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

Completed Research Full Paper

Marc-Fabian Körner
Fraunhofer FIT, Germany
University of Bayreuth, Germany
marc-fabian.koerner@fit.fraunhofer.de

Marcus Schober
FIM Research Center, University of Bayreuth, Germany
marcus.schober@fim-rc.de

Tobias Ströher
FIM Research Center, University of Bayreuth, Germany
tobias.stroeher@fim-rc.de

Jens Strüker
Fraunhofer FIT, Germany
University of Bayreuth, Germany
jens.strueker@fit.fraunhofer.de

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

Introduction

Designing and implementing approaches for a more sustainable future and mitigating the impacts of global climate change by accelerating decarbonization (i.e., an effective reduction of greenhouse gas (GHG) emissions) is the societal and moral imperative of our time. While tackling this imperative is an interdisciplinary task, literature widely recognizes the critical role of Information Systems (IS), especially the role of Green IS, and digitalization for a sustainable future and for accelerating decarbonization (Melville 2010; Strüker et al. 2021b). As a majority of global emissions is related to the energy sector, causing 36,3 Gt of CO2 in 2021 (IEA 2022), decarbonizing our energy systems is a highly relevant task – which a plethora of related research from the Green IS community illustrates, see, for example, Fridgen et al. (2021), Watson et al. (2010), and Watson et al. (2022). Thereby, scholars have already made enormous and interdisciplinary contributions to decarbonization by elaborating on solutions that cope with current challenges of the energy sector, which increasingly relies on renewable energy sources, for example, by supporting grid stability in times of increasingly fluctuating electricity generation (Bjørndal et al. 2023; Fridgen et al. 2022; Hanny et al. 2022; Watson et al. 2022). Nevertheless, with an eye on carbon emissions related to the energy sector, we still need to find solutions that enable and accelerate purposeful decarbonization in this sector.

Policy recognized and addressed this need already decades ago (e.g., by implementing Emissions Trading Systems (ETSs), concrete emissions reduction plans following the Clean Development Mechanism, or Guarantees of Origin for “green” electricity). Existing approaches often include a market for trading respective rights or certificates that a variety of stakeholders can use (e.g., for compliance (reporting) or to voluntarily offset their emissions). While these approaches already represent effective tools against climate change, they often work with estimated or averages ex-post values for the accounting of specific carbon emissions – highlighting the need for improving and accelerating existing solutions (Körner and Strüker), cf. the recent scandal concerning the emissions label company Verra (Greenfield 2023). Hence, scholars from the Green IS community have only recently recognized the need to improve decarbonization, specifically through digital solutions such as more precise and verifiable accounting of emissions, avoidance of carbon leakage, and providing transparency for end-users, often with a focus on the energy sector (Babel et al. 2022; Müller et al. 2023; Zampou et al. 2022). Currently, enterprises are facing pressure from three sides that demand for better solutions regarding carbon accounting (CA) (Müller et al. 2023): First, the share of consumers that demands for insights into the GHG emissions related to products and services rises. Second, different regulations, like the European Carbon Border Adjustment Mechanism or the recently passed German supply chain law, demand for precise and fine-granular tracking of carbon emissions related to products and services Third, corporate as well as private investors are shifting towards “green” investments (e.g., based on ESG criteria (Amel-Zadeh and Serafeim 2018)) – asking for a trustworthy CA.

To enable an efficient way to manage the increasingly tremendous amount of correspondingly necessary emission data, both researchers and practitioners suggested various, yet specific, digital system architectures for CA (hereafter: CA architectures), predominantly focusing on the energy sector. These architectures, which often use digital technologies like distributed ledger technologies (DLTs), possess several shared characteristics that serve as the foundation for the implementation of digital CA. To the best of our knowledge, literature lacks a comprehensive overview of CA architectures and their key characteristics. Hence, this research paper aims at developing a deeper understanding of the subject and at providing a strong basis for further research in this area by answering the following question:

What are key characteristics of digital carbon accounting system architectures in the energy sector?

To answer our research question, we derive these characteristics in a deductive and descriptive way based on an extensive, structured literature review including an initial set of 1312 research items following the approach of Webster and Watson (2002). Our results highlight the crucial features of CA architectures and acknowledge that current research has made a significant contribution by emphasizing the automation of data flows, integration, and interoperability. According to our findings, we suggest a stronger focus on digital machine identity management and setting up digital master data registries to enable a more fine-granular and verifiable data basis for improving digital CA. We contribute to the body of knowledge by providing an overview of existing architectures as well as their current areas of focus as a basis for deriving potentials for future research on digital CA.

The remainder of this paper is structured as follows: In Section 2, we provide an overview of related research streams and corresponding literature. In Section 3, we explain our methodological approach and the procedure while Section 4 presents our findings, including five key characteristics for CA architectures. In Section 5, we discuss our results and outline our contributions. Lastly, we discuss the limitations of our work and conclude in Section 6.

Background and Related Literature

To provide an overview of related literature and of the background relevant to our paper, we briefly introduce corresponding work and research streams in the following.

Green Information Systems and Energy Informatics

The research streams on Energy Informatics and Green Information Systems (IS) share large thematic overlaps and are considered to be highly interdisciplinary (Staudt et al. 2019; Watson et al. 2010). In general, Green IS research analyzes, designs, and models digital solutions for a sustainable future (Melville 2010; Patel et al. 2019). The range of Green IS literature is wide and includes a variety of applications, for example, in sustainable logistics and supply chain management (Choi et al. 2019; Reefke and Sundaram

2018), in the mobility sector (Ketter et al. 2022), in the energy sector (Fridgen et al. 2021), for a circular economy (Zeiss et al. 2021), or for environmental collaboration (Aoun et al. 2011). Recently, Green IS scholars increasingly drew attention on the need for accelerating the reduction of GHG emissions (Müller et al. 2023; Preukschat et al. 2021; Seidel et al. 2017; Tito et al. 2021; Zampou et al. 2022).

Against this background, a variety of research focuses on the technical implementation of digital carbon credits or similar digital assets like proofs of origin or renewable energy credits. Literature already addresses the need for digital credit schemes that, for example, provide more transparency and traceability for organizations (see, for example, Chakraborty et al. (2022)) and end-users (see, for example, Rosado da Cruz et al. (2020)) or address regulatory issues like privacy (see, for example, Babel et al. (2022)). Green IS also elaborates on the potentials of digital technologies in carbon markets for better identity management as well as rising efficiency, (e.g., through automated transactions in carbon trading via smart contracts, see, for example, Li et al. (2021)). Green IS furthermore emphasizes the need for architectures and frameworks in this area, see, for example, Ning et al. (2022) for electricity trading or Al Sadawi et al. (2021) for emission trading.

Carbon Accounting and Digital Measurement, Reporting, and Verification

Policymakers around the world established various guidelines for decarbonization across various areas and sectors, for example, the Kyoto Protocol and the Paris Agreement (UNFCCC 1997, 2015). Policymakers implemented these two frameworks via different (sub-) national and international laws and policies, such as various ETSs, and respective regulations for CA. GHG accounting or CA can be defined as "the recognition, the non-monetary and monetary evaluation and the monitoring of greenhouse gas emissions on all levels of the value chain and the recognition, evaluation and monitoring of the effects of these emissions" (Stechemesser and Guenther 2012). CA appears on different scales where correspondingly different standards apply (Damsø et al. 2016; Stechemesser and Guenther 2012): On the territorial scale, CA includes all emissions within a specific geographic area, such as a country. In this case, the relevant standard would be the guidelines for national GHG inventories of the International Panel on Climate Change (IPCC) (IPCC 2019). Entity scale CA refers to emissions related to entities like companies or organizations (Damsø et al. 2016). The GHG protocol provides the most widely used standards on this scale. GHG accounting on project scale includes the emissions of specific projects (e.g., for emissions offsetting) (Damsø et al. 2016). The relevant standards here differ according to the markets. In compliance markets, the Clean Development Mechanism of the Kyoto protocol sets the boundaries. In voluntary carbon markets, participants can use various standards.

CA is often associated with monitoring, reporting, and verification (MRV) (Körner and Strüker; Woo et al. 2020). In this context, *monitoring* refers to the measurement or estimation of GHG emissions and *reporting* includes the aggregation, recording, and reporting of GHG emissions to authorities, while *verification* means a third-party assessment of compliance according to specific guidelines (Bellassen and Stephan 2015). Hence, we note that there is a difference between accounting and MRV. However, since the two terms are closely related and not always strictly separated in literature, we include papers focusing on both, CA and MRV, in our literature review.

Distributed Ledger Technologies and Blockchain

As we outline in the following, all papers that result from our literature review discuss at least once blockchain (BC) technology or related distributed ledger technologies (DLTs). Accordingly, we give a very brief overview of the relevant details in this paragraph: BC technology does not rely on an intermediary to manage and share data or transactions. Instead, it uses a network of nodes that work together to verify and record information. BCs represent a distributed ledger that can record transactions securely and transparently. The specific data on the BC is encrypted and once saved it cannot be changed or deleted. BC has many use-cases, from digital currency to supply chain management and authentication in the energy sector (Körner et al. 2022; Nakamoto 2008). As literature illustrates, BC and other DLTs are considered a key enabler of sharing and managing sensitive data in digital ecosystems in the context of CA. While centralized systems represent a single point of failure, the use of cryptographic algorithms in decentralized systems such as DLTs may provide additional security (Beck et al. 2018). Hence, they may offer a solution for building a secure, transparent, and collaborative platform and a way to increase data security and trust.

The brief overview of related literature results in three key conclusions: First, as the multiplicity of current literature on CA in the Green IS and Energy Informatics community indicates, IS research can and should further contribute to this topic. Second, CA is a highly interdisciplinary field, bringing together experts from various communities, such as business sciences, policy, finance, and IS. Third, despite the considerable body of research in this field, a significant research gap remains, as there is no comprehensive overview of system architectures for CA and their respective key characteristics. This research gap highlights the need for further investigation in this area, which is the primary focus of our study.

Methodological Approach

The aim of our paper is to present key characteristics of current CA architectures. To achieve this, we first perform an extensive, structured literature review. Subsequently, we extract their corresponding key characteristics in a deductive and descriptive way. To perform a structured literature review and find relevant research papers in a comprehensive and holistic way, we follow the well-known concept of Webster and Watson (2002). Considering the interdisciplinarity of CA, we conduct the initial search in various databases, especially covering environmental, economic, and IS topics (cf. Table 1). We search for the string *(digital OR data OR cloud) AND (architecture OR ecosystem) AND (GHG OR "greenhouse gas" OR carbon OR CO2 OR emission) AND (account OR trac* OR trad* OR market)* in the abstract search in the Association for Computing Machinery (ACM) Digital Library, Association for Information Systems (AIS) eLibrary, Business Source Premier (BSP), Econbiz (EB), Institute of Electrical and Electronic Engineers (IEEE) Xplore Digital Library, JSTOR, Web of Science (WoS) Core Collection, and Wiley Online Library. In ScienceDirect (SD), only a maximum of eight Booleans (AND, OR, NOT), no wildcards (*), and no dedicated abstract search are supported. Hence, we search for *(architecture OR ecosystem) AND (carbon OR emission) AND (account OR track) AND (digital OR data OR cloud)* in the title, abstract, and keywords. Across all ten databases, we limit our search to literature published from 2018 to 2023 due to the rapid development of the subject of digital architectures for CA. After seeking out non-English and non-accessible literature, we sort out hits by consecutively performing a title, abstract, and full-text screening (cf. Table 1).

	ACM	AIS	BSP	EB	EI	IEEE	JSTOR	SD*	WoS	Wiley	Σ
Filters	a), b)	a), c)	a), b), d)	a), d), e)	a), e)	a), b), e)	a)	a), b), d)	a), b), d), e)	d)	-
Initial	10	3	4	2	0	88	11	91	999	104	1312
Title	4	0	1	0	0	40	0	8	67	2	122
Abstract	2	0	0	0	0	22	0	6	22	1	53
Full text	1	0	0	0	0	6	0	1	0	0	**8**
Backward	-	-	-	-	-	-	-	-	-	-	**11**
Forward	-	-	-	-	-	-	-	-	-	-	**9**
Final											**28**

a) Journal Articles b) Conference Articles/Proceedings c) Peer-Reviewed d) Full Text Access e) Working Papers/Early Access

Table 1. Structured literature review

Following Webster and Watson (2002), we then search backwards in literature by analyzing the bibliography of the eight relevant hits from the initial search. Afterwards, we perform a forward search to find literature that cited the research papers that we consider relevant in the initial and backward search. After sorting out duplicates, our structured literature review results in 28 distinct research papers about CA architectures within the energy context.

After performing an extensive literature review, we apply a deductive and descriptive approach. To do so, we follow the deductive method as described by Gibbs (2006), where, "a particular situation is explained by deduction from a general statement about the circumstances". Deductive and descriptive approaches are widely used in IS research, see, for example, Azzouz and Sambasivam (2019) or Fominykh et al. (2016). In line with Gibbs (2006), we start with theories and concepts that we examine. Also – as Gibbs (2006) suggests – we use the deductive method in tandem with data collection, in our case via an extensive, structured literature review. We then cluster our data to derive our characteristics and describe our results.

Results

This research paper aims to derive key characteristics of CA architectures entailed in current literature to provide an overview and guidance for both, scholars and practitioners (cf. also Table 2 below).

Integration and Interoperability

The first characteristic that we derive from the current literature is the need for interoperability of CA architectures (Mandaroux et al. 2021; Schletz et al. 2020). The literature considers interoperability as the ability of architectures to be integrated into existing infrastructures. An infrastructure can be defined as "all elements of interrelated systems that provide goods and services essential to enabling, sustaining or enhancing societal living conditions" (Da Silva and Wheeler 2017). In the case of CA, especially the integration into existing environmental policies (e.g., EU ETS), markets (e.g., for carbon credits), and systems (e.g., ERP-systems) is necessary for the establishment of digital architecture (Ito et al. 2022; Khaqqi et al. 2018; Schletz et al. 2020; Wang et al. 2021; Yang et al. 2021). Hence, scholars emphasize the need for CA architectures for interoperability to achieve the integration in existing infrastructures (Mandaroux et al. 2021; Schletz et al. 2020; Shokri et al. 2022). While IEEE (1991) defines interoperability as "the ability of two or more systems or components to exchange information and to use the information that has been exchanged", researchers point out that – for interoperability in digital CA –new systems (e.g., based on DLT) must not only be interoperable with other new systems, but also with legacy systems (Mandaroux et al. 2021). Schletz et al. (2020), for example, propose a platform that aggregates and harmonizes data from existing data sources and accounting platforms to achieve an interoperable network.

Automation of Data Flows

The second characteristic that we find is the automated handling and verification of data. Thereby, scholars focus on various aspects regarding data flows, such as data security (Ito et al. 2022; Yang et al. 2021), transparency (Sipthorpe et al. 2022), and storage (especially regarding big data) (Ju et al. 2022; Yang et al. 2021), as well as transaction management (e.g., enabling real-time transactions) (Hu et al. 2022). There are also approaches to obtain data in a more precise and automated way in the first place: Here, Wang et al. (2021), for example, mention the usage of sensor data, Schletz et al. (2020) satellite monitoring, and Babel et al. (2022) smart meters. Sensor data can be collected over the Internet of Things and may be recorded on a BC (Babel et al. 2023; Wang et al. 2021). Ideas also include the establishment of an international data ecosystem: Ito et al. (2022) suggest using GAIA-X (a project that aims to establish a trustworthy data infrastructure for Europe) as a data sharing platform in this context. We note that the automation of data flows is among the most discussed characteristics in the literature that we analyzed. Concerning the communication and sharing of data between entities, the respective network structure is responsible for the communication of the nodes with each other via specific propagation protocols and data verification mechanisms, not only within, but also between different entities, such as enterprises (Zhao et al. 2022). Thereby, we note that the approaches in our literature review often suggest the use of peer-to-peer networks, which do not need intermediaries, possibly resulting in cost reductions (Mandaroux et al. 2021).

Measurement, Reporting, and Verification of Emissions Data

Building on the automation of data flows, the literature acknowledges that CA architectures should be able to measure, report, and verify emissions data. MRV refers – in accordance with our definition in this work (cf. Section 2) – to the actual accounting parts of a respective architecture. Regarding the measurement of emissions, scholars mainly propose BC technology due to its feature of being non-modifiable, and therefore, representing a trustworthy, transparent system (Kim and Huh 2020). The presentation of data in the context of MRV is defined as reporting, for which researchers also propose the use of BC technology due to high transparency, tamper-resistance, and interoperability with other systems without a third-party intermediary (Khaqqi et al. 2018). Our literature review illustrates that scholars widely agree that a CA architecture needs a verification method that is transparent and trustworthy. To achieve this, multiple researchers suggest the use of machine learning for the verification of data from independent data sources (Schletz et al. 2020) – also in combination with a BC ecosystem (Babel et al. 2022; Kim and Huh 2020).

Identity and User Management

While only three of the research papers that we find in our extensive, structured literature review focus on identity management, they emphasize its pivotal relevance by highlighting this aspect as a central part of their architectures (Babel et al. 2022; Golding et al. 2022; Li et al. 2021). Here, identity management refers to the handling of personal data and identities of users and machines to gain access to specific services in a system (Bernal Bernabe et al. 2017). Researchers point out that a proper authentication of entities is a key issue for CA architectures (Chakraborty et al. 2022). Hence, CA architectures need proper channels, applications, and user services (i.e., user management). Scholars suggest the use of wallets – which exist in both, BC and Self-Sovereign Identity (SSI) approaches – for users to easily access the system and, for example, to see their emissions on their mobile devices (Chakraborty et al. 2022). Woo et al. (2020), for example, use the Hyperledger Fabric BC platform since it allows the network starters to choose a consensus mechanism that represents the relationships between different participants.

Governance

Finally, governance represents a key characteristic for CA architectures. It can be defined as “a generic term for the actions of all decision-making processes that create, update, and discard the formal and informal rules of a system” (Kim and Huh 2020). Also for questions concerning governance, scholars propose BC technology (Al Sadawi et al. 2021). BC may adapt the governance of an architecture in such a way that there is no central authority that inherits all decision-making power, but a decentralized governance where the participants control the system together (Al Sadawi et al. 2021). BC governance, however, faces various challenges, such as privacy, scalability, and slow speed (Kim and Huh 2020). Therefore, scholars reach out to overcome this challenge, see, for example, Babel et al. (2022), who use so-called Zero-Knowledge Proofs to cope with privacy issues, or Kim and Huh (2020), who provide a hybrid governance protocol.

#	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 for 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 monitoring, 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 in combination with 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 distinct.	Al Sadawi et al. (2021), Babel et al. (2022), Kim and Huh (2020)

Table 2. Key characteristics of digital carbon accounting system architectures

Discussion and Contribution

We first briefly discuss our findings and present the contribution of our study (i.e., we contribute to a deeper understanding of digital CA that leads to the further development of research for and implementation of corresponding CA architectures).

First, our findings illustrate that CA is a relevant topic to IS research. We identify five key characteristics that lay the foundation for CA systems and their underlying architectures. We note that all papers mention

BC technology at least once. The reason for this widespread focus on BC may be the various features of BCs that the authors describe in their research papers (e.g., transparency, traceability, anonymity, and immutability) and that may foster the verifiability of carbon emission data flows. Further, two of the most central aspects in the context of digital CA architectures evident from the literature are the integration and interoperability as well as the automation of data flows. In this context, the literature acknowledges that it is necessary to provide a data structure that is tamper-resistant and transparent.

Moreover, based on our findings, we recommend that research should continue to delve more deeply into identity management in the context of CA (resp. MRV in general) as existing literature points out the necessity of digital identification processes that protect privacy and competition-relevant data and credentials while ensuring verifiability at the same time. Approaches from the SSI context may provide one possibility to cope with the need for privacy: The basic principle of SSI is the trust triangle, in which the relationships of the involved parties are represented (Lacity and Carmel 2022; Strüker et al. 2021a). SSI approaches may allow individuals to control their digital assets and personal data instead of relying on central authorities, like governments or service providers. Additionally, SSI enables security of (privacy-preserving) data and allows individuals to share (a part) of their identity data with third parties when necessary. SSI can provide digital identities for machines or organizations, which is a central aspect of digital CA, as researchers already acknowledge (e.g., in the context of green electricity tracking) (Babel et al. 2022; Sedlmeir et al. 2022).

Regarding the contribution of our findings, our key characteristics advance the scholarly and practical development of CA architectures and may help to create standards as a basis for a uniform system by providing a sound basis for interdisciplinary research. Furthermore, the implementation of such CA architectures may also provide benefits for enterprises seeking to improve their environmental performance and strengthen their corporate social responsibility profile. Especially for programs like the Carbon Border Adjustment Mechanism of the EU, verifiability and interoperability play an important role. Based on our results, we also note that the creation of digital data registries can enhance the overall development and performance of CA by verifying master as well as transaction data for integrating this data in a data ecosystem. Such an ecosystem may provide a solution for sharing verified data between companies for a more precise CA system in highly interwoven and international supply chains. A possible way to achieve cross-organizational data sharing is specifically found in interactions with data spaces: Scholars currently analyze data spaces at national and international level within the context of various research projects in different sectors, especially for managing and sharing of data (Otto et al. 2022). To ensure tamper-evident and more trustworthy (i.e., verifiable) data within data ecosystems, SSI-based identity management may also be, among other technologies, a promising approach.

Conclusion, Limitations, and Outlook

In order to cope with climate change and the associated social, economic, and environmental risks, it is necessary that emissions are reduced and – in order to do so – precisely accounted in all relevant sectors. Due to its high emissions and reduction potentials, the energy sector may be the key to enable an effective decarbonization. Against this background, various policymakers, researchers, and organizations contributed to CA with different ideas and solutions for respective CA architectures, so far. While these contributions are highly valuable, they are often rather case-specific, and hence, do not comprehensively address all relevant aspects for a CA architecture. Therefore, we perform a structured literature review on digital CA architectures, based on which we derive five key characteristics using a deductive and descriptive approach. In total, we derive five key characteristics for CA architectures: Integration and interoperability, automation of data flows, MRV of emissions data, identity and user management, and governance. We find that scholars set a strong focus on the former two – pointing out the advantages of BC and related technologies in this area (e.g., transparency and tamper-resistance), while we find literature focusing on identity and user management to be rather scarce. Furthermore, current literature (implicitly and explicitly) strongly emphasizes the importance of an automated and digital data collection process, especially in the context of MRV, for enabling an improved data quality, and finally, a more precise accounting that is needed to accelerate decarbonization. We conclude that improving digital identity management, digital registries, and data ecosystems for cross-organizational data sharing may enhance a verifiable CA.

Our research is, of course, subject to several limitations due to the methods that we use as well as due to the community background of the authors. First, with our focus on CA architectures in the literature review, we set some boundaries. Our research only contributes to a specific part of the overall research landscape of CA and should be viewed in the overall context of literature coping with deep decarbonization. Second, we derive the key characteristics based on a deductive, descriptive procedure. Therefore, these characteristics stem from the ideas of current approaches in research. This means that this work merges current considerations rather than providing entirely new ones. Moreover, our literature review focusses on the energy sector as the sector with a significant potential for further carbon emissions reduction.

Thereby, this work provides a sound basis for future research. Scholars may evaluate our derived characteristics, for example, by including knowledge from practitioners in the field of CA. Furthermore, researchers may follow the recommendation we make in this work by further evaluating digital identity management, digital registries, and data ecosystems in the context of CA. Future research may also elaborate on the role of and options for cross-organizational data sharing that is highly relevant for CA along supply chains. In addition, we also note that scholars may consider the relationship between a verifiable CA and climate-related financial disclosures which we find to be highly relevant – especially with an eye to current regulation.

Acknowledgements

We gratefully acknowledge the financial support of the project "ID-Ideal" (Grant-Number: 01MN21001l) by the Federal Ministry for Economic Affairs and Climate Action (BMWK) and the project supervision by the project management organization DLR.

References

Al Sadawi, A., Madani, B., Saboor, S., Ndiaye, M., and Abu-Lebdeh, G. 2021. "A comprehensive hierarchical blockchain system for carbon emission trading utilizing blockchain of things and smart contract". *Technological Forecasting and Social Change* (173), pp. 121-124.

Amel-Zadeh, A., and Serafeim, G. 2018. "Why and How Investors Use ESG Information: Evidence from a Global Survey". *Financial Analysts Journal* (74:3), pp. 87-103.

Aoun, C., Vatanasakdakul, S., and Bunker, D. 2011. "From Cloud to Green: E-Collaboration for Environmental Conservation" in *Proceedings of the IEEE Ninth International Conference on Dependable, Autonomic and Secure Computing*.

Azzouz, A., and Sambasivam, S. 2019. "Strategies Needed by Social Network Builders to Develop Information Privacy" in *Proceedings of the Conference on Information Systems Applied Research*.

Babel, M., Gramlich, V., Guthmann, C., Schober, M., Körner, M.-F., and Strüker, J. 2023. "Trust through Digital Identification: On SSI's Contribution to the Integration of Decentralized Oracles in Information Systems". *HMD Praxis der Wirtschaftsinformatik* (60:2), pp. 478-493.

Babel, M., Gramlich, V., Körner, M.-F., Sedlmeir, J., Strüker, J., and Zwede, T. 2022. "Enabling End-To-End Digital Carbon Emission Tracing With Shielded NFTs". *Energy Informatics* (5).

Beck, R., Mueller-Bloch, C., and King, J. 2018. "Governance in the Blockchain Economy: A Framework and Research Agenda". *Journal of the Association for Information Systems* (19), pp. 1020-1034.

Bellassen, V., and Stephan, N. 2015. *Accounting for Carbon*, Cambridge: Cambridge University Press.

Bernal Bernabe, J., Hernandez-Ramos, J. L., and Skarmeta Gomez, A. F. 2017. "Holistic Privacy-Preserving Identity Management System for the Internet of Things". *Mobile Information Systems*, pp. 1-20.

Bjørndal, E., Bjørndal, M. H., Coniglio, S., Körner, M.-F., Leinauer, C., and Weibelzahl, M. 2023. "Energy storage operation and electricity market design: On the market power of monopolistic storage operators". *European Journal of Operational Research* (307:2), pp. 887-909.

Chakraborty, S., Anand, A., Kalash, D., and Srivastava, A. 2022. "Transparency in Carbon Credit by Automating Data-Management Using Blockchain" in *Proceedings of the IEEE International Conference on Blockchain and Distributed Systems Security*.

Da Silva, J. M. C., and Wheeler, E. 2017. "Ecosystems as infrastructure". *Perspectives in Ecology and Conservation* (15:1), pp. 32-35.

Damsø, T., Kjær, T., and Christensen, T. B. 2016. "Counting carbon: contextualization or harmonization in municipal GHG accounting?". *Carbon Management* (7:3-4), pp. 191-203.

Fominykh, M., Prasolova-Førland, E., Divitini, M., and Petersen, S. A. 2016. "Boundary objects in collaborative work and learning". *Information Systems Frontiers* (18:1), pp. 85-102.

Fridgen, G., Halbrügge, S., Körner, M.-F., Michaelis, A., and Weibelzahl, M. 2022. "Artificial Intelligence in Energy Demand Response: A Taxonomy of Input Data Requirements". *Proceedings of the Wirtschaftsinformatik*.

Fridgen, G., Körner, M.-F., Walters, S., and Weibelzahl, M. 2021. "Not All Doom and Gloom: How Energy-Intensive and Temporally Flexible Data Center Applications May Actually Promote Renewable Energy Sources". *Business & Information Systems Engineering* (63:3), pp. 243-256.

Gibbs, G. 2006. *How to Analyse Qualitative Data*, Los Angeles: Sage Publications Inc.

Golding, O., Yu, G., Lu, Q., and Xu, X. 2022. "Carboncoin: Blockchain Tokenization of Carbon Emissions with ESG-based Reputation" in *Proceedings of the IEEE Conference on Blockchain*, pp. 1-5.

Greenfield, P. 2023. "Revealed: more than 90% of rainforest carbon offsets by biggest certifier are worthless, analysis shows", available at https://www.theguardian.com/environment/2023/jan/18/revealed-forest-carbon-offsets-biggest-provider-worthless-verra-aoe, accessed on Feb 24 2023.

Hanny, L., Körner, M.-F., Leinauer, C., Michaelis, A., Strüker, J., Weibelzahl, M., and Weissflog, J. 2022. "How to trade electricity flexibility using artificial intelligence: An integrated algorithmic framework." in *Proceedings of the 55nd Hawaii International Conference on System Sciences 2022*.

Hu, H., Sun, F., Guo, W., and Pan, L. 2022. "Net-Zero Intelligent Energy System: Road to a Successful Carbon Neutral Future" in *Proceedings of the 12th International Conference on Power*, pp. 285-291.

IEA. 2022. "Global Energy Review: CO2 Emissions in 2021", Paris: International Energy Agency.

IEEE. 1991. "IEEE Standard Computer Dictionary: A Compilation of IEEE Standard Computer Glossaries", IEEE Publications.

IPCC. 2019. "2019 Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories".

Ito, A., Sakaino, A., Chino, S., Horikoshi, T., Fujishima, M., Ogawa, S., Takeuchi, T., and Amano, Y. 2022. "Device Data Application Phase1 on Trusted Data Platform GAIA-X for Decarbonization in Industry" in *Proceedings of the 61st Conference of the Society of Instrument and Control Engineers*, pp. 17-24.

Ju, C., Shen, Z., Bao, F., Weng, P., Xu, Y., and Xu, C. 2022. "A Novel Credible Carbon Footprint Traceability System for Low Carbon Economy Using Blockchain Technology". *International journal of environmental research and public health* (19:16).

Ketter, W., Schroer, K., and Valogianni, K. 2022. "Information Systems Research for Smart Sustainable Mobility: A Framework and Call for Action". *Information Systems Research* (in press).

Khaqqi, K. N., Sikorski, J. J., Hadinoto, K., and Kraft, M. 2018. "Incorporating seller/buyer reputation-based system in blockchain-enabled emission trading application". *Applied Energy* (209), pp. 8-19.

Kim, S.-K., and Huh, J.-H. 2020. "Blockchain of Carbon Trading for UN Sustainable Development Goals". *Sustainability* (12:10).

Körner, M.-F., Sedlmeir, J., Weibelzahl, M., Fridgen, G., Heine, M., and Neumann, C. 2022. "Systemic risks in electricity systems: A perspective on the potential of digital technologies". *Energy Policy* (164).

Körner, M.-F., and Strüker, J. "Digital Data Ecosystems for the Verification of Corporate Carbon Emission Reporting" in *Posterpresentation at Bayreuth Digital Science Conference 2023*.

Lacity, M., and Carmel, E. 2022. "Self-Sovereign Identity and Verifiable Credentials in Your Digital Wallet". *MIS Quarterly Executive* (21:3).

Li, G., Li, J., and Lili-Li. 2021. "Application and Research of Carbon Asset Management Based on Blockchain" in *Proceedings of the 5th International Conference on Electronic 2021*.

Mandaroux, R., Dong, C., and Li, G. 2021. "A European Emissions Trading System Powered by Distributed Ledger Technology: An Evaluation Framework". *Sustainability* (13:4).

Melville. 2010. "Information Systems Innovation for Environmental Sustainability". *MIS Quarterly* (34:1).

Müller, F., Leinauer, C., Hofmann, P., Körner, M.-F., and Strüker, J. 2023. "Digital Decarbonization: Design Principles for an Enterprise-wide Emissions Data Architecture" in *Proceedings of the 56th Hawaii International Conference 2023*.

Nakamoto, S. 2008. "Bitcoin: A Peer-to-Peer Electronic Cash System". *SSRN Electronic Journal*.

Ning, Y., Yongwei, L., Wentao, L., Chuncheng, G., Shiqiang, Z., and Qian, Z. 2022. "Power trading system design and key technology research based on micro-services" in *Proceedings of the 7th Asia Conference on Power*, pp. 488-493.

Otto, B., Hompel, M. ten, and Wrobel, S. (eds.). 2022. *Designing Data Spaces: The Ecosystem Approach to Competitive Advantage*, Cham: Springer International Publishing; Imprint Springer.

Patel, B., Peko, G., and Sundaram, D. 2019. "Adaptive Sustainable Organizations: System Dynamic Models of a University Balancing the Virtuous and the Vicious" in *Proceedings of the 52nd Hawaii International Conference 2019*.

Preukschat, A., Reed, D., and Searls, D. 2021. *Self-sovereign identity*: *Decentralized digital identity and verifiable credentials*, Shelter Island, NY: Manning.

Rosado da Cruz, A., Santos, F., Mendes, P., and Cruz, E. 2020. "Blockchain-based Traceability of Carbon Footprint: A Solidity Smart Contract for Ethereum" in *Proceedings of the 22nd International Conference on Enterprise 2020*, pp. 258-268.

Schletz, M., Franke, L. A., and Salomo, S. 2020. "Blockchain Application for the Paris Agreement Carbon Market Mechanism—A Decision Framework and Architecture". *Sustainability* (12:12).

Sedlmeir, J., Völter, F., and Strüker, J. 2022. "The next Stage of Green Electricity Labeling: Using Zero-Knowledge Proofs for Blockchain-Based Certificates of Origin and Use". *SIGENERGY Energy Inform. Rev.* (1:1), pp. 20-31.

Seidel, S., Bharati, P., Fridgen, G., Watson, R. T., Albizri, A., Boudreau, M.-C., Butler, T., Chandra Kruse, L., Guzman, I., Karsten, H., Lee, H., Melville, N., Rush, D., Toland, J., and Watts, S. 2017. "The Sustainability Imperative in Information Systems Research". *Communications of the AIS*, pp. 40-52.

Shokri, A., Shokri, A., White, D., Gelski, R., Goldberg, Y., Harrison, S., and Rashidi, T. H. 2022. "EnviroCoin: A Holistic, Blockchain Empowered, Consensus-Based Carbon Saving Unit Ecosystem". *Sustainability* (14:12).

Sipthorpe, A., Brink, S., van Leeuwen, T., and Staffell, I. 2022. "Blockchain solutions for carbon markets are nearing maturity". *One Earth* (5:7), pp. 779-791.

Staudt, P., Lehnhoff, S., and Watson, R. 2019. "Call for Papers, Issue 3/2021". *Business & Information Systems Engineering* (61:6), pp. 767-769.

Stechemesser, K., and Guenther, E. 2012. "Carbon accounting: a systematic literature review". *Journal of Cleaner Production* (36), pp. 17-38.

Strüker, J., Urbach, N., Guggenberger, T., Lautenschlager, J., Ruhland, N., Schlatt, V., Sedlmeir, J., Stoetzer, J.-C., and Völter, F. 2021a. "Self-Sovereign Identity: Grundlagen, Anwendungen und Potenziale portabler digitaler Identitäten", Fraunhofer FIT (ed.), Bayreuth: Projektgruppe Wirtschaftsinformatik des Fraunhofer-Instituts für Angewandte Informationstechnik FIT.

Strüker, J., Weibelzahl, M., Körner, M.-F., Kießling, A., Franke-Sluijk, A., and Hermann, M. 2021b. "Decarbonisation through digitalisation: Proposals for Transforming the Energy Sector", Universität Bayreuth, Germany (ed.).

Tito, S. R., Soltic, S., Parkash, B., Rehman, A. U., Nieuwoudt, P., Aslam, S., Lie, T. T., Pandey, N., and Ahmed, M. D. 2021. "Is Edge Computing the Answer for Smart Building Energy Management System?" in *Proceedings of the International Conference on Technology*, pp. 378-383.

UNFCCC (ed.). 1997. *Kyoto Protocol to the UNFCCC,* Kyoto, Japan, 11.12.1997.

UNFCCC (ed.). 2015. *Paris Agreement under the UNFCCC,* Paris, France, 12.12.2015.

Wang, H., Ma, S., Guo, C., Wu, Y., Dai, H.-N., and Di Wu. 2021. "Blockchain-Based Power Energy Trading Management". *ACM Transactions on Internet Technology* (21:2).

Watson, Boudreau, and Chen. 2010. "Information Systems and Environmentally Sustainable Development: Energy Informatics and New Directions for the IS Community". *MIS Quarterly* (34:1).

Watson, R. T., Ketter, W., Recker, J., and Seidel, S. 2022. "Sustainable Energy Transition: Intermittency Policy Based on Digital Mirror Actions". *Journal of the AIS* (23:3), pp. 631-638.

Webster, J., and Watson, R. T. 2002. "Analyzing the Past to Prepare for the Future: Writing a Literature Review". *MIS Quarterly* (26:2), pp. xiii-xxiii.

Woo, J., Kibert, C. J., Newman, R., Kachi, A. S. K., Fatima, R., and Tian, Y. 2020. "A New Blockchain Digital MRV Architecture for Existing Building Energy Performance" in *Proceedings of the 2nd Conference on Blockchain Research 2020*, pp. 222-226.

Yang, Q., Zhengyun, S., Sheng, C., Haiwang, Z., and Hua, H. 2021. "An Outlook of Flexibility Aggregation of Distributed Energy Sources over a Blockchain-enabled Energy Internet" in *Proceedings of the IEEE International Conference on Energy 2021*, pp. 185-190.

Zampou, E., Mourtos, I., Pramatari, K., and Seidel, S. 2022. "A Design Theory for Energy and Carbon Management Systems in the Supply Chain". *Journal of the AIS* (23:1), pp. 329-371.

Zeiss, R., Ixmeier, A., Recker, J., and Kranz, J. 2021. "Mobilising information systems scholarship for a circular economy". *Information Systems Journal* (31:1), pp. 148-183.

Zhao, C., Sun, J., Gong, Y., Li, Z., and Zhou, P. 2022. "Research on the Blue Carbon Trading Market System under Blockchain Technology". *Energies* (15:9).