artifacts, architectures, and frameworks were developed using design-oriented methodologies, qualitative analyses, and expert interviews. While these approaches are well-suited for theory building, conceptualization, and artifact design, large-scale empirical validation across heterogeneous industries, geographies, and regulatory contexts remains an open challenge. Further, despite following established and rigorous methodological foundations, the qualitative approaches I applied are subject to a certain degree of subjectivity (e.g., regarding the evaluation of literature sections or the clustering of taxonomy dimensions).

At both the intra- and inter-organizational levels, the implementation of digital MRV infrastructures faces significant socio-technical barriers. Concerns relating to data privacy, competitive sensitivity, and liability continue to constrain organizations' willingness to share primary emissions data. Although technological approaches such as SSI and ZKPs as well as decentralized governance mechanisms offer promising solution approaches, fostering trust and coordination among competing actors remains a fundamental challenge that extends beyond technical system design. Thus, researchers should address social and psychological questions from users' perspective such as perceived trust and privacy related to carbon data sharing.

From a regulatory perspective, the rapid evolution of sustainability reporting frameworks, such as the EU's CSRD, creates a moving target for digital MRV system development. While increasing regulatory specificity may ultimately strengthen the demand for digital solutions, it also requires MRV architectures to remain adaptable to changing legal and methodological requirements. Thus, I encourage researchers to examine how digital MRV systems can be designed for regulatory robustness and long-term adaptability. Also, future research should address how to design effective regulatory frameworks to facilitate the path to digital MRV while protecting rights of individuals and competitiveness of organizations. This adaptability is particularly relevant at the time of writing this dissertation, given the current political climate: recent developments such as the European Commission's Digital Omnibus Package, which proposes to substantially reduce the scope of the CSRD, as well as a broader international retreat from multilateral climate commitments, illustrate that the regulatory foundation for carbon accounting cannot be assumed to be stable. As the imperative of global GHG emissions reduction is independent of the regulatory frameworks designed to govern them, robust digital MRV infrastructures are even more important as political support for mandatory disclosure fluctuates.

Looking ahead, the integration of digital MRV into cross-organizational data spaces represents a promising avenue for both research and practice. Such ecosystems have the potential to internalize environmental externalities by directly embedding fine-granular emissions data into industrial coordination and market mechanisms. In this context, addressing governance and interoperability questions relating to multiple data ecosystems that exist in different sectors or regions provides an interesting direction for research.

As particularly AI continues to advance at the time of writing, its roles in digital MRV are likely to evolve from supporting data extraction and classification toward semi-autonomous or autonomous agents that may significantly improve the quantification and reduction of GHG emissions. Thus, future research in *Digital MRV for Decarbonization* should focus on understanding how such systems can be designed, governed, and constrained to ensure transparency, accountability, and alignment with regulatory and societal objectives.

Ultimately, future research should understand the transition toward digital decarbonization not merely as a technological improvement to existing reporting practices, but as a deeper transformation in how global value chains perceive, quantify, and manage environmental impacts. By reframing carbon information as a shared, actionable, and economically relevant signals, digital MRV research can provide a robust foundation for more coordinated and adaptive responses to climate change.

Use of writing assistance Please note that I have utilized various writing assistance software programs (e.g., ChatGPT, DeepL, and Grammarly) to enhance the language and readability of this work. Nevertheless, I take full responsibility for its content and have thoroughly reviewed and edited the material as necessary.

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A Appendix

A.1 Overview of Research Papers

A.1.1 Research Papers Included in This Dissertation

Research Paper P1: Digital Measuring, Reporting, and Verification (dMRV) for Decarbonization

Körner, M.-F., Leinauer, C., Ströher, T., & Strüker, J. (2025). Digital Measuring, Reporting, and Verification (dMRV) for Decarbonization. *Business & Information Systems Engineering*
(VHB-JQ3[1]: B; VHB-R2024[2]: B; JIF-2024[3]: 10.4; SJR[4]: 2.201 (Q1))

Research Paper P2: Digital Carbon Accounting for Accelerating Decarbonization: Characteristics of IS-Enabled System Architectures

Körner, M.-F., Schober, M., Ströher, T., & Strüker, J. (2023). Digital Carbon Accounting for Accelerating Decarbonization: Characteristics of IS-Enabled System Architectures [Top 25% paper]. In *29th Americas Conference on Information Systems (AMCIS) 2023*. https://amcis2023.aisconferences.org/
(VHB-JQ3: D; VHB-R2024: C; JIF-2024: -; SJR: -)

Research Paper P3: Leveraging Large Language Models for Information Extraction

Paetzold, F., Guggenberger, T., Jungk, T., Protschky, D., Ströher, T., & Strüker, J. (2026). Leveraging Large Language Models for Information Extraction [Major Revision]. *Scientific Journal*
(VHB-JQ3: B; VHB-R2024: B; JIF-2024: 6.8; SJR: 2.325 (Q1))

Research Paper P4: Systematizing Corporate Carbon Accounting from a Data Perspective to Enable CO2-Adaptive Decision-Making

Körner, M.-F., Paetzold, F., Ströher, T., & Strüker, J. (2026). Systematizing Corporate Carbon Accounting from a Data Perspective to Enable CO2-Adaptive Decision-Making [Submitted]. *Scientific Journal*
(VHB-JQ3: C; VHB-R2024: C; JIF-2024: 3.7; SJR: 0.925 (Q1))

Research Paper P5: Bridging Carbon Data's Organizational Boundaries: Toward Automated Data Sharing in Sustainable Supply Chains

Ströher, T., Körner, M.-F., Paetzold, F., & Strüker, J. (2025). Bridging Carbon Data's Organizational Boundaries: Toward Automated Data Sharing in Sustainable Supply Chains. *Electronic Markets*
(VHB-JQ3: B; VHB-R2024: B; JIF-2024: 6.8; SJR: 2.325 (Q1))

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[1] VHB-JQ3: VHB-JOURQUAL3

[2] VHB-R2024: VHB-Rating 2024

[3] Journal Impact Factor 2024

[4] Scimago Journal & Country Rank

Research Paper P6: From Papers to Power Plants: A Taxonomy of Power Flow Tracing Methods in Research and Practice
Ströher, T., Strüker, J., & Konoval, V. (2026). From Papers to Power Plants: A Taxonomy of Power Flow Tracing Methods in Research and Practice. *Bayreuth Reports on Information Systems Management*
(VHB-JQ3: -; VHB-R2024: -; JIF-2024: -; SJR: -)

Research Paper P7: Quality Check for Lemons: A Voluntary Carbon Market Maturity Model (VCM^3)
Körner, M.-F., Leinauer, C., Ströher, T., & Strüker, J. (2026). Quality Check for Lemons: A Voluntary Carbon Market Maturity Model (VCM^3) [Prepared for Submission]. *Scientific Journal*
(VHB-JQ3: B; VHB-R2024: B; JIF-2024: 6.3; SJR: 2.088 (Q1))

Research Paper P8: Accelerating Decarbonization Digitally: Status Quo And Potentials Of Greenhouse Gas Emission Tracking And Trading
Babel, M., Körner, M.-F., Ströher, T., & Strüker, J. (2024). Accelerating Decarbonization Digitally: Status Quo And Potentials Of Greenhouse Gas Emission Tracking And Trading. *Journal of Cleaner Production*
(VHB-JQ3: B; VHB-R2024: B; JIF-2024: 10.0; SJR: 2.174 (Q1))

A.1.2 Index of Further Papers

Over the course of the dissertation, I also authored and co-authored the following research papers, studies, and reports. These papers are not part of this dissertation.

Gramlich, V., Körner, M.-F., Ströher, T., Strüker, J., & Volland, M. (2024). Decentralization Technologies in the Context of ESG Accounting and Reporting. In G. Fridgen, T. Guggenberger, J. Sedlmeir, & N. Urbach (Eds.), *Decentralization Technologies: Financial Sector in Change* (pp. 177–194). Springer Nature Switzerland. https://doi.org/10.1007/978-3-031-66047-4_10

Körner, M.-F., Paetzold, F., Ströher, T., & Strüker, J. (2024). Digital Proofs of Origin for Sustainability: Assessing a Digital Identity-Based Approach in the Energy Sector. https://doi.org/10.24406/publica-3224

Ströher, T., & Strüker, J. (2024). Power Flow Tracing - Analyzing the Embedding of Eleks Dakar in Research and Practice. https://doi.org/10.24406/w-34707

Körner, M.-F., Paetzold, F., Ströher, T., & Strüker, J. (2025). Feingranulare und digitale CO2-Herkunftsnachweise für Strom. In J. Anke, M. Kubach, & J. Sürmeli (Eds.), *Digitale Identitäten und Nachweise: Lösungsansätze für vertrauenswürdige Interaktionen zwischen Menschen, Unternehmen und Verwaltung* (pp. 237–250). Springer Fachmedien Wiesbaden. https://doi.org/10.1007/978-3-658-47708-0_15

Babel, M., Guthmann, C., Paetzold, F., Ströher, T., & Strüker, J. (2025). DIVE – Digitale Identitäten als Vertrauensanker im Energiesystem: 01 Überblick, Einordnung und Evaluation [Abschlussbericht]. Retrieved March 2, 2026, from https://www.dena.de/

Babel, M., Paetzold, F., Ströher, T., & Strüker, J. (2025). Digitale Identitäten im Energiesektor: Der Beitrag für eine zukunftsgerichtete Dateninfrastruktur. Retrieved March 2, 2026, from https://www.dena.de/

Strüker, J., Löschel, A., Schneider, M., & Ströher, T. (2025). Granulare Herkunftsnachweise für Deutschland - Analyse und Entwicklung eines Transformationspfads. Retrieved March 2, 2026, from https://www.50hertz.com/xspProxy/api/staticfiles/50hertz-client/dokumente/unternehmen/partnerschaften/fhg-layout_studie_granulare_hkn_final.pdf

Fraunhofer FIT & Fraunhofer IPA. (2025). Mehr Wettbewerbsfähigkeit durch Digitalisierung und Nachhaltigkeit - Twin Transformation in Oberfranken. Retrieved March 2, 2026, from https://publica.fraunhofer.de/entities/publication/e6fd7bd0-917c-4c2d-9512-4b30b11655b7

Leinauer, C., Joglekar, C. M., Paetzold, F., Ströher, T., Strüker, J., Williams, R. P., & Wirtz, N. (2025). Der Einsatz von Web3 in der Energiebranche - Bausteine und Grundlagen erklären, Potenziale und Einsatzmöglichkeiten aufzeigen. Retrieved March 2, 2026, from https://www.dena.de/fileadmin/dena/Publikationen/PDFs/2025/Der_Einsatz_von_Web3_in_der_Energiebranche.pdf

Ströher, T., & Strüker, J. (2026). Regenerative Finance (ReFi). In R. Beck (Ed.), *Elgar Encyclopedia of Cryptocurrencies, Blockchain, and DLT*. Edward Elgar Publishing

A.1.3 Individual Contribution to the Included Research Papers

This cumulative dissertation comprises eight research papers, all co-authored with multiple collaborators. This section details the context and outlines my contributions to the two papers.

Research Paper P1 entitled "Digital Measuring, Reporting, and Verification (dMRV) for Decarbonization" (Körner, Leinauer, et al., 2025, Appendix A.2) was written by a team of four authors. All authors contributed equally to the paper. Together with all co-authors, I conceptualized and co-developed the research project. Moreover, one co-author and I contributed primarily by analyzing the theoretical and technical foundations of the paper, developing the results, elaborating major parts of the text, and executing several revisions. The two other co-authors, beside aiding in the conceptualization, participated in research discussions, provided feedback on the paper's content and structure, contributing to the theoretical framing, giving continuous feedback, and mentoring the project throughout.

Research Paper P2 entitled "Digital Carbon Accounting for Accelerating Decarbonization: Characteristics of IS-Enabled System Architectures" (Körner et al., 2023, Appendix A.3) was written by a team of four authors. All authors contributed equally to the paper. Together with all co-authors, I co-developed the research project. Together with one co-author, I conducted the literature and developed the key characteristics on the basis of our deductive and descriptive approach. Further, this author and I wrote major parts of the text and I coordinated the execution of a revision. The two other co-authors aided in the conceptualization of the methodological proceeding and provided feedback on our results as well as mentoring. Further, they provided a significant share of input for our discussion section.

Research Paper P3 entitled "Leveraging Large Language Models for Information Extraction" (Paetzold et al., 2026, Appendix A.4) was written by a team of six authors. This paper was led by a co-author who initiated and coordinated the research project and acted as a single lead author. My contribution primarily consisted of analyzing the background and related work for the paper, co-developing the results, providing continuous feedback on the paper, as well as editing the initial draft for a revision. Two other authors contributed mainly by developing our proposed prototype as well as writing sections for the first draft of the paper. The remaining two authors, beside aiding in the conceptualization, participated in research discussions, provided feedback on the paper's content and provided feedback as well as mentoring during the project.

Research Paper P4 entitled "Systematizing Corporate Carbon Accounting from a Data Perspective to Enable CO2-Adaptive Decision-Making" (Körner, Paetzold, et al., 2026, Appendix A.5) was written by a team of five authors. Together with three other authors, I contributed equally to the paper. I primarily conceptualized the content and methodological proceeding of this research project. Moreover, one co-author and I contributed primarily by developing the main artifact, writing major parts of the text, and executing several revisions. The two other co-authors participated in research discussions and provided continuous feedback on the paper's content and structure as well as mentoring. They further contributed to the theoretical framing of the paper and providing valuable input to the discussion section. The remaining author acted as a subordinate author and supported the project by conceptualizing and writing some sections of the initial draft.

Research Paper P5 entitled "Bridging Carbon Data's Organizational Boundaries: Toward Automated Data Sharing in Sustainable Supply Chains" (Ströher et al., 2025, Appendix A.6) was written by a team of four authors. I initiated and coordinated the research project. My contribution spanned all phases of the work, including conceptualization, artifact development, writing of the initial draft as well as several revisions. Another co-author contributed mainly to the artifact development and writing, thus contributing along most research stages, except conceptualization. The remaining two co-authors provided supervision and scientific guidance, offering feedback that helped refine the manuscript's content and theoretical framing throughout the process. Accordingly, I served as the single lead author, while the other three co-authors contributed as subordinate authors.

Research Paper P6 entitled "From Papers to Power Plants: A Taxonomy of Power Flow Tracing Methods in Research and Practice" (Ströher et al., 2026, Appendix A.7) was written by a team of three authors. I initiated, conceptualized, and coordinated the research project. My contribution spanned all phases of the work, including literature analysis, writing, artifact development, and overall project management. The other two co-authors provided supervision and feedback. Accordingly, I acted as the single lead author, while the other two co-authors contributed as subordinate authors.

Research Paper P7 entitled "Quality Check for Lemons: A Voluntary Carbon Market Maturity Model (VCM^3)" (Körner, Leinauer, et al., 2026, Appendix A.8) was written by a team of four authors. All authors contributed equally to the paper. Together with all co-authors, I conceptualized and co-developed the research project. Moreover, one co-author and I contributed primarily by developing the maturity model, conducting expert interviews and a focus group, and writing major parts of the text. The two other co-authors, beside aiding in the conceptualization, participated in research discussions, provided continuous feedback on the paper, helped in the artifact development, contributed to the theoretical framing, and acted as mentors.

Research Paper P8 entitled "Accelerating Decarbonization Digitally: Status Quo And Potentials Of Greenhouse Gas Emission Tracking And Trading" (Babel et al., 2024, Appendix A.9) was written by a team of four authors. Together with one co-author, I initiated and coordinated the research project. I also contributed substantially to the writing and conceptual development of the work. I authored the major share of the manuscript and collaborated mainly with one co-author on the paper's conceptual framing and revisions. Consequently, that co-author and I acted as the lead authors of the paper. The remaining two co-authors concentrated on supervising the project and giving continuous scientific feedback. Their contributions are therefore considered subordinate.

A.2 Research Paper P1: Digital Measuring, Reporting, and Verification (dMRV) for Decarbonization

Authors:

M.-F. Körner, C. Leinauer, T. Ströher, and J. Strüker

Published as:

Körner, M.-F., Leinauer, C., Ströher, T., & Strüker, J. (2025). Digital Measuring, Reporting, and Verification (dMRV) for Decarbonization. *Business & Information Systems Engineering*

Abstract:

Enterprises face growing regulatory and market pressure to achieve their sustainability objectives. A significant share of current efforts centers on carbon emissions data associated with the enterprise itself, its supply chain, or individual products. To effectively track and leverage carbon emissions and other sustainability data, robust MRV processes across various schemes and standards are essential. Beyond enabling compliance with auditing requirements, robust MRV processes can support competitive advantage, improved decision-making, and novel business models. MRV is particularly relevant in carbon markets, where it has a direct economic impact on incentivizing sustainable behavior. As recent scandals have demonstrated, however, current MRV practices face considerable challenges, especially regarding credibility. These challenges arise, among other factors, from the predominantly manual error-prone collection and processing of sustainability data. By leveraging a variety of digital solutions and emerging technologies, research in Business and Information Systems Engineering can address these challenges and establish a promising new research stream: digital Measuring, Reporting, and Verification (dMRV) for decarbonization.

Keywords:

Carbon emissions; Data ecosystems; Data sharing; Decarbonization; Digital measuring, reporting, and verification; ESG; MRV

A.3 Research Paper P2: Digital Carbon Accounting for Accelerating Decarbonization: Characteristics of IS-Enabled System Architectures

Authors:

M.-F. Körner, M. Schober, T. Ströher, and J. Strüker

Published as:

Körner, M.-F., Schober, M., Ströher, T., & Strüker, J. (2023). Digital Carbon Accounting for Accelerating Decarbonization: Characteristics of IS-Enabled System Architectures [Top 25% paper]. In *29th Americas Conference on Information Systems (AMCIS) 2023*. https://amcis2023.aisconferences.org/

Abstract:

To cope with climate change, an effective reduction of greenhouse gas (GHG) emissions is necessary. An acceleration of decarbonization still lacks an efficient way to precisely account GHG emissions. Recent literature acknowledges the role of Information Systems (IS) research, particularly Green IS, to contribute to decarbonization by enabling digital carbon accounting (CA). In this context, various scholars set out to design system architectures – often focusing on the energy sector due to its large potential for decarbonization. As research and practice lack a comprehensive overview (e.g., to develop standards), our work aims at reducing this identified gap by providing key characteristics of digital CA system architectures that we derive from an extensive, structured literature review and a consecutive deductive and descriptive approach. We argue that a stronger focus on both, user and identity management and interoperable registries, may be beneficial to foster digital CA.

Keywords:

Carbon Accounting; Decarbonization; Digital MRV; DLT; Green IS

A.4 Research Paper P3: Leveraging Large Language Models for Information Extraction

Authors:
F. Paetzold, T. Guggenberger, T. Jungk, D. Protschky, T. Ströher, and J. Strüker

Published as:
Paetzold, F., Guggenberger, T., Jungk, T., Protschky, D., Ströher, T., & Strüker, J. (2026). Leveraging Large Language Models for Information Extraction [Major Revision]. *Scientific Journal*

Extended Abstract:
Effective Project Risk Management (PRM) is essential for project success but remains challenging in increasingly complex and dynamic project environments (Willumsen et al., 2019). Empirical evidence consistently shows that a substantial share of projects fail to meet their original scope, time, or budget targets (Standish Group, 2020), and research indicates that managing risks in complex projects requires continuous attention to informal signals that conventional processes routinely overlook (Thamhain, 2013). While formal risk management processes typically rely on structured reports, workshops, and periodic reviews, early warning signals of emerging risks often originate in informal and unstructured communication channels such as emails, meeting notes, chat messages, issue trackers, and external reports (Afzal et al., 2021). These signals are frequently weak, fragmented, and distributed across heterogeneous information sources (Nikander & Eloranta, 2001; Williams et al., 2012). Moreover, they evolve over time and only become meaningful when interpreted in the context of a project's changing environment. As a result, a temporal detection gap emerges between the occurrence of risk-relevant information and its formal identification within project risk management processes (Baghizadeh et al., 2020).

Recent advances in Large Language Models (LLMs) have demonstrated substantial potential for extracting information from unstructured data (Dagdelen et al., 2024). However, existing approaches to Information Extraction (IE) are often designed for query-driven and episodic extraction scenarios and do not adequately address the continuous, context-dependent, and evolving nature of project risk identification. Furthermore, challenges such as hallucinations, limited transparency, and insufficient auditability restrict the applicability of LLMs in organizational decision-making contexts.

To address these limitations, this study investigates how LLMs can be leveraged for continuous, auditable, and adaptable information extraction in project risk management (Gregor & Hevner, 2013; Hevner et al., 2004; Peffers et al., 2007). Our study follows the Design Science Research (DSR) paradigm and combines literature analysis, expert involvement, artifact development, prototype implementation, and multi-stage evaluation. The problem space was initially explored through a review of literature on PRM, IE, LLMs, and multi-agent systems. Based on the identified challenges, five design objectives were derived and subsequently refined through semi-structured interviews with project management practitioners. An architecture for LLM-based information extraction was then designed and iteratively refined through an ex-ante focus group involving researchers from the fields of Information Systems and Artificial Intelligence. The resulting architecture was instantiated as a working prototype and evaluated through a combination of qualitative and quantitative ex-post evaluation activities involving both practitioners and researchers.

Our proposed architecture addresses the challenge of identifying emerging project risks from unstructured communication streams through a layered multi-agent design governed by two complementary mechanisms: an Information Flow that continuously transforms heterogeneous project communication into structured and evidence-linked risk indicators, and an Extraction Control Flow that manages prompts, configurations, schemas, thresholds, and project-specific contextual information. The architecture consists of four layers. The Input Layer ingests heterogeneous project information from sources such as emails, meeting minutes, issue trackers, and external reports, attaching metadata and provenance information from the beginning of the processing chain to support traceability (Afzal et al., 2021; Okudan et al., 2021). The Extraction Layer implements a collaborative multi-agent system in which an Orchestrator Agent classifies incoming documents and routes them to domain-specific Risk Agents, whose outputs are subsequently consolidated by an Aggregator Agent that reconciles findings across domains, removes duplicates, resolves inconsistencies, and identifies emerging risk patterns (Allmendinger et al., 2026). The Storage Layer maintains extracted indicators together with provenance information, prompt versions, configuration states, and execution histories to enable reproducibility and auditing. Finally, the Output Layer provides project managers with interfaces for inspecting extracted indicators, reviewing evidence, tracing decision paths, and adapting extraction configurations as project circumstances change.

Our architecture was evaluated using a combination of qualitative and quantitative methods (Venable et al., 2016). Practitioners consistently confirmed that relevant project risks frequently emerge in informal communication channels long before they appear in formal project documentation, and perceived the continuous ingestion and analysis capabilities of the architecture as particularly valuable. Experts highlighted the benefits of the domain-specialized multi-agent design for semantic precision and nuanced interpretation, and emphasized the importance of evidence linking, provenance tracking, and transparency mechanisms for building trust in LLM-generated outputs. The quantitative evaluation demonstrated that multi-agent approaches achieved higher extraction quality than simpler baselines; while these improvements required additional computational resources, practitioners considered the trade-off acceptable given the strategic importance of early risk identification and auditability.

Beyond the specific artifact, our study abstracts four transferable design principles: Domain-Specific Semantic Isolation, which recommends isolating semantically distinct domains through specialized agents to reduce interference and improve precision; Cross-Domain and Temporal Reconciliation, which calls for consolidating extracted information across domains, sources, and time to surface weak signals and emerging patterns (Rohrbeck et al., 2015); Contextual Alignment through Continuous Configuration Refinement, which enables organizations to continuously adapt extraction behavior to evolving project conditions (Baghizadeh et al., 2020); and

Versioned and Governed Provenance, which links all extraction results to evidence, prompts, configurations, and model versions to support transparency, reproducibility, and organizational accountability (Papagiannidis et al., 2025). Together, these principles provide guidance for designing LLM-based information extraction systems in environments characterized by heterogeneous information sources, evolving contexts, and high requirements regarding trustworthiness.

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Willumsen, P., Oehmen, J., Stingl, V., & Geraldi, J. (2019). Value creation through project risk management. *International Journal of Project Management*, *37*(5), 731–749. https://doi.org/10.1016/j.ijproman.2019.01.007

Keywords:
Design Science Research; GenAI; Information Extraction; Multi-Agent System; Project Management; Risk Identification

A.5 Research Paper P4: Systematizing Corporate Carbon Accounting from a Data Perspective to Enable CO2-Adaptive Decision-Making

Authors:
M.-F. Körner, F. Paetzold, T. Ströher, and J. Strüker

Published as:
Körner, M.-F., Paetzold, F., Ströher, T., & Strüker, J. (2026). Systematizing Corporate Carbon Accounting from a Data Perspective to Enable CO2-Adaptive Decision-Making [Submitted]. *Scientific Journal*

Extended Abstract:

Organizations face growing pressure to measure, manage, and disclose their greenhouse gas (GHG) emissions. This pressure arises from increasing stakeholder expectations as well as expanding regulatory requirements such as the CSRD and the Carbon Border Adjustment Mechanism (CBAM). Beyond regulatory compliance, carbon-related information is becoming increasingly relevant for managerial decision-making, investment planning, supply chain management, and corporate strategy (Abrams et al., 2021; Nguyen et al., 2023; San Ong et al., 2021). Despite the growing importance of corporate carbon accounting (CA), many organizations continue to rely on fragmented, manual, and error-prone processes for collecting and processing emissions data. These challenges are particularly pronounced in complex global supply chains, where emissions data often originate from multiple organizations, information systems, and geographical regions (Babel et al., 2024; Stechemesser & Guenther, 2012).

Recent advances in digital technologies, including AI, IoT, Distributed Ledger Technologies (DLTs), and Data Spaces, offer promising opportunities to improve data collection, verification, and reporting processes. However, existing research on carbon accounting primarily focuses on methodological, regulatory, or reporting-related aspects and lacks a systematic perspective on the underlying data structures required for digitally enabled carbon accounting (Körner et al., 2025; Ströher et al., 2025; Truant et al., 2024). To address this gap, this study investigates how corporate carbon accounting frameworks can be systematized from a data perspective to lay the foundation for enabling CO_2-adaptive decision-making.

The study combines a Systematic Literature Review (SLR), taxonomy development, and semi-structured expert interviews. Our SLR follows the methodology of Webster and Watson (2002) and analyzes corporate and supply-chain-related carbon accounting frameworks published between 2018 and 2025. Based on the resulting literature base, a taxonomy was developed following the taxonomy development method of Nickerson et al. (2013). To complement the literature-based findings, eleven semi-structured expert interviews were conducted with practitioners and researchers specializing in carbon accounting, sustainability reporting, and digital technologies.

The central contribution of this study is a taxonomy that systematizes corporate carbon account-

ing frameworks through a data-oriented lens. Unlike existing classifications that primarily focus on regulatory requirements or accounting methodologies, the proposed taxonomy emphasizes the underlying data structures, data flows, and information processing mechanisms required for effective carbon accounting. Our taxonomy is organized around three overarching levels: Counting, Accounting, and Accountability. Across these levels, twelve dimensions characterize carbon accounting frameworks from a data perspective, including data foundations, data collection approaches, accounting frequency, levels of analysis, scope coverage, reporting commitments, and auditing mechanisms.

The taxonomy reveals substantial heterogeneity among existing carbon accounting frameworks. One important observation is the growing shift from secondary-data-based approaches toward primary-data-driven accounting systems. While many organizations still rely heavily on emission factors and industry averages, emerging frameworks increasingly seek to integrate directly measured emissions data from operational processes and supply chain partners (Bausch et al., 2023; Comello et al., 2023; Xiang et al., 2024). Furthermore, accounting practices are evolving from periodic reporting mechanisms toward more dynamic and event-driven approaches, reflecting increasing demands for timely emissions information and supporting the integration of sustainability metrics into operational decision-making processes (Bausch et al., 2023; Eleftheriadis & Anagnostopoulou, 2024; Heiss et al., 2024). Our taxonomy also highlights the growing relevance of product-level accounting and lifecycle-based assessments, which complement traditional organization-level reporting by providing more granular emissions information across supply chains (Balduf et al., 2024; Kennelly et al., 2019).

Combining insights from the taxonomy and expert interviews, the study identifies three central challenges that currently limit the effectiveness of corporate carbon accounting. First, organizations frequently struggle to obtain accurate and timely emissions data, particularly for Scope 3 emissions, which often depend on information beyond organizational boundaries (Comello et al., 2023; Reichelstein, 2024; Ströher et al., 2025). Second, despite the widespread adoption of frameworks such as the GHG Protocol, organizations continue to apply different interpretations, calculation methods, and reporting practices, thereby reducing interoperability and comparability (Hoogerbrugge et al., 2023; Klaaßen & Stoll, 2021; Luo et al., 2024). Third, ensuring the credibility and reliability of carbon data remains challenging because validation and auditing mechanisms are often costly and difficult to scale (Guo, 2022; Reichelstein, 2024).

Our findings suggest that digital technologies can play a crucial role in addressing these challenges and advancing the maturity of corporate carbon accounting systems. IoT technologies can support automated collection of primary emissions data and enable more timely accounting processes. Distributed Ledger Technologies and Data Spaces can facilitate secure and verifiable sharing of emissions information across organizational boundaries, while Artificial Intelligence can assist organizations in managing large volumes of heterogeneous sustainability data and improving data quality (Babel et al., 2024; Baehr et al., 2024; Eleftheriadis & Anagnostopoulou, 2024; Heiss et al., 2024; Körner et al., 2025). Beyond individual technologies, our study emphasizes the importance of integrated digital ecosystems that combine technical infrastructures, governance mechanisms, and common data standards.

As carbon information becomes more granular, timely, and verifiable, organizations can increasingly integrate emissions metrics into management accounting systems. This enables carbon-related considerations to become part of budgeting, investment decisions, performance measurement, and operational planning (Arkhipova et al., 2024; Jassem & Abdelfattah, 2025). More broadly, carbon accounting is evolving from a compliance-oriented reporting function into a data-intensive management capability that supports continuous decision-making, organizational control, and cross-organizational governance.

This study contributes to research and practice by providing a structured taxonomy of corporate carbon accounting frameworks from a data perspective and by highlighting how digital technologies can support the development of reliable, interoperable, and decision-relevant carbon accounting systems. By linking carbon accounting, digitalization, and data governance, the study advances understanding of how organizations can leverage carbon data for more informed and adaptive decision-making.

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Keywords:

Corporate Carbon Accounting; Digital Measuring, Reporting, and Verification; Green IS; Emerging Economies; Systematic Literature Review; Taxonomy

A.6 Research Paper P5: Bridging Carbon Data's Organizational Boundaries: Toward Automated Data Sharing in Sustainable Supply Chains

Authors:
T. Ströher, M.-F. Körner, F. Paetzold, and J. Strüker

Published as:
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Abstract:
The accounting of greenhouse gas (GHG) emissions is seen as an essential element to mitigate global climate change. Robust "carbon accounting" (CA) is supposed to enable the quantification of GHG emissions and identification of reduction potential, thereby enabling CO2-adaptive decision-making for various stakeholders, including organizations and end-users. In this regard, digital technologies can not only improve the efficiency and accuracy of CA in various ways, but also support the effective sharing of carbon data along supply chains. However, the current use of digital technologies in CA practices is often limited to an intra-organizational perspective. Extending the application of digital technologies for automated data sharing beyond organizational boundaries appears promising for addressing supply chain emissions accounting and potentially closing today's huge Scope 3 emissions accounting gap. This is especially relevant since upstream Scope 3 emissions can cause up to 80% of the total GHG emissions for most manufacturing industries. Furthermore, automated data sharing beyond organizational boundaries can provide the necessary foundation for fostering automation in supply chain management based on sustainability metrics. In this paper, we provide a comprehensive framework for automated data sharing in supply chains to support CA within and beyond organizations' boundaries. Our findings suggest that the use of a combination of digital technologies can not only strengthen CA practices within organizations and their supply chain, but also foster the development of digital supply chain ecosystems, allowing automated sharing of data for a plethora of use cases.

Keywords:
Carbon accounting; Data sharing; Digital decarbonization; Grounded theory; Supply chain automation; Sustainable supply chain

A.7 Research Paper P6: From Papers to Power Plants: A Taxonomy of Power Flow Tracing Methods in Research and Practice

Authors:
T. Ströher, J. Strüker, and V. Konoval

Published as:
Ströher, T., Strüker, J., & Konoval, V. (2026). From Papers to Power Plants: A Taxonomy of Power Flow Tracing Methods in Research and Practice. *Bayreuth Reports on Information Systems Management*

Abstract:
Power flow tracing (PFT) methods algorithmically reconstruct how electricity generators supply specific loads and contribute to network losses, enabling physically grounded attribution of electricity flows across a grid. Despite nearly three decades of research, the field lacks a unified conceptual framework that integrates academic and industry perspectives. In this paper, we address this gap by conducting a multivocal literature review (MLR) covering 52 academic and industry sources published between 2019 and 2025, and developing a taxonomy of PFT methods structured along six dimensions and 20 characteristics: input, output, tracing approach, application area, topology model, and level of analysis. Our analysis reveals that linear-equation-based methods embodying the proportional sharing principle dominate both academic and practitioner contexts, and that emissions attribution and renewable energy certification have emerged as the primary application areas, primarily driven by tightening sustainability reporting requirements. While PFT methodologies themselves exhibit considerable maturity, we find that limited data availability, granularity, and quality represent the central barrier to broader practical adoption. We discuss how digital technologies can support the measuring, reporting, and verification of electricity data to overcome these barriers, and propose a research agenda from a data perspective. Our taxonomy supports policymakers and grid operators in selecting suitable PFT methods for regulatory, technical, and operational contexts.

Keywords:
Electricity Pricing; Grid Management; Guarantees of Origin; MRV; Multivocal Literature Review; Power Flow Tracing; Scope 2 Emissions; Taxonomy

A.8 Research Paper P7: Quality Check for Lemons: A Voluntary Carbon Market Maturity Model (VCM^3)

Authors:

M.-F. Körner, C. Leinauer, T. Ströher, and J. Strüker

Published as:

Körner, M.-F., Leinauer, C., Ströher, T., & Strüker, J. (2026). Quality Check for Lemons: A Voluntary Carbon Market Maturity Model (VCM^3) [Prepared for Submission]. *Scientific Journal*

Extended Abstract:

Voluntary Carbon Markets (VCMs) have become an increasingly important instrument for organizations and individuals seeking to compensate unavoidable greenhouse gas emissions and contribute to global decarbonization efforts. Driven by growing net-zero commitments and sustainability targets, demand for carbon credits has increased substantially in recent years (Diamond & Kuan, 2024; Leinauer et al., 2024). Carbon credits traded on VCMs typically originate from projects such as afforestation, reforestation, regenerative agriculture, or carbon removal initiatives.

Despite their growing relevance, contemporary VCMs face significant challenges. Repeated controversies regarding the environmental integrity of carbon credits have raised concerns about transparency, credibility, and market effectiveness (Greenfield, 2023). Many of these challenges can be explained through Akerlof's concept of the "market for lemons" (Akerlof, 1970). Buyers often lack sufficient information to distinguish high-quality from low-quality carbon credits, creating information asymmetries that can result in adverse selection, declining trust, and ultimately market failure. Recent research increasingly addresses these challenges and discusses both governance-related and technological approaches for improving VCMs (Delacote et al., 2024; Kreibich & Hermwille, 2021; Miltenberger et al., 2021; Wongpiyabovorn et al., 2023). Digital technologies such as Distributed Ledger Technologies (DLTs), Artificial Intelligence, Remote Sensing, and Internet of Things technologies have been proposed as potential enablers of more transparent and trustworthy market infrastructures (Körner et al., 2025; Pan et al., 2022; van Dam et al., 2024; Vilkov & Tian, 2023). However, existing contributions typically focus on individual market problems rather than providing a holistic conceptualization of what constitutes a mature and well-functioning voluntary carbon market.

To address this gap, this study develops a Voluntary Carbon Market Maturity Model (VCM^3) and investigates how the maturity of Voluntary Carbon Markets (VCMs) can be systematically assessed. The objective is to provide researchers and practitioners with a structured framework for evaluating current market maturity, identifying development priorities, and supporting the design of more credible and effective carbon markets.

Our study follows a Design Science Research approach and applies the maturity model development methodology proposed by Becker et al. (2009). Maturity models are established artifacts for assessing the current state of complex systems and identifying pathways for systematic improve-

ment (Mettler & Ballester, 2021). Our development process consisted of a systematic literature review following Webster and Watson (2002), nine semi-structured expert interviews, a focus group evaluation, and an exemplary application of the resulting artifact. Our literature review covered major interdisciplinary databases and focused on challenges, capabilities, opportunities, and improvement mechanisms related to VCMs. Insights from scientific literature were iteratively refined and validated through expert involvement to ensure both theoretical rigor and practical relevance.

Our resulting VCM^3 conceptualizes the maturity of VCMs through eight interrelated capabilities and five maturity levels ranging from *Non or Minimal* to *Maximal* maturity. The eight capabilities are Emissions Impact, Robust Assessment, Effective MRV Processes, Transparency, Market Design, Knowledge Management, Governance, and Coherence with Other Sustainability Dimensions. These capabilities are operationalized through 30 sub-dimensions that collectively capture the essential characteristics of a well-functioning voluntary carbon market. Unlike many maturity models that produce a single aggregated score, the VCM^3 allows for differentiated maturity profiles across capabilities, thereby enabling more targeted assessments and development strategies (Breiter et al., 2024).

The evaluation highlights several important findings. First, the capabilities are highly interdependent. Weaknesses in one area frequently reinforce weaknesses in others, particularly with regard to the relationship between environmental integrity, assessment methodologies, and MRV processes. Second, transparency emerged as one of the most critical bottlenecks limiting market maturity. Experts repeatedly emphasized that fragmented registries, opaque pricing mechanisms, and limited public access to information increase transaction costs and reinforce information asymmetries, thereby contributing to adverse selection and reduced market confidence. Third, governance structures play a crucial role in determining whether market participants can establish and maintain trust in carbon credits and associated market institutions.

Our study further indicates that digital technologies can contribute to increasing maturity across multiple capabilities simultaneously. Technologies such as satellite-based remote sensing, IoT sensor networks, artificial intelligence, and distributed ledger technologies can improve measuring, reporting, and verification as well as transparency and traceability (Körner et al., 2025; Pan et al., 2022; van Dam et al., 2024; Vilkov & Tian, 2023). However, experts also emphasized that technology alone cannot resolve existing market deficiencies. Digital solutions are most effective when they address clearly identified maturity deficits and are complemented by appropriate governance mechanisms and institutional reforms (Kotsialou et al., 2022; Stanley, 2024).

This study contributes to both research and practice by providing a structured conceptualization of voluntary carbon market maturity. The VCM^3 integrates macroeconomic and microeconomic perspectives on market functioning and offers a practical instrument for assessing current market conditions and identifying targeted improvement measures. By making the multidimensional nature of market maturity explicit, the model supports researchers, policymakers, standard setters, platform operators, and market participants in developing more transparent, credible, and effective voluntary carbon markets.

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Keywords:
Capabilities; Digital Decarbonization; Maturity Model; Voluntary Carbon Markets

A.9 Research Paper P8: Accelerating Decarbonization Digitally: Status Quo And Potentials Of Greenhouse Gas Emission Tracking And Trading

Authors:
M. Babel, M.-F. Körner, T. Ströher, and J. Strüker

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Abstract:
To effectively mitigate climate change, policymakers worldwide established various GHG tracking and trading systems. In the light of ambitious climate goals, stricter regulations, and increasing demand for climate action, various groups such as researchers and governmental institutions suggested additional approaches. This paper addresses the complexity that arises from the breadth of suggested approaches and implemented systems for GHG tracking and trading. By doing so, it synthesizes relevant dimensions in a way that is understandable to enterprises and policymakers, enabling them to design meaningful systems incorporating the reduction of GHG emissions and advance cleaner production. Therefore, this paper presents a first-of-its-kind taxonomy of GHG tracking and trading approaches through a systematic literature review. It illustrates ten main design and implementation dimensions with 30 corresponding characteristics. To accelerate decarbonization, this paper sets impulses for future GHG tracking in the electricity sector based on semi-structured expert interviews. Consecutively, it provides policy directions for CO2-adaptive decision-making for enterprises, formulated as a Call for Action with seven prospective questions. These include, for example, questions concerning technical aspects like data management, legal issues like the sufficiency of existing data security and privacy regulations, as well as economic topics like the calculation of an appropriate local and temporal granularity.

Keywords:
Decarbonization; Emissions; Greenhouse gas; Taxonomy; Tracking; Trading