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RESEARCH PAPER

Enhancing trust in global supply chains: Conceptualizing Digital Product Passports for a low-carbon hydrogen market

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Abstract
Industries and energy markets around the world are facing mounting pressure to decarbonize, prompting them to transform processes and supply chains towards sustainability. However, a lack of credible sustainability data proves to be a considerable barrier for emerging markets for sustainable products: Against the background of complex and globalized supply chains, it is necessary to verify the sustainability claim of products in order to demand price premiums for sustainable products in the long run. To enable this, it is necessary that stakeholders in globalized supply chains are willing to share relevant data along the entire supply chain for increasing traceability and reducing information asymmetries. Using the example of international hydrogen supply chains, we study how data can be shared between different stakeholders using Digital Product Passports while addressing stakeholders' concerns about data privacy and disclosure. In our work, we develop design principles that provide insight into how a Digital Product Passport should be designed to verify the hydrogen's carbon footprint in a reliable way and to ensure the willingness of stakeholders to share their data. We follow a multi-step approach with a structured literature review followed by expert interviews and qualitative content analysis for a synthesis of design principles. Our research illustrates that a Digital Product Passport must collect data comprehensively and automatically, process it in a decentralized and tamper-proof manner, protect privacy and sovereignty of stakeholders, and ensure interoperability.

Keywords Data economy · Decarbonization · Digital Product Passports · Hydrogen · Supply chains · Verification

JEL Classification Q55

Introduction

Data has become increasingly valuable in the digital economy as it accelerates processes, drives innovation, and creates new business models (Beverungen et al., 2022; Bouwman et al., 2018). Accordingly, organizations process and share their own data and use also external data for various purposes, e.g., for active risk management in supply chains, see, e.g., Agahari et al. (2022) and Schniederjans et al. (2020). Among others, due to stricter regulations and requirements for sustainability and emissions reporting (Kaplan & Ramanna, 2021), the need for traceable and verifiable information, and hence, for cross-organizational collaboration in today's complex and globally meshed supply chains is rapidly increasing (Zampou et al., 2022). As a result, data develops as a strategic resource for organizations to verify the sustainability of products, such as carbon footprints (Krasikov & Legner, 2023). However, to date, the majority of relevant sustainability data is not shared

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along supply chains, leading to information asymmetries and preventing target-oriented sustainability measures—as recently largely stated in academic research; see, e.g., Bauer et al. (2020), Bjørn et al. (2022), and Luers et al. (2022). This may further result in market failures as products cannot be priced differently, e.g., according to their contribution to decarbonization (Downar et al., 2021; White et al., 2021).

One of the major challenges of sharing data in supply chains is the balance between transparency and confidentiality, as organizations fear losing competitive advantages by disclosing sensitive information. Here, information systems (IS) research is tasked with designing digital solutions that ensure information verifiability and privacy preservation in complex and international supply chains (Agahari et al., 2022; Saberi et al., 2019). Decentralized concepts and technologies for sharing and processing data — among others linked to recent research in the area of data ecosystems (Beverungen et al., 2022; Heinz et al., 2022) — may serve as a promising starting point.

Against this background, this paper is aimed at paving the way for data sharing along supply chains in the form of a Digital Product Passport (DPP). As we will outline in the following, such a DPP not only preserves the privacy of involved organizations but also enables verifiability of carbon emissions data of specific products (Berger et al., 2022). We refer to a DPP as a digital solution for sharing product-specific information along the supply chain to any (including end) customers. While we highly acknowledge the enormous contribution that scholars already provided in recent years, we see that existing literature either lacks specificity (Walden et al., 2021), focuses on specific data and information requirements only (Berger et al., 2023; Jensen et al., 2023), or maintains a more generalized perspective on DPP system requirements (Jansen et al., 2023). Consequently, research and practice need a stronger analysis on how DPPs should be built from a technological perspective and on how data should be shared in globalized supply chains to enable verification, rather than which exact data is actually needed or what are the general areas of application for the DPPs.

For our study, we shed light on hydrogen supply chains as an exemplary use case while — to increase sustainability and corresponding decarbonization efforts worldwide — only low-emission hydrogen is considered a cornerstone for achieving our climate goals (Falcone et al., 2021; Husarek et al., 2021). While hydrogen supply chains characterize as highly complex and international with various production and transportation steps, the final product itself does not provide any information about how it was produced and what emissions were generated in the process. To guarantee a more sustainable hydrogen production, and hence, to also enable price premiums for low-carbon hydrogen (White et al., 2021), our paper outlines how traceability and data sharing along supply chains empower the verification of hydrogen's carbon footprint.

As previous literature contributes by analyzing the suitability of specific technologies for supply chain traceability (Bodkhe et al., 2020; Liu et al., 2021b; Saberi et al., 2019), research and practice are still searching for applicable solutions. While we embrace the promising field of DPPs, this study reaches out to answer the following research question:

How should a Digital Product Passport be designed to enable data sharing and verification of information along international supply chains of hydrogen?

To close this research gap, we develop six design principles for a hydrogen DPP that enables verification in complex hydrogen supply chains but makes allowances for the concerns and challenges of different stakeholders regarding data sharing. For this purpose, we apply a multi-step approach to derive design principles as requirements. We conduct a structured literature review to identify existing traceability and data sharing challenges and derive the necessary design principles. Based on this, interviews with various experts from practice and research complement the results with special expertise from both a technological and hydrogen perspective. This multi-step approach ensures both rigor and relevance of our design principles. Thereby, our work contributes in at least three ways: First, with our findings, we extend the research in data sharing and provide new insights for IS research on supply chain traceability. Second, our design principles demonstrate how digital technologies can be used to contribute to the global challenge of sustainability and decarbonization. A DPP reduces information asymmetries, and environmental damage can be priced in or manufacturers can demand price premiums for their environmentally friendly production methods. Third, our research provides a starting point for realizing a DPP in hydrogen supply chains to enable markets for low-carbon products as our results represent guidelines on how to design a DPP that is applicable in industry.

The remainder of this article is organized as follows: In the next section, we give an overview on "Background and related work." Further, we describe our research methodology in "Method" and present our result—the six design principles—in the Section "Findings". Afterwards in "Discussion and contribution," we examine the results and elaborate the contribution. Last, we complete our research in "Conclusion and outlook," declare the limitations of our work, and give an outlook on future research opportunities.

Background and related work

To provide an overview of related literature and previous work relevant for the topic of this paper, the section is structured as follows: First, we present literature on challenges of stakeholders to share data in data ecosystems; and second, how digital technologies may overcome these to enable traceability in complex supply chains. Third, we introduce recent work on DPPs as a digital solution for data sharing along supply chains and collaboration between the various stakeholders. Last, we give a literature-based overview of the low-carbon hydrogen supply chain.

Data sharing in data ecosystems

In research and practice, data is considered as a key driver and a strategic resource of the digital economy and can drive innovation and sustainability (Gelhaar & Otto, 2020; Jetzek et al., 2019; Renland Haugjord & Kempton, 2022). To truly harness the potential of data, there is a need for cross-organizational collaboration in the form of data sharing. However, literature emphasizes that one barrier to share data is the concern of disclosing valuable information that could endanger a stakeholder's competitive advantage (Agahari et al., 2022; Gelhaar & Otto, 2020; Westerkamp et al., 2020). Therefore, stakeholders must recognize the benefits of collaborating and sharing data to be willing to participate (Agahari et al., 2022; Lis & Otto, 2020). At the same time, stakeholders should be assured of sovereignty over their data to reduce the fear of data disclosure (Beverungen et al., 2022; Gelhaar & Otto, 2020). Research also underlines the need for the stakeholder's trust in the network (Agahari et al., 2022; Gelhaar & Otto, 2020).

Against this background, the IS community has recently been taking a closer look at the topic of data ecosystems in which collaborated data sharing between different stakeholders takes place (Heinz et al., 2022). Oliveira and Lóscio (2018) describe a data ecosystem as a network of autonomous actors that consume, produce, or provide data and resources, where each actor plays one or more roles and is connected to others through relationships that foster collaboration and competition. In their work, on multi-sided data platforms, e.g., in the form of data spaces, Otto and Jarke (2019) point out that trustworthy data sharing and data sovereignty are key elements to ensure the success of an ecosystem in which data is shared. Gelhaar and Otto (2020) study the challenges in the emergence of data ecosystems, thus offering essential insights for advancing collaborative data sharing, while Gelhaar et al. (2021) develop a taxonomy for data ecosystems to enable a deeper understanding of the growing research field. Aaen et al. (2022), on the other side, highlight that data use in these ecosystems can also have negative consequences. Uncoordinated growth of data ecosystems might lead to privacy problems and a lack of stakeholder trust in the data ecosystem, calling for an appropriate governance. Moreover, research shows that the distribution of power between units that generate, collect, and analyze data can be imbalanced leading to knowledge asymmetries, lock-in effects, and dominant entities (Someh et al., 2019). While current literature on data sharing in data ecosystems also elaborates on corresponding threats and challenges, it mainly highlights the enormous potential of data sharing for cross-organizational collaboration.

Sustainability and supply chain traceability

Data sharing is seen in literature as a major factor of supply chain transparency and sustainability, enabling stakeholders to track and verify the environmental, social, and economic impacts of production and distribution processes (Saberi et al., 2019; Tröger & Alt, 2017). Research also emphasizes that the demand for verifiable production information is growing in order to meet global climate targets as well as human rights standards. For this reason, recent academic literature is concerned with how digital technologies can contribute to the verifiability and traceability of supply chains, especially with regard to sustainability (Müller et al., 2023). Various approaches are being explored to address supply chain traceability by using a shared data layer: Saberi et al. (2019) study the blockchain's impact on sustainable supply chains, finding a lack of information on ecological products and a need for real-time emission data to create low-carbon asset markets. Benefits of using blockchain include improved reliability, trust, and transparency, but also face barriers to adoption due to privacy issues. Menon and Jain (2022) study blockchain for transparency in agri-food supply chains, classifying 25 use cases and highlighting the technology's potential and limitations. For this purpose, they point out current limitations and give hints for future research directions. Also, in the vein of using a shared data layer, Tsolakis et al. (2021) design blockchain-centric supply chains for sustainability, defining four principles and an implementation framework for more resilient and sustainable supply chains. The research of Tröger and Alt (2017) goes in a similar direction: They identify design options for supply chain visibility through a case study approach. Appelhanz et al. (2016) develop a traceability information system and an according cost–benefit model for wood products, and Asante et al. (2022) present a comprehensive review of the use of distributed ledger technologies in supply chains. Liu et al., (2021b) examine the role of information and communication technology in agriculture supply chains, highlighting challenges such as fear of data misuse and lack of data sharing due to loss of control.

Against this background, research points out that a major challenge in this area is the dilemma between transparency, e.g., concerning product information, and confidentiality of sensitive business data (Berger et al., 2022; Jarke et al., 2019; Menon & Jain, 2022). Thus, recent research focuses on how to guarantee verifiability of relevant information while avoiding disclosure of data. For example, Djamali et al. (2021) develop a blockchain-based data platform for asset logging in the energy sector with end-to-end encrypted communication channels. Their solution meets identified requirements, such as tamper-resistance and integrity of stored data while enabling scalability and protecting sensitive data. To address certification and guarantees of origin in the energy context, Sedlmeir et al., (2021b) analyze using zero-knowledge proofs (ZKPs) to label electricity from renewable energy sources. A similar direction is taken by Babel et al. (2022): They design a carbon emission tracing system that ensures verifiability while incorporating privacy-preserving measures by non-fungible tokens and ZKPs. Nevertheless, despite all efforts of research, determining the environmental impact of products is still challenging and lacks applicable solutions.

Digital Product Passports

To bring supply chain traceability into practice and enable a global sustainable economy, only recently legislative bodies introduce new concepts and strategies. The EU, for example, passed a law for improved sustainability reporting, using digital technologies for comparable and reliable information flows (European Commission, 2021). DPPs aim to pass on product-specific information along supply chains to inform consumers about the product's environmental impact. The EU acknowledges the advantage of the digitalization of product passports to reduce administrative burden (European Commission, 2022). DPPs are being considered as a tool for comprehensively tracing sustainability aspects (Adisorn et al., 2021), and thus, enabling sustainable supply chains (Berger et al., 2022). While the concept of DPPs is gaining attention in policy, economy, and research (Plociennik et al., 2022; Walden et al., 2021), it requires further research to apply DPPs as solutions for verifiable sustainability information. To this end, initial studies aim to advance DPPs, while a current focus is on circular economy and the reuse of materials from a specific product, see, e.g., Adisorn et al. (2021), Plociennik et al. (2022), or Walden et al. (2021). Berger et al. (2022) propose a digital passport for electric vehicle batteries that promote circularity and incorporates value chain data. Among others, they analyze data requirements for stakeholders involved in circular battery value chains. In their new work, Berger et al. (2023) build upon existing research and provide a value chain actors' perspective on data requirements for sustainability management. Jensen et al. (2023) take a similar approach and define and evaluate data needs in DPPs for product life-cycle decision making. King et al. (2023) propose a universal definition of a DPP ecosystem that is broader than previous work, which has so far focused sporadically on information requirements, policy, or other dimensions for a DPP. They identify nine capabilities of the DPP ecosystem and explore each capability in more detail. Jansen et al. (2023) are the first to identify broader requirements for DPP systems and thus provide an explanation for current DPP developments. Nevertheless, current research on DPPs also acknowledges the tension between transparency and data-privacy while not yet providing applicable solutions that ensure verifiability under technologies' requirements and stakeholder concerns.

In this work, we expand the research in the area of supply chain traceability and connect the idea of data ecosystems for supply chain traceability with the emerging concept of DPPs. Data sharing along supply chains and collaboration between relevant stakeholders opens new business models and enables new options for value creation. The role of IS and the use of data to drive sustainability are gaining increasing attention — especially in context where production processes involve various steps and where the final product itself does not disclose any information about its carbon intensity.

Low-carbon hydrogen supply chain and market

Low-carbon hydrogen, produced by splitting water with electricity, is considered as a key fuel for achieving global climate goals and promoting the energy transition (Akhtar et al., 2023) and serves as an illustrative example for the relevance of tracing emissions along supply chains. On the one hand, this is due to its versatile applicability, while on the other hand, as an energy carrier, hydrogen offers flexible storage and transport options for renewable, low-carbon energies (Li et al., 2019). The options of how hydrogen is produced, via which international transportation route, and in which form it reaches its end consumers are numerous (Seo et al., 2020). Figure 1 illustrates a selection of hydrogen supply chain options, whereby the product hydrogen itself does not allow any conclusions to be drawn about the production method, conditioning, transportation, and storage. Therefore, the environmental impact in the form of carbon emissions that has occurred along its supply chain is not traceable without any further measures.

However, hydrogen can only contribute to decarbonization if produced environmentally friendly (Shiva Kumar & Lim, 2022). To this end, renewable-powered electrolysis for the generation of low-carbon hydrogen is needed (Velazquez

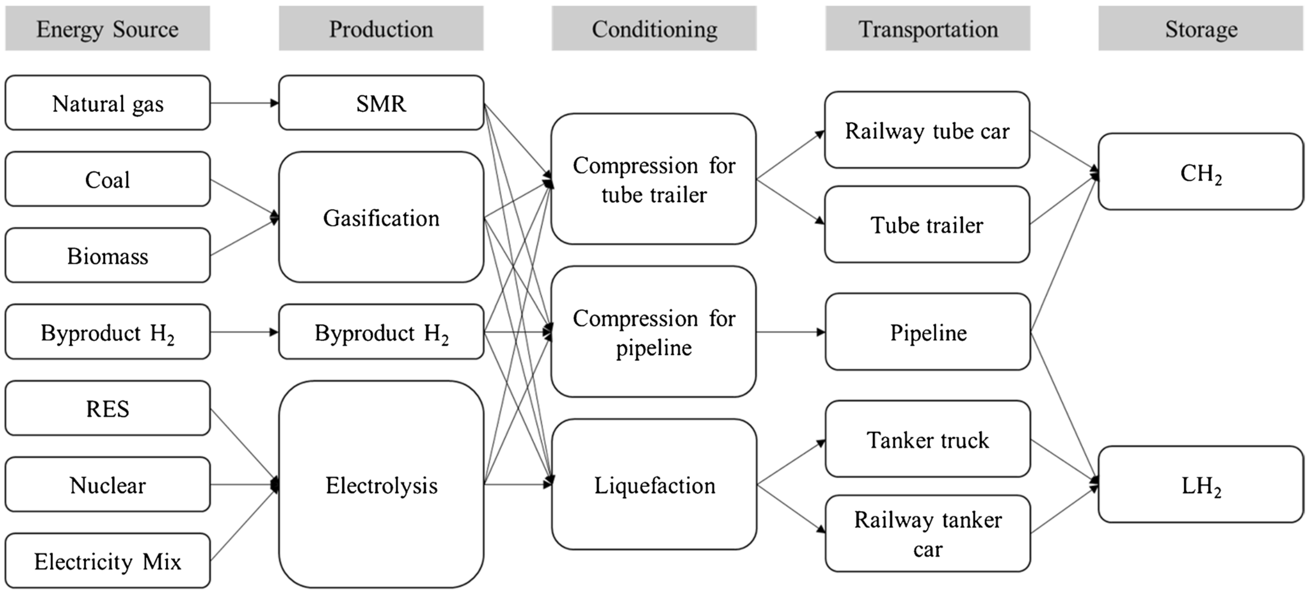

Fig. 1 Hydrogen supply chain options (own illustration based on Li et al. (2019) and Seo et al. (2020)) (RES = renewable energy system, SMR = steam methane reforming, CH_2 = compressed hydrogen, LH_2 = liquid hydrogen, H_2 = Hydrogen)

Abad & Dodds, 2020). Notwithstanding, since this type of production requires large amounts of renewable, low-carbon energy, not every location is suitable to produce low-carbon hydrogen. As a result, many countries, e.g., in the EU, seek partnerships to expand their hydrogen economy, build international supply chains, and import hydrogen from more suitable locations, e.g., Australia, due to its superior solar and wind potential (Akhtar et al., 2023; Wappler et al., 2022). Moreover, due to various production steps and challenging transportation, low-carbon hydrogen is currently more expensive than conventional hydrogen — so-called gray hydrogen — with a higher carbon footprint (Akhtar et al., 2023). However, as Hahn et al. (2015) state, the demand for low-carbon hydrogen is increasing due to sustainability targets or incentives such as shareholder and consumer pressure, emission pricing, and further regulation. Recent literature points out that in order to reduce greenhouse gasses along the supply chain, consumers are willing to pay a premium for guaranteed low-carbon hydrogen (White et al., 2021). However, if buyers do not know how carbon-friendly the hydrogen is produced, a market failure occurs due to asymmetric information. The market for low-carbon hydrogen will not emerge since buyers cannot be sure whether the premium price is justified. For this reason, certifications help to reduce information asymmetries and provide transparency in the supply chain (Velazquez Abad & Dodds, 2020; White et al., 2021). In their work, Velazquez Abad and Dodds (2020) give an overview on existing certification standards and guarantee of origins for "green" hydrogen, noting that these differ, for instance, in how they are characterized, such as guarantee of origin, regulation, or standard. Of particular importance are the differences in the baseline greenhouse gas threshold, the qualification level, i.e., meaning that different definitions of what "green" (or other colors that are related to the specific carbon intensity of hydrogen) exist (White et al., 2021). For instance, the French guarantee of origin scheme AFHYPAC labels hydrogen as "green" if the used electricity originates from 100% renewable sources, while the guarantee of origin scheme CERTIFHY defines hydrogen as "green" if the emissions are a certain amount lower than from "gray" hydrogen and the British standard BEIS, on the other hand, defines a threshold differentiated according to end use (Velazquez Abad & Dodds, 2020). Research further emphasizes the issue that there is no uniform definition where in the supply chain the carbon intensity is measured and that boundaries for carbon accounting vary widely among different initiatives from the point of production to the entire lifecycle of hydrogen (Valente et al., 2017; Velazquez Abad & Dodds, 2020). These differences result in the failure that no consistent, standardized market with price premiums for low-carbon hydrogen can be developed. Moreover, literature underlines that in certain systems, only green hydrogen—according to their individual definition — can be traded (Valente et al., 2017). Hence, it is not possible to mix hydrogen with different supply chains and certify improvements in emissions of non-100% green hydrogen (Schlund & Schönfisch, 2021; Velazquez Abad & Dodds, 2020). These aspects prevent well-functioning international trade of low-carbon hydrogen and, finally, the energy transition (White et al., 2021).

Against the background of previous literature, we identify the need for a more coherent approach to enable traceability in hydrogen supply chains. As a digital enabler, DPPs can be a necessary building block for an applicable solution, offering the potential to enable verification of sustainability criteria and track emissions along the complex supply chain of low-carbon hydrogen. Recent advances in IS research, especially in the area of data ecosystems, demonstrate promising ways to share data in a trustworthy and traceable manner and, thus, pave the way forward for DPPs. To build appropriate DPPs, research and practice are in need for clarifying and addressing challenges and developing design principles first.

Method

As previously discussed, we observe a research gap on how to design a DPP to enable reliable verification of hydrogen supply chains (Step I). Hence, in our research, we develop design principles as requirements for building a hydrogen DPP and capture relevant design knowledge. We thereby follow a multi-step approach with a structured literature review followed by expert interviews and qualitative content analysis for a synthesis of design principles (c.f. Figure 2). The approach is based on the Design Cycle Research of Hevner et al. (2004) and covers especially the first steps of that procedure.

In Step II, we conduct a systematic literature review in line with vom Brocke et al. (2015) to define our design objectives (c.f. Step III) and to develop the initial design principles (c.f. Step III). In doing so, we study the existing knowledge base and extract specific challenges of supply chain transparency. We apply the search string ("Supply Chain" OR "Value Chain" OR "Chain of Custody") AND (Trace* OR Track* OR Guarantee OR "Product Passport") AND ("Information System*" OR Digital* OR ICT OR "Information and Communication Technology" OR Virtual*). For our search, we use the following databases: Web of Science, IEEE Xplore, AIS eLibrary, Science Direct, and JSTOR. We limit the results of our query to papers published from 2016 to the present to reflect the fast pace of this research area. Initially, our search results in a total of 448 research articles. After screening titles, abstracts, and the content of the articles, we reduce the number of relevant publications for our purpose to 23 in accordance with our inclusion and exclusion criteria (cf. Table 1). Conducting a forward and backward search gives us additional six articles which adds up to a total of final 29 articles.

To guide our work and the development of our results, we first analyze in Step III the challenges around supply chain traceability, data sharing, and sustainable hydrogen. In doing so, we identify nine challenges. To overcome these challenges, we arrive at the following research objective: Develop design principles for a Digital Product Passport to enable data sharing and verification of information along international supply chains of hydrogen. In line with Peffers et al. (2007) and Walls et al. (1992), we then derive three meta-requirements as design objectives for a DPP from the nine previously identified challenges for our design principles. Additionally, we discuss the meta-requirements in the research group and finalize them through reasoning. These meta-requirements specify what the final design principles

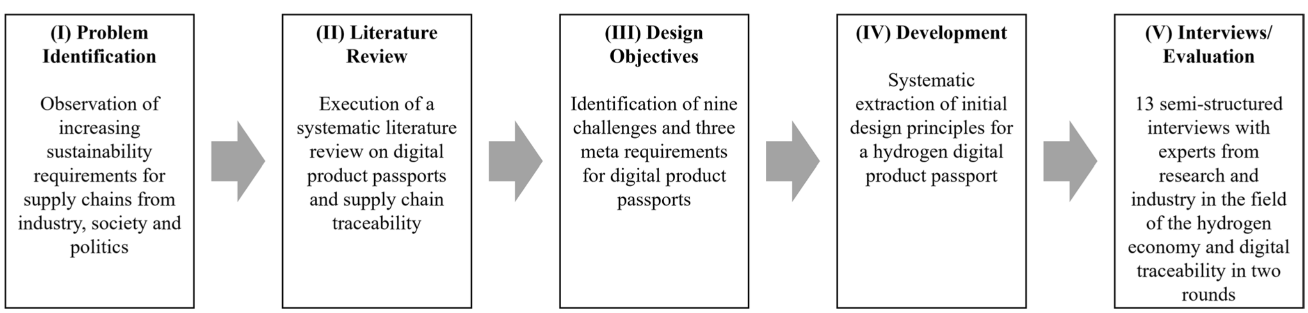

Fig. 2 Executed research approach

Table 1 Inclusion and exclusion criteria of our systematic literature review

Inclusion criteria	Exclusion criteria
• Contains knowledge about supply chain traceability • Includes digitalization components or contains IS context • Includes frameworks, descriptions, and conceptualization about DPPs, guarantee of origin, or related domains	• Was published before 2016 (and thus, does not reflect the contemporary state of research) • Literature such as books, presentations, or non-peer-reviewed articles • Content that is not relevant to the considered problem, e.g., logistic management • Articles that are not written in English

should ultimately fulfill and, thus, provide the starting point for the development of our design principles.

In Step IV, we develop our design principles for a DPP in hydrogen supply chains by applying the design principle scheme of Gregor et al. (2020) to summarize the various aspects of the statements in a reasonable way, i.e., aim, context, mechanism, and rationale. From our literature review and building on the previously derived meta-requirements, we formulate an initial set of design principles. While the derived meta-requirements are use-case-agnostic, the first draft of design principles has a broader base and is applied to the hydrogen context by means of general background information from the authors about hydrogen supply chains and certification.

Following the initial development of design principles, we evaluate these in Step V by 13 semi-structured expert interviews, following Schultze and Avital (2011). In two rounds of interviews and within the author's team, we develop and evaluate our design principles against the criteria of ease of use, understandability, simplicity, elegance, and completeness (Sonnenberg & vom Brocke, 2012). The interviewees were selected based on their expertise either in the field of hydrogen or in the field of data sharing and verification to assess the specifics of our design principles for a hydrogen DPP (see Table 2). Care was taken to include stakeholders at different points in the hydrogen supply chain and with diverse roles in order to receive feedback from different points of view. To better prepare for the interview, we inform the experts about our research before the meeting. All interviews are recorded and transcribed in agreement with the interview partners and last between 30 and 75 min. We follow the predetermined interview guide (see Appendix A) to conduct the evaluation. After a brief personal introduction followed by a short overview about hydrogen and DPPs, we asked the interviewees to evaluate the design principles. In the end, we take the time for broader feedback on the research topic. This includes discussions about the added value of hydrogen DPPs, current challenges, and future steps necessary for the DPP implementation. During the interviews, we take notes of relevance which, together with the transcripts, we incorporate into the updated versions of the design principles. With the first seven expert interviews (see Table 2), we evaluate the first draft of design principles. Using the feedback, we review and adopt the design principles and revise the design principles by six additional expert interviews. Finally, the author's team discusses the feedback of the two previous process iterations in detail and finalizes the six design principles.

Findings

We present our results in two subsections. First, we illustrate the challenges for supply chain traceability that we find within the first step of our process — as outlined in the previous section. From these challenges, we derive meta-requirements that give guidance for the formulation of the design principles by providing clear, overarching requirements that a DPP must meet for an improved supply chain transparency. Second, we present the final six design principles for a DPP.

Challenges and meta-requirements for supply chain traceability

In the following, we briefly outline the challenges of supply chain traceability and data sharing in supply chains that we find in the literature. Thereinafter, we present the meta-requirements that consider these challenges. Thereby, we note that both, the challenges and meta-requirements, are

Table 2 Experts selected for evaluation interviews

Interview round	ID	Role of interviewee	Professional background and expertise	Duration
1	1	Researcher	IS, decarbonization, hydrogen	75 min
	2	Researcher	IS, sustainability, blockchain	60 min
	3	Researcher	IS, energy, decentralized technologies	60 min
	4	Head of department	Steel, hydrogen	60 min
	5	Senior project manager	Energy, hydrogen, sustainability	60 min
	6	Industry innovation manager	Hydrogen, energy	53 min
	7	Senior project development manager	Hydrogen, energy, sustainability	42 min
2	8	Researcher	IS, traceability, blockchain	54 min
	9	Stakeholder engagement manager	Green gas, hydrogen, energy, political affairs	37 min
	10	Researcher	Digital Product Passports, traceability	56 min
	11	Head of corporate development	Port operations, hydrogen, decarbonization	31 min
	12	Solution specialist	Environmental traceability, software solutions	59 min
	13	Managing director	Public utilities, hydrogen, decarbonization	51 min

application agnostic, i.e., they do hold for any, not only for the hydrogen supply chain. Table 3 gives an overview of these challenges and illustrates how they match into the meta-requirements.

As already introduced above, we find that a lack of transparency is a major challenge. Here, Berger et al. (2022) underline a lack of high-quality information to improve supply chains towards sustainability, while Adisorn et al. (2021) highlight the need for a "holistic and comprehensive recording of sustainability aspects." We see that literature clearly points out that only if information asymmetries can be reduced and product-specific information is shared along supply chains, the true value of a product, i.e., including its external costs for the environment, can be derived (Appelhanz et al., 2016; Saberi et al., 2019). However, this desired transparency is hampered by a lack of willingness among supply chain stakeholders to share their data (Berger et al., 2022; Liu et al., 2021b). This reluctance results from a set of further issues which constitute challenges for data sharing in globalized supply chain networks. As mentioned in the introduction and in line with literature, see, e.g., Bodkhe et al. (2020), Ebinger and Omondi (2020), and Straubert and Sucky (2021), we find that a major challenge is posed by privacy concerns of a supply chain's stakeholders. The fear of privacy leakage and the potential loss of business advantage through sharing sensitive information withhold stakeholders from sharing relevant supply chain data (Westerkamp et al., 2020; Zhao et al., 2019). In addition, many stakeholders also fear the loss of control over their data once they allow sharing it (Appelhanz et al., 2016; Liu et al., 2021b). Moreover, we find system vulnerability to be a further, significant challenge. One corresponding issue that can be found in several articles is the single point of failure (Appelhanz et al., 2016; Saberi et al., 2019; Zhao et al., 2019). This issue arises if all data is centralized at one single point of the ecosystem and, thus, poses a major risk of data loss, manipulation, malicious attacks, or technical failure. In line with, e.g., Nozari et al. (2022), we find that the general vulnerability of technological systems poses a challenge that, as long as it remains unanswered, leads to a reduced willingness of stakeholders to disclose their information. The potential threat of data misuse by third parties also poses a problem. This misuse does not have to be caused by unauthorized persons who obtain information through hacking attacks but can also occur within the framework of the authorized users of the ecosystem (Ebinger & Omondi, 2020; Raja Santhi & Muthuswamy, 2022; Saberi et al., 2019). Of course, we note that this is strongly related to a lack of trust. For one thing, stakeholders might not trust other stakeholders with whom they are supposed to share their data because of the aforementioned reasons (Appelhanz et al., 2016; Westerkamp et al., 2020). For another, data sharing is only of value for traceability systems in supply chains if the data shared is perceived as trustworthy (Bodkhe et al., 2020; Raja Santhi & Muthuswamy, 2022). This means that two sides of trust issues play a role in this case. On the one hand, stakeholders do not trust other parties to not misuse the data they shared with them. On the other hand, stakeholders must trust that the data they receive is reliable. Hence, we state there are two kinds of information asymmetries that lead

Table 3 Overview of challenges in data sharing in supply chains

ID	Challenge	Meta-requirement	Supporting literature
C-1	Lack of transparency	MR-1	Adisorn et al. (2021); Appelhanz et al. (2016); Berger et al. (2022); Saberi et al. (2019)
C-2	Privacy concerns	MR-2	Bodkhe et al. (2020); Ebinger and Omondi (2020); Liu et al., (2021a); Menon and Jain (2022); Saberi et al. (2019); Sezer et al. (2022); Straubert and Sucky (2021); Zhao et al. (2019)
C-3	Loss of control	MR-2	Appelhanz et al. (2016); Cocco et al. (2021); Liu et al., (2021b)
C-4	System vulnerability	MR-3	Appelhanz et al. (2016); Bodkhe et al. (2020); Nozari et al. (2022); Saberi et al. (2019); Zhao et al. (2019)
C-5	Threat of data misuse	MR-2, MR-3	Ebinger and Omondi (2020); Liu et al., (2021b); Raja Santhi and Muthuswamy (2022); Saberi et al. (2019)
C-6	Lack of trust	MR-2, MR-3	Ahmed and MacCarthy (2021); Appelhanz et al. (2016); Bodkhe et al. (2020); Raja Santhi and Muthuswamy (2022); Rana et al. (2021); Saberi et al. (2019); Westerkamp et al. (2020); Zhao et al. (2019)
C-7	Data integrity	MR-3	Ahmed and MacCarthy (2021); Asante et al. (2022); Bodkhe et al. (2020); Da Rosado Cruz et al. (2020); Leng et al. (2018); Li et al. (2020); Liu et al., (2021a); Raja Santhi and Muthuswamy (2022); Salah et al. (2019); Sezer et al. (2022); Tsolakis et al. (2021); Zhao et al. (2019)
C-8	Lack of interoperability	MR-1	Asante et al. (2022); Bodkhe et al. (2020); Hardt et al. (2017); Li et al. (2020); Liu et al., (2021b); Raja Santhi and Muthuswamy (2022); Sezer et al. (2022); Tsolakis et al. (2021)
C-9	Data processing	MR-1, MR-2	Ashley and Johnson (2018); Westerkamp et al. (2020)

to trust-related problems. When discussing the trustworthiness of data, another key challenge comes into play, namely, ensuring data integrity (Ahmed & MacCarthy, 2021; Liu et al., 2021a; Sezer et al., 2022; Tsolakis et al., 2021). Data sharing in globalized supply chains can highly contribute to promoting sustainability if it can be ensured that data is not illegally manipulated and falsified. Building on this, we find in literature that a lack of interoperability is also a problem for comprehensive traceability (Bodkhe et al., 2020; Hardt et al., 2017; Raja Santhi & Muthuswamy, 2022; Sezer et al., 2022; Tsolakis et al., 2021): If data cannot be shared between different nodes in the supply chain ecosystem because communication between digital systems is not possible, the whole traceability is at stake. In addition, the information obtained from the shared data must be usable across different application areas, countries, regulations, and standards in order to contribute to verification. Here, we find that not only technical but also content-related interoperability is necessary (White et al., 2021). In addition, we find that it is also relevant how data is processed to display specific information at specific stages within supply chains—of course, this also partly interrelates with interoperability while being a separate challenge itself. Concerning the processing of data, it is pivotal to consider which level of aggregation of granular data is necessary for verifying certain information about certain production processes in supply chains (Westerkamp et al., 2020). Here, it also plays a significant role whether the data is generated automatically, autonomously, and in real-time (Ashley & Johnson, 2018).

After we identify and find the above-mentioned challenges, i.e., C-1 to C-9 (see Table 3), we cluster these challenges and derive the following meta-requirements to be the basis for our design principles (see next section):

MR-1: Enable traceability and efficient data processing along the entire supply chain.
MR-2: Ensure sufficient confidentiality and meet the sovereignty requirements of stakeholders.
MR-3: Ensure the reliability and trustworthiness of the shared data.

We also note that our literature review reveals several other challenges, including, for example, infrastructure development, management, and investment decisions (Liu et al., 2021b; Nozari et al., 2022; Saberi et al., 2019). While these issues relate to other levels of supply chain traceability through digital technologies, we do not specifically consider them in the formulation of the meta-requirements and the development of our design principles. Moreover, we state that the challenges and meta-requirements that we derive from literature are agnostic to any specific supply chain or DPP.

Design principles for a Digital Product Passport

In this section, we present the final design principles for a hydrogen DPP. As outlined in the method section, we develop these iteratively. Initial interviews indicate that the initial draft needs to be refined to meet the criteria of clarity, simplicity, and elegance. Suggestions primarily focus on design principle formulation, wording, and sentence structure. Researchers tend to analyze design principles linguistically, whereas industry experts evaluate their applicability and overall comprehensibility, assigning particular importance to practicality. Further, a major change after the first round of interviews is the merging of the former DP-2 "Data sovereignty" and DP-3 "Concealed traceability" into the new DP-2 "Data privacy."

The final set of six design principles—after conducting all 13 interviews—is listed in Table 4. The scheme applied to develop the design principles is based on Gregor et al. (2020) that structure the design principles in title, aim, context, mechanism, and rationale. The aim describes the desired outcome of a certain design principle thus what we want to achieve. The context indicates at what stage in the development the design principle gains most attention (Alter, 2013). The mechanism demonstrates how the design principle realizes the aim while the rationale finally explains why the design principle is necessary and justified.

While we see a DPP as an option to pass information along supply chains, we give a detailed description of each design principle for a DPP in hydrogen supply chains in the following:

DP-1 — holistic data capture: This design principle ensures the collection of data along the entire hydrogen supply chain. This is necessary to enable traceability and to correctly reflect the environmental impact since all points of a hydrogen supply chain contribute to the greenhouse gas emissions (Velazquez Abad & Dodds, 2020; White et al., 2021). Holistic data capture aims at reporting data on a fine-granular level in order to avoid erroneous estimations and, thus, ensures the usefulness of a DPP for sustainability improvements in supply chains. To do so, it must be possible to monitor data and report it. This includes not only data from machines used to generate hydrogen, such as in electrolysis, but also data that reflects individual information about transportation and storage. This is crucial due to the wide range of options in a hydrogen supply chain and their corresponding carbon footprints (see Fig. 1). This design principle addresses challenge C-1 and meta-requirement MR-1.

DP-2 — data privacy: This design principle addresses the concerns of supply chain stakeholders regarding data control and information disclosure (Liu et al., 2021b; Saberi

Table 4 Six design principles for a DPP in hydrogen supply chain

ID	Design principle	Aim	Context	Mechanism	Rationale	Supporting literature
DP-1	Holistic data capture	Report fine-granular data along the entire H_2 value chain	Initiation, development, operation	Collect all relevant environmental data at every point of the H_2 value chain	"[Greenhouse gas] emissions can occur at all stages along the hydrogen value chain" (Velazquez Abad & Dodds, 2020). In order to always ensure accurate data and independently of the H_2 production process, environmental data must be recorded comprehensively and at a fine granular level in the DPP	Adisorn et al. (2021); Appelhanz et al. (2016); Tsolakis et al. (2021); Velazquez Abad and Dodds (2020); White et al. (2021)
DP-2	Data privacy	Preserve privacy and data sovereignty of the H_2 stakeholders	Initiation, development, operation	Share and display verifiable environmental information in the DPP with minimal transfer of data	Disclosure of key business information is a hurdle in sharing relevant data for smooth traceability and creation of automated DPP. Therefore, the DPP must make it possible to prove information while maintaining confidentiality of sensitive business data	Ahmed and MacCarthy (2021); Appelhanz et al. (2016); Asante et al. (2022); Bodkhe et al. (2020); Menon and Jain (2022); Saberi et al. (2019); Sezer et al. (2022); Westerkamp et al. (2020)
DP-3	Decentralized data administration	Avoid a central authority and ensure collaboration without the need for trust in one entity	Implementation, operation	Apply a decentralized platform between H_2 value chain stakeholders to share and edit the DPP	Data collection from a central data manager increases the risk of single point of failure and makes it difficult for different parties to agree on a trustworthy unit. To prevent a system crash and ensure collaboration without agreeing on a central authority, the DPP should be managed in a decentralized system	Appelhanz et al. (2016); Bodkhe et al. (2020); Da Rosado Cruz et al. (2020); Liu et al., (2021b); Raja Santhi and Muthuswamy (2022); Saberi et al. (2019); Salah et al. (2019); Sezer et al. (2022)
DP-4	Forgery-proof data	Ensure data integrity of the DPP	Initiation, development, operation	Construct a tamper-proof DPP architecture	The (green) hydrogen market is only viable if the accuracy of emissions and environmental data can be guaranteed. A tamper-proof architecture assures the authenticity of the data and thus enables high data quality	Asante et al. (2022); Berger et al. (2022); Bodkhe et al. (2020); Liu et al., (2021a, b); Rana et al. (2021); Sezer et al. (2022)

Table 4 (continued)

ID	Design principle	Aim	Context	Mechanism	Rationale	Supporting literature
DP-5	Automated passport processing	Enable efficient and automatic updates of the DPP along the value chain	Operation	Apply a recursive approach where one single DPP verifies the past value chain stages by merging several DPPs into a new DPP with accurate, up-to-date information	The production process as well as transport and storage of hydrogen means the occurrence of emissions at many points in the value chain. It is also possible that hydrogen is mixed with hydrogen produced in other ways at certain points in the chain. All this information must be recorded and updated in the DPP so that the DPP outputs the correct information at each point of the value chain	Westerkamp et al. (2020)
DP-6	Interoperability	Enable integration of the DPP in established information as well as certification systems	Development	Construct an interoperable DPP architecture which permits connection and communication to stakeholders' established information systems and contains information needed for different standards of sustainability certification or reporting	Interoperability is key in enabling a quick and easy dissemination of the DPP system among H_2 value chain stakeholders which in turn is the condition for the success of the DPP and its use in a sustainable international H_2 market	Ahmed and MacCarthy (2021); Hardt et al. (2017); Menon and Jain (2022); Raja Santhi and Muthuswamy (2022); Tsolakis et al. (2021)

H_2 is short for hydrogen

et al., 2019). As stated in the previous sections, the core function of a DPP is traceability. The need for sustainability disclosure for decarbonizing hydrogen supply chains is the main driver for developing a DPP that enables verification of hydrogen origins and usage. Complex and international hydrogen supply chains result in a high number of different stakeholders in an ecosystem using DPPs. As a result, individual stakeholders lose track of what happens to data they share in the system and how it is used by others. This leads to the issue that the willingness to share their data in the first place is limited because they fear losing control over their own data (Liu et al., 2021b). In some industrial processes, such as steel production, precise disclosure of hydrogen data also allows conclusions to be drawn about the production processes and should therefore also be minimized from an antitrust perspective. The design of a DPP must incorporate privacy-preserving measures that ensure that stakeholders are willing to share data within the DPP but keep sovereignty over their data. DPPs can ensure this through disclosure of selected data that is necessary to enable traceability but does not lead to full visibility of sensitive business information. Such technical approaches for tracing systems that satisfy privacy requirements already exist in literature — see Babel et al. (2022). This design principle solves challenges C-2 and C-3 as well as C-5 and C-6 and, thus, addresses meta-requirement MR-2.

DP-3 — decentralized data administration: In order to avoid a central authority that has to be trusted by all stakeholders of the DPP—which is of particular relevance in international and intercontinental supply chains—our research illustrates that a decentralized data administration should be reflected in the design of a DPP. A decentralized data administration ensures collaboration without agreeing on a central entity for data administration and can address the vulnerability of systems as it prevents single-point failures since an attack or technological failure at one point does not lead to an entire failure of the DPP infrastructure. This is particularly important since hydrogen networks are likely to grow and be distributed globally in countries and regions with different regulatory bodies. This design principle includes establishing a decentralized structure that does not assign a single authority to manage data and, thus, does not collect data in a central location. Moreover, to ensure the smooth operation of this distributed DPP system, it is necessary to define clear governance, e.g., concerning rules on access and editing rights of each stakeholder. The design principle therefore addresses the challenges C-4, C-5, and C-6 and mainly supports meta-requirement MR-3.

DP-4 — forgery-proof data: Our research illustrates that data integrity is indispensable to ensure a DPP's usefulness and applicability (Bodkhe et al., 2020; Zhao et al., 2019). The trade and use of hydrogen will have a significant impact on promoting sustainability. In order to fully exploit this leverage, it is of particular importance to ensure the accuracy of certification for this product. Hence, this design principle is essential to enable verification along the hydrogen supply chain. A tamper-proof architecture ensures stakeholders' trust in a DPP system and reduces the fear of data misuse. In order to achieve forgery-proof data, one could include the use of cryptographic or decentralized approaches such as Blockchain technology to ensure tamper-proof data input and transfer. We note that our interviewees mention that directly writing primary data on a transparent ledger, such as blockchains, is not an option at all. One approach would be to develop secure authentication for stakeholders with editing rights to prevent manipulation from unauthorized parties. Besides, it is important to already install security mechanisms at the data entry devices to guarantee data integrity at the very beginning of the data transfer. Challenges C-5, C-6, and C-7 are thus considered by this design principle. Since the forgery-proof data ensures the quality of traceability and the trustworthiness of the system the design principle addresses meta-requirements MR-1 and MR-3.

DP-5 — automated passport processing: Processing a DPP along an entire hydrogen supply chain is complex (c.f. Figure 1), as the supply chain is globally meshed with various stakeholders at different levels of the supply chain. Therefore, automated processing of information shared within a DPP is necessary to ensure efficient data management on the stakeholders' side. This also includes the option to aggregate DPPs with different supply chain histories in the sense of cross-organizational collaboration across different domains. Especially for a hydrogen supply chain, automated passport processing is important as this market contains various stages, such as production, conversion, transport, or storage, that all influence the hydrogen's environmental and social footprint. The automated process also needs to address the specifics of the hydrogen supply chain in more detail. For example, certain transport containers can never be completely emptied, but mix different batches of hydrogen together, which also affects the environmental impact of each delivery. When it is necessary to create a new DPP — e.g., due to a transformation step in the supply chain — the DPP must automatically verify previous information, incorporate new information, and aggregate it into a new DPP. Hence, this design principle ensures that the DPP always holds accurate and includes the most recent information. It, thus, addresses challenge C-9 and realizes meta-requirement MR-1.

DP-6 — interoperability: A DPP is especially useful and realizable when it can be used with already existing systems. On the one hand, this includes technical interoperability. This means that data from different systems can be used and incorporated into the DPP. On the other hand, a DPP should be interoperable with various existing certifications (e.g., AFHYPAC and CERTIFHY) and sustainability standards (e.g., TÜV SÜD, BEIS, and California Low Carbon Fuel Standard). For global verification of hydrogen, DPPs must function across existing certification standards and reporting requirements. Therefore, DPPs must be designed interoperable. Both technical and functional interoperability with existing systems must be ensured so that the DPPs can be used without problems and greater investments in the future. The design principle solves challenge C-8 and fulfills meta-requirement MR-1.

Discussion and contribution

In the following section, we first discuss the previously presented results and findings, and further, we elaborate on our theoretical und practical contributions.

Our research yields six design principles for a DPP that brings verification to hydrogen supply chains and, thus, promotes decarbonization in the industrial sector. The final set of design principles provides guidance for the development of a DPP that addresses the problem of information asymmetries along hydrogen supply chains. The implementation of DPPs permits the verification of the carbon footprint of a product-specific hydrogen supply chain, and therefore, it enables the internalization of social costs that occur through environmental damage. In this sense, we consider IS-based solutions, i.e., a DPP, as enablers for increasing trust by verifiability that is a prerequisite for the emergence of international and complex markets for low-carbon hydrogen. Our study thus contributes to the use of data sharing for solving societal challenges and promoting sustainability. With the focus on hydrogen supply chains, our work also finds application in the energy informatics context as it helps to effectively advance the energy transition in line with sustainability goals and find digital solutions that simplify sustainability verification in complex globalized contexts. At the same time, our work studies the potential of data sharing for environmental purposes and the challenges that need to be considered. With our derived challenges and meta-requirements being application-agnostic, we contribute by illustrating how to enable data-sharing for cross-organizational collaboration along the supply chain in the sense of verifiability and how to gain stakeholders' trust in DPPs through privacy-enhancing approaches.

The core of our developed artifact lies in guidelines on how to enable an efficient sharing and use of data for promoting sustainability. We follow the work of vom Brocke et al. (2013) and provide insights for IS and research on data sharing that aims at solving the challenge of information asymmetry in international supply chains concerning sustainability. To ensure the applicability of our research outside the IS community, we brought in the perspective of hydrogen experts and stakeholders from the energy sector and, hence, gained valuable interdisciplinary insights for our research (vom Brocke et al., 2013). In doing so, we are paving the way to endorse initial literature that aims at connecting the research streams of data economies and Green IS, such as Zeiss et al. (2021), while we also use our work to apply the IS-enabled solution to other contexts and support progress in other disciplines.

Discussion

Nevertheless, our research also clearly carries out that the willingness to use and an adoption of a DPP in practice strongly depends on its design and how data is shared with respect to privacy concerns. Hence, the design principles developed in this work respect the concerns of different stakeholders regarding data sharing and traceability systems and incorporate the requirements into the DPP design (c.f. Table 5). In particular, we address the need for confidentiality and the protection of sensitive business information with the privacy preserving DP-2. Moreover, DP-4 prevents data misuse and, thus, removes an essential concern against data sharing. Thereby, we also note that one challenge in the actual development of DPPs that needs to be solved is

Table 5 Overview of design principles and corresponding challenges and meta-requirements

ID	Design principle	Addressed challenges	Supported meta-requirement
DP-1	Holistic data capture	C-1	MR-1
DP-2	Data privacy	C-2, C-3, C-5, C-6	MR-2
DP-3	Decentralized data administration	C-4, C-5, C-6	MR-3
DP-4	Forgery-proof data	C-5, C-6, C-7	MR-1, MR-3
DP-5	Automated passport processing	C-9	MR-1
DP-6	Interoperability	C-8	MR-1

the balancing of the design principles with the right nuance to successfully combine interests of different stakeholders.

As mentioned above, we see clear synergies of our conceptualization of a DPP with the research field of data ecosystems. The goal of a DPP for hydrogen supply chains is to use it as a tool to create value for each stakeholder in the value chain, as each stakeholder is more likely to benefit from price premiums for low-carbon hydrogen if verification through a DPP can be ensured. Hence, this value is only created when all supply chain stakeholders collaborate in sharing their data along the chain by using DPPs. Therefore, we link our research to data ecosystems that aim for enabling collaboration and data sharing for the benefit of all stakeholders. The core principles of data ecosystems harmonize with the design principles of our research: sharing data in a decentralized ecosystem (cf. DP-3), protecting the data sovereignty of data providers (cf. DP-2), and thus avoiding power imbalances (Aaen et al., 2022), and reducing the need to trust all other participants (Gelhaar & Otto, 2020; Otto & Jarke, 2019).

Nonetheless, we acknowledge that there may be points for discussion concerning specific design principles. A general question is the feasibility of implementing the design principles. The paradigms and digital technologies that we mentioned above and that may be applied for a real-world implementation of DPPs, such as ZKPs or self-sovereign identities (Babel et al., 2022), still have to reach certain technology readiness levels. Further, we note that only the capturing of all relevant sustainability data can realize a DPP's full potential, i.e., including information on social conditions of a product, such as "good working conditions." However, our interviewees state that it is difficult to include those in a well-measurable way because this information is often vague. Thus, to develop a realizable and concrete solution for the pressing challenge of climate change, we decide to focus the design of the DPP on the ecological aspect of sustainability, i.e., decarbonization, without losing any generalizability, especially regarding the contributions on how to share data in global supply chains.

While a DPP receives sufficient data through DP-1, DP-4 ensures their accuracy to enable verifiability of the supply chain's carbon footprint. Here, a challenge may be to merge both design principles, i.e., to ensure integrity (DP-4) already at the data collection stage (DP-1) and to collect verifiably primary data (interviewees 2, 3, and 8). This challenge is of course related to the Oracle problem (Babel et al., 2023), which still needs to be solved in this context. Additionally, DP-1 and DP-2 need to be balanced since data capture and, thus, also data sharing may contrast with stakeholders' privacy needs (Menon & Jain, 2022; Interviewee 10). While selective disclosure of data is key to ensure DP-2, we expect the practice to define which concrete data must necessarily be shared in a DPP and which can be withheld by the stakeholders. Moreover, as outlined in Section "Background and Related Work," there are some approaches in IS and supply chain research that explore blockchain solutions for traceability and verifiability (Asante et al., 2022; Menon & Jain, 2022; Saberi et al., 2019). However, while decentralized solutions such as blockchain and distributed ledger technologies ensure verifiability through immutability and, thus, address DP-3 and DP-4, pure blockchain-based solutions may have an issue with data privacy (Ishmaev, 2021) or high energy consumption (Sedlmeir et al., 2020). While there are new blockchain approaches that do not characterize as energy intense technologies (Sedlmeir et al., 2021a), we note that blockchain is only one of several building blocks for decarbonization and traceability solutions (Körner et al., 2023). Research already knows the first approaches to overcome the privacy issue by combining blockchain solutions with identity management and other decentralized technologies to enable data sharing without absolute disclosure (Babel et al., 2022; Körner et al., 2022). This privacy issue also influences DP-5: While our research illustrates that it is inevitable to process and forward the DPP in a user-friendly and automated manner, our interviewees are not sure about how the aggregation of data from previous supply chain stages may work—partly as this also depends on which data is needed and disclosed to other stakeholders of the supply chain. Nevertheless—and as all of our interviewees confirm—our design principles provide a necessary and essential basis for implementing such a DPP in practice.

Regarding the implementation of a hydrogen DPP, our research holds several initial insights that we illustrate in the following. Hereby, our design principles may serve as a valuable guideline in the process of prototyping and field testing of the DPP. As already indicated in relation to the individual design principles, various approaches are either already in place or are in the process of being developed to fulfill the various characteristics. Against this background, for example, DP-3 guides developers to consider concepts such as distributed ledger technology and data ecosystems which are becoming increasingly relevant for decentralized data administration (Saberi et al., 2019). Moreover and in regard to privacy requirements, DP-2 ensures that implementation may include digital (machine) identities and approaches such as self-sovereign identities, combined with ZKPs, to enable verification without data disclosure (Babel et al., 2023). Further, the addition of an immutable layer such as blockchain technology into the DPP infrastructure may be required to fulfill DP-4 and to make those ZKPs forgery-proof (Babel et al., 2022). In addition, DP-1 and DP-5 indicate that extensive research and development in the field of IoT making data collection and automated processing increasingly efficient and accurate should be considered for the DPP implementation (Fotiou et al., 2018). On top of that, DP-6 urges developers to consider and actively participate in the many consortia which are working on standardizing these concepts and technologies, making a major contribution to future interoperability (ETSI, 2023). Developers of the DPP should familiarize themselves with the existing approaches and may apply our design principles when designing and implementing a DPP. However, real-world implementations still need to reflect on how to combine the design principles in a suitable manner and prioritize them according to the stakeholders' needs.

Theoretical and practical contribution

With our work, we extend the existing body of knowledge concerning data sharing and supply chain traceability for sustainability. While the research field of data sharing for cross-organizational collaboration is increasingly growing (Beverungen et al., 2022; Fürstenau et al., 2021), it leaves space for concrete consideration of how data sharing can play a role in the pressing global challenge of decarbonization. Moreover, if literature considers the relevance of tracing sustainability-related data in supply chains, it often lacks an appropriate consideration of data sovereignty and privacy (Berger et al., 2022; Tsolakis et al., 2021). Our work contributes by combining these two foci and elaborating on traceability of sustainability-related data in supply chains from a data sharing and data ecosystem perspective. While hydrogen is an energy carrier of particular relevance in the course of the energy transition towards decarbonization, we also contribute to energy system-based research and on scholarly work in the context of energy informatics by providing insights on the topic of guarantees of origin and on how to verify hydrogen's carbon footprint (Burmistrz et al., 2016; Velazquez Abad & Dodds, 2020). With our results, we continue to expand Green IS research by laying a foundation for how IS and digital technologies may contribute to sustainable development in the form of DPPs, providing solutions to a pressing societal challenge (vom Brocke et al., 2013). Finally, we contribute to our academic repertoire by illustrating how we can overcome market asymmetries—in our context with respect to carbon footprints—to promote the establishment of new or more efficient markets, thereby extending the literature on quality uncertainty and market failure (Akerlof, 1978). With our IS-based approach, we pave the way to remove the need for non-verifiable color-code on international hydrogen markets. Moreover, our DPP enables more specific pricing mechanisms—either from the supplier or from the customer side — that can reflect the social costs of products, i.e., their carbon footprint.

Further, our findings demonstrate how supply chain verifiability for hydrogen can be enabled through IS and how data sharing among unknown stakeholders can be implemented while preserving privacy and contributing to the global challenge of sustainability and decarbonization. In doing so, our design principles for a DPP provide a basis for a nascent design theory regarding the topics of data sharing, supply chain traceability, and decarbonization of the energy sector (Gregor & Hevner, 2013). Accordingly, and in line with Gregor and Jones (2007), we present six components of a nascent design theory based on our research while the components specify our theoretical contribution (Table 6).

We note that the two additional components that are mentioned by Gregor and Jones (2007), namely, principles of implementation and expository instantiation, are subject for further research or application in practice as we do not yet implement the DPP.

Concerning the practical contribution of our work, our interviewees strongly confirm that the hydrogen market is gaining relevance and that various industries are in need of a reliable traceability system for sustainable hydrogen to verify the hydrogen's carbon footprint (White et al., 2021). Whether impelled by regulation, shareholders, or market pressure, our whole economy is in the process of improving its carbon disclosure and accurate sustainability reporting. The verification of hydrogen supply chains proves to be a significant part in this. Our research contributes to this development and provides a starting point for a real-world application of a DPP in hydrogen supply chains to enable markets for low-carbon products. The design principles

Table 6 Components of a nascent IS design theory based on our results (Gregor & Jones, 2007)

Component	Description
Purpose and scope	The aim of our research is to bring verification in hydrogen supply chains by enabling traceability and ensuring trustworthiness while preserving privacy
Constructs	Supply chain traceability, data sharing, information asymmetry, carbon disclosure
Principle of form and function	Six design principles for a DPP to verify hydrogen supply chains
Artifact mutability	The DPP is subject to change during further development and evaluation cycles due to additional challenges and expertise incorporated in the DPP
Testable proposition	The application of the design principles in the development of a DPP leads to a reliable traceability system that verifies hydrogen supply chains and accounts for stakeholders' privacy concerns
Justificatory knowledge	Knowledge of data sharing, supply chain traceability, sustainability certification, and hydrogen economy

represent guidelines on how the DPP must be designed to be applicable for industries. They serve as components that future developers may consider and incorporate in the development of the DPPs.

Moreover, our design principles highly underline the privacy concerns of different supply chain stakeholders and protect sensitive business data up to a certain level while enabling reliable traceability and, thus, verification of hydrogen. Our work holds thereby relevant insights for existing certification solutions and lays the foundation for an overarching traceability system across borders and jurisdictions. In addition, our research enables the hydrogen industry to not only categorize hydrogen into one specific color, i.e., by applying the DPP, hydrogen is not labeled as "green" or "not green" according to specific criteria but displays relevant sustainability criteria quantitatively and with different gradations. Consequently, the DPP is able to display improvements in hydrogen supply chains. This is essential for enabling efficient markets in which differentiated products are traded with different market values depending on their degree of sustainability.

Conclusion and outlook

An increasingly pressing demand for verification of sustainability-related information in globalized supply chains, e.g., the certification of low-carbon hydrogen, requires evolving and new solutions for digital traceability. In line with previous work, our research highlights that digital technologies are a key-enabler for such solutions, i.e., for sharing relevant information along the supply chain and establishing global markets for sustainable products by reducing information asymmetries that will prevent market failures of sustainable commodities and support decarbonization in industry — especially in the energy sector. By verifiably certifying the carbon footprint of hydrogen, corresponding environmental damage can be priced in, and thus, negative externalities can be internalized, enabling manufacturers of low-carbon hydrogen to demand price premiums for their environmentally friendly production methods. As we outline in this paper, such verifiable information may be passed along the supply chain in the form of a DPP. Thus, our research develops design principles for a hydrogen DPP to share verifiable production data along a highly complex, international supply chain while following the multi-step approach with a structured literature review followed by expert interviews and qualitative content analysis. Based on this, we derive six design principles for such a DPP, namely, (1) holistic data capture, (2) data privacy, (3) decentralized data administration, (4) forgery-proof data, (5) automated passport processing, and (6) interoperability. While we link our findings to previous literature from our domains, we specifically discuss the role of IS for addressing data sovereignty and privacy concerns regarding data sharing. We note that our solution can enable collaboration between untrusted stakeholders for supply chain traceability. With our findings, we extend the research in data ecosystems and provide new insights for supply chain traceability. In addition, our design principles serve as guidelines for the implementation of a digital traceability solution and, thus, are highly relevant for practice.

Nevertheless, our work is subject to specific limitations. The selected criteria for our literature review, such as keywords, databases, and relevance criteria, are subjective and, if modified and extended, may lead to other results. Furthermore, our evaluation was limited by 13 interviews with experts from research and industry. Although the interviewees represented a valuable sample of experts in the field of digital traceability solutions, data sharing, and hydrogen stakeholders, more interviews with representatives of the hydrogen economy with different backgrounds and knowledge on certification and data sharing challenges might have provided more insight into the needs and requirements of the respective supply chain stakeholders. In addition, it was up to the paper team to weigh the statements accordingly and draw final conclusions for the design principles of the hydrogen DPP.

Our work also opens up research opportunities for future work. While the design principles are an important step towards the introduction of the DPP, they need to be evaluated not only theoretically but also implemented and tested in pilot projects to address the urgent need for applicable solutions in the context of decarbonization. Thus, future research may investigate how to implement the design principles. Scholars may also shed specific light on the role of different digital technologies for balancing data privacy and transparency or for ensuring interoperability while maintaining digital verifiability. Further, future work may also analyze how to set up a corresponding data infrastructure at the organization level that is able to provide the necessary information for DPPs. Moreover, future research may also dive into the process of proposing a target-oriented alignment of the regulatory environment to enable DPPs. While hydrogen provides a concrete example as its certification plays a major role in decarbonization, scholars may discuss the applicability of our results in other supply chains. For this, it would also be beneficial to investigate how different solutions of individual supply chains can be made interoperable to interact with each other. Therefore, as a first step, future work could investigate the compatibility of green electricity certificates with the hydrogen DPP. In the long term, the DPPs of each product may be interoperable.

In conclusion, current developments provide many opportunities to further explore and investigate the topic of DPPs and data sharing in a globalized data economy. The question of how data sharing, and IS in general, can contribute to decarbonization and combating climate crisis by enabling the traceability and verification of sustainability-related information is urging and provides a plethora of future research opportunities.

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Declarations

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References

Aaen, J., Nielsen, J. A., & Carugati, A. (2022). The dark side of data ecosystems: A longitudinal study of the DAMD project. *European Journal of Information Systems, 31*(3), 288–312. https://doi.org/10.1080/0960085X.2021.1947753

Adisorn, T., Tholen, L., & Götz, T. (2021). Towards a digital product passport fit for contributing to a circular economy. *Energies, 14*(8), 2289. https://doi.org/10.3390/en14082289

Agahari, W., Ofe, H., & de Reuver, M. (2022). It is not (only) about privacy: How multi-party computation redefines control, trust, and risk in data sharing. *Electronic Markets, 32*(2), 1577–1602. https://doi.org/10.1007/s12525-022-00572-w

Ahmed, W. A. H., & MacCarthy, B. L. (2021). Blockchain-enabled supply chain traceability in the textile and apparel supply chain: A case study of the fiber producer, Lenzing. *Sustainability, 13*(19), 10496. https://doi.org/10.3390/su131910496

Akerlof, G. A. (1978). The market for "lemons": Quality uncertainty and the market mechanism. In *Uncertainty in Economics* (pp. 235–251). Elsevier. https://doi.org/10.1016/B978-0-12-214850-7.50022-X

Akhtar, M. S., Khan, H., Liu, J. J., & Na, J. (2023). Green hydrogen and sustainable development – A social LCA perspective highlighting social hotspots and geopolitical implications of the future hydrogen economy. *Journal of Cleaner Production, 395*, 136438. https://doi.org/10.1016/j.jclepro.2023.136438

Alter, S. (2013). Work system theory: Overview of core concepts, extensions, and challenges for the future. *Journal of the Association for Information Systems, 14*(2), 72–121. https://doi.org/10.17705/1jais.00323

Appelhanz, S., Osburg, V.-S., Toporowski, W., & Schumann, M. (2016). Traceability system for capturing, processing and providing consumer-relevant information about wood products: System solution and its economic feasibility. *Journal of Cleaner Production, 110*, 132–148. https://doi.org/10.1016/j.jclepro.2015.02.034

Asante, M., Epiphaniou, G., Maple, C., Al-Khateeb, H., Bottarelli, M., & Ghafoor, K. Z. (2022). Distributed ledger technologies in supply chain security management: A comprehensive survey. *IEEE Transactions on Engineering Management*, 1–27. https://doi.org/10.1109/TEM.2021.3053655

Ashley, M. J., & Johnson, M. S. (2018). Establishing a secure, transparent, and autonomous blockchain of custody for renewable energy credits and carbon credits. *IEEE Engineering Management Review, 46*(4), 100–102. https://doi.org/10.1109/EMR.2018.2874967

Babel, M., Gramlich, V., Körner, M.-F., Sedlmeir, J., Strüker, J., & Zwede, T. (2022). Enabling end-to-end digital carbon emission tracing with shielded NFTs. *Energy Informatics, 5*(S1), 27. https://doi.org/10.1186/s42162-022-00199-3

Babel, M., Gramlich, V., Guthmann, C., Schober, M., Körner, M.-F., & 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), 478–493. https://doi.org/10.1365/s40702-023-00955-3

Bauer, I., Zavolokina, L., & Schwabe, G. (2020). Is there a market for trusted car data? *Electronic Markets, 30*(2), 211–225. https://doi.org/10.1007/s12525-019-00368-5

Berger, K., Schöggl, J.-P., & Baumgartner, R. J. (2022). Digital battery passports to enable circular and sustainable value chains: Conceptualization and use cases. *Journal of Cleaner Production, 353*, 131492. https://doi.org/10.1016/j.jclepro.2022.131492

Berger, K., Baumgartner, R. J., Weinzerl, M., Bachler, J., Preston, K., & Schöggl, J.-P. (2023). Data requirements and availabilities for a digital battery passport – A value chain actor perspective. *Cleaner Production Letters, 4*, 100032. https://doi.org/10.1016/j.clpl.2023.100032

Beverungen, D., Hess, T., Köster, A., & Lehrer, C. (2022). From private digital platforms to public data spaces: Implications for the digital transformation. *Electronic Markets, 32*(2), 493–501. https://doi.org/10.1007/s12525-022-00553-z

Bjørn, A., Lloyd, S. M., Brander, M., & Matthews, H. D. (2022). Renewable energy certificates threaten the integrity of corporate science-based targets. *Nature Climate Change, 12*(6), 539–546. https://doi.org/10.1038/s41558-022-01379-5

Bodkhe, U., Tanwar, S., Parekh, K., Khanpara, P., Tyagi, S., Kumar, N., & Alazab, M. (2020). Blockchain for Industry 4.0: A comprehensive review. *IEEE Access, 8*, 79764–79800. https://doi.org/10.1109/ACCESS.2020.2988579

Bouwman, H., Nikou, S., Molina-Castillo, F. J., & de Reuver, M. (2018). The impact of digitalization on business models. *Digital Policy, Regulation and Governance, 20*(2), 105–124. https://doi.org/10.1108/DPRG-07-2017-0039

Burmistrz, P., Chmielniak, T., Czepirski, L., & Gazda-Grzywacz, M. (2016). Carbon footprint of the hydrogen production process utilizing subbituminous coal and lignite gasification. *Journal of Cleaner Production, 139*, 858–865. https://doi.org/10.1016/j.jclepro.2016.08.112

Cocco, L., Tonelli, R., & Marchesi, M. (2021). Blockchain and self sovereign identity to support quality in the food supply chain. *Future Internet, 13*(12), 301. https://doi.org/10.3390/fi13120301

Da Rosado Cruz, A., Santos, F., Mendes, P., & Cruz, E. (2020). Blockchain-based traceability of carbon footprint: A solidity smart contract for Ethereum. *Proceedings of the 22nd International Conference on Enterprise Information Systems* (pp. 258–268). SCITEPRESS - Science and Technology Publications. https://doi.org/10.5220/0009412602580268

Djamali, A., Dossow, P., Hinterstocker, M., Schellinger, B., Sedlmeir, J., Völter, F., & Willburger, L. (2021). Asset logging in the energy sector: A scalable blockchain-based data platform. *Energy Informatics, 4*(S3), 22. https://doi.org/10.1186/s42162-021-00183-3

Downar, B., Ernstberger, J., Reichelstein, S., Schwenen, S., & Zaklan, A. (2021). The impact of carbon disclosure mandates on emissions and financial operating performance. *Review of Accounting Studies, 26*(3), 1137–1175. https://doi.org/10.1007/s11142-021-09611-x

Ebinger, F., & Omondi, B. (2020). Leveraging digital approaches for transparency in sustainable supply chains: A conceptual paper. *Sustainability, 12*(15), 6129. https://doi.org/10.3390/su12156129

ETSI. (2023). *Electronic Signatures and Infrastructures (ESI); Analysis of selective disclosure and zero-knowledge proofs applied to Electronic Attestation of Attributes: Technical report.* European Telecommunications Standards Institute. https://www.etsi.org/deliver/etsi_tr/119400_119499/119476/01.01.01_60/tr_119476v010101p.pdf. Accessed 9 Jan 2024

European Commission. (2021). *Proposal for a directive of the European parliament and of the council amending Directive 2013/34/EU, Directive 2004/109/EC, Directive 2006/43/EC and Regulation (EU) No 537/2014, as regards corporate sustainability reporting*. https://eur-lex.europa.eu/legal-content/EN/TXT/HTML/?uri=CELEX:52021PC0189. Accessed 9 Jan 2024

European Commission. (2022). *Proposal for a directive of the European parliament and of the council on corporate sustainability due diligence and amending Directive: EU-2019/1937*. European Commission. https://eur-lex.europa.eu/resource.html?uri=cellar:bc4dcea4-9584-11ec-b4e4-01aa75ed71a1.0001.02/DOC_1&format=PDF. Accessed 9 Jan 2024

Falcone, P. M., Hiete, M., & Sapio, A. (2021). Hydrogen economy and sustainable development goals: Review and policy insights. *Current Opinion in Green and Sustainable Chemistry, 31*, 100506. https://doi.org/10.1016/j.cogsc.2021.100506

Fotiou, N., Siris, V. A., Mertzianis, A., & Polyzos, G. C. (2018). Smart IoT data collection. *2018 IEEE 19th International Symposium on "A World of Wireless, Mobile and Multimedia Networks" (WoWMoM)* (pp. 588–599). IEEE. https://doi.org/10.1109/WoWMoM.2018.8449766

Fürstenau, D., Klein, S., Vogel, A., & Auschra, C. (2021). Multi-sided platform and data-driven care research. *Electronic Markets, 31*(4), 811–828. https://doi.org/10.1007/s12525-021-00461-8

Gelhaar, J., & Otto, B. (2020). Challenges in the emergence of data ecosystems. *Proceedings of the 24th Pacific Asia Conference on Information Systems*. https://aisel.aisnet.org/pacis2020/175/

Gelhaar, J., Groß, T., & Otto, B. (2021). A taxonomy for data ecosystems. *Proceedings of the 54th Hawaii International Conference on System Sciences*. http://hdl.handle.net/10125/71359

Gregor, S., & Hevner, A. R. (2013). Positioning and presenting design science research for maximum impact. *MIS Quarterly, 37*(2), 337–355. https://doi.org/10.25300/MISQ/2013/37.2.01

Gregor, S., Kruse, L., & Seidel, S. (2020). Research perspectives: The anatomy of a design principle. *Journal of the Association for Information Systems, 21*, 1622–1652. https://doi.org/10.17705/1jais.00649

Gregor, S., & Jones, D. (2007). The anatomy of a design theory. *Journal of the Association of Information Systems*, *8*(5), 60. http://hdl.handle.net/1885/32762

Hahn, R., Reimsbach, D., & Schiemann, F. (2015). Organizations, climate change, and transparency: Reviewing the literature on carbon disclosure. *Organization & Environment, 28*(1), 80–102. https://doi.org/10.1177/1086026615575542

Hardt, M. J., Flett, K., & Howell, C. J. (2017). Current barriers to large-scale interoperability of traceability technology in the seafood sector. *Journal of Food Science, 82*(S1), A3–A12. https://doi.org/10.1111/1750-3841.13796

Heinz, D., Benz, C., Fassnacht, M., & Satzger, G. (2022). Past, present and future of data ecosystems research: A systematic literature review. *Proceedings of the 26th Pacific Asia Conference on Information Systems*. https://aisel.aisnet.org/pacis2022/46/

Hevner, A. R., March, S. T., Park, J., & Ram, S. (2004). Design science in information systems research. *Management Information Systems Quarterly, 28*, 75. https://doi.org/10.2307/25148625

Husarek, D., Schmugge, J., & Niessen, S. (2021). Hydrogen supply chain scenarios for the decarbonisation of a German multi-modal energy system. *International Journal of Hydrogen Energy, 46*(76), 38008–38025. https://doi.org/10.1016/j.ijhydene.2021.09.041

Ishmaev, G. (2021). Sovereignty, privacy, and ethics in blockchain-based identity management systems. *Ethics and Information Technology, 23*(3), 239–252. https://doi.org/10.1007/s10676-020-09563-x

Jansen, M., Meisen, T., Plociennik, C., Berg, H., Pomp, A., & Windholz, W. (2023). Stop guessing in the dark: Identified requirements for digital product passport systems. *Systems, 11*(3), 123. https://doi.org/10.3390/systems11030123

Jarke, M., Otto, B., & Ram, S. (2019). Data sovereignty and data space ecosystems. *Business & Information Systems Engineering, 61*(5), 549–550. https://doi.org/10.1007/s12599-019-00614-2

Jensen, S. F., Kristensen, J. H., Adamsen, S., Christensen, A., & Waehrens, B. V. (2023). Digital product passports for a circular economy: Data needs for product life cycle decision-making. *Sustainable Production and Consumption, 37*, 242–255. https://doi.org/10.1016/j.spc.2023.02.021

Jetzek, T., Avital, M., & Bjorn-Andersen, N. (2019). The sustainable value of open government data. *Journal of the Association for Information Systems*, 702–734. https://doi.org/10.17705/1jais.00549

Kaplan, R. S., & Ramanna, K. (2021). *Accounting for climate change - The first rigorous approach to ESG reporting*. Harvard Business Review. https://hbr.org/2021/11/accounting-for-climate-change

King, M. R., Timms, P. D., & Mountney, S. (2023). A proposed universal definition of a Digital Product Passport Ecosystem (DPPE): Worldviews, discrete capabilities, stakeholder requirements and concerns. *Journal of Cleaner Production, 384*, 135538. https://doi.org/10.1016/j.jclepro.2022.135538

Körner, M.-F., Sedlmeir, J., Weibelzahl, M., Fridgen, G., Heine, M., & Neumann, C. (2022). Systemic risks in electricity systems: A perspective on the potential of digital technologies. *Energy Policy, 164*, 112901. https://doi.org/10.1016/j.enpol.2022.112901

Körner, M.-F., Schober, M., Ströher, T., & Strüker, J. (2023) Digital carbon accounting for accelerating decarbonization: Characteristics of IS-enabled system architectures. *Proceedings of the 29th Americas Conference on Information Systems (AMCIS).* Panama City, Panama: 2023.

Krasikov, P., & Legner, C. (2023). Introducing a data perspective to sustainability: How companies develop data sourcing practices for sustainability initiatives. *Communications of the Association for Information Systems*(53). https://aisel.aisnet.org/cais/vol53/iss1/5

Leng, K., Bi, Y., Jing, L., Fu, H.-C., & van Nieuwenhuyse, I. (2018). Research on agricultural supply chain system with double chain architecture based on blockchain technology. *Future Generation Computer Systems, 86*, 641–649. https://doi.org/10.1016/j.future.2018.04.061

Li, L., Manier, H., & Manier, M.-A. (2019). Hydrogen supply chain network design: An optimization-oriented review. *Renewable and Sustainable Energy Reviews, 103*, 342–360. https://doi.org/10.1016/j.rser.2018.12.060

Li, J., Maiti, A., Springer, M., & Gray, T. (2020). Blockchain for supply chain quality management: Challenges and opportunities in context of open manufacturing and industrial internet of things. *International Journal of Computer Integrated Manufacturing, 33*(12), 1321–1355. https://doi.org/10.1080/0951192X.2020.1815853

Lis, D., & Otto, B. (2020). Data governance in data ecosystems – Insights from organizations. *Proceedings of the 26th Americas Conference* *on Information Systems*. https://aisel.aisnet.org/amcis2020/strategic_uses_it/strategic_uses_it/12/

Liu, P., Hendalianpour, A., Hamzehlou, M., Feylizadeh, M. R., & Razmi, J. (2021a). Identify and rank the challenges of implementing sustainable supply chain blockchain technology using the Bayesian best worst method. *Technological and Economic Development of Economy, 27*(3), 656–680. https://doi.org/10.3846/tede.2021.14421

Liu, W., Shao, X.-F., Wu, C.-H., & Qiao, P. (2021b). A systematic literature review on applications of information and communication technologies and blockchain technologies for precision agriculture development. *Journal of Cleaner Production, 298*, 126763. https://doi.org/10.1016/j.jclepro.2021.126763

Luers, A., Yona, L., Field, C. B., Jackson, R. B., Mach, K. J., Cashore, B. W., Elliott, C., Gifford, L., Honigsberg, C., Klaassen, L., Matthews, H. D., Peng, A., Stoll, C., van Pelt, M., Virginia, R. A., & Joppa, L. (2022). Make greenhouse-gas accounting reliable — Build interoperable systems. *Nature, 607*(7920), 653–656. https://doi.org/10.1038/d41586-022-02033-y

Menon, S., & Jain, K. (2022). Blockchain technology for transparency in agri-food supply chain: Use cases, limitations, and future directions. *IEEE Transactions on Engineering Management*, 1–15. https://doi.org/10.1109/TEM.2021.3110903

Müller, F., Leinauer, C., Hofmann, P., Körner, M.-F., & Strüker, J. (2023). Digital decarbonization: Design principles for an enterprise-wide emissions data architecture. *Proceedings of the 56th Hawaii International Conference on System Sciences (HICSS)*. - Maui, USA 2023.

Nozari, H., Szmelter-Jarosz, A., & Ghahremani-Nahr, J. (2022). Analysis of the challenges of artificial intelligence of things (AIoT) for the smart supply chain (case study: Fmcg Industries). *Sensors, 22*(8), 2931. https://doi.org/10.3390/s22082931

Oliveira, M. I. S., & Lóscio, B. F. (2018). What is a data ecosystem? In *Proceedings of the 19th Annual International Conference on Digital Government Research: Governance in the Data Age* (pp. 1–9). ACM. https://doi.org/10.1145/3209281.3209335

Otto, B., & Jarke, M. (2019). Designing a multi-sided data platform: Findings from the International Data Spaces case. *Electronic Markets, 29*(4), 561–580. https://doi.org/10.1007/s12525-019-00362-x

Peffers, K., Tuunanen, T., Rothenberger, M. A., & Chatterjee, S. (2007). A design science research methodology for information systems research. *Journal of Management Information Systems, 24*(3), 45–77. https://doi.org/10.2753/MIS0742-1222240302

Plociennik, C., Pourjafarian, M., Saleh, S., Hagedorn, T., Carmo Precci Lopes, Alice do, Vogelgesang, M., Baehr, J., Kellerer, B., Jansen, M., Berg, H., Ruskowski, M., Schebek, L., & Ciroth, A. (2022). *Requirements for a digital product passport to boost the circular economy* (pp. 1485–1494). Gesellschaft für Informatik, Bonn. Künstliche Intelligenz in der Umweltinformatik (KIU-2022). Hamburg. 26.-30. September 2022 https://doi.org/10.18420/INF2022_127

Raja Santhi, A., & Muthuswamy, P. (2022). Influence of blockchain technology in manufacturing supply chain and logistics. *Logistics, 6*(1), 15. https://doi.org/10.3390/logistics6010015

Rana, S. K., Kim, H.-C., Pani, S. K., Rana, S. K., Joo, M.-I., Rana, A. K., & Aich, S. (2021). Blockchain-based model to improve the performance of the next-generation digital supply chain. *Sustainability, 13*(18), 10008. https://doi.org/10.3390/su131810008

Renland Haugjord, B., & Kempton, A. M. (2022). Achieving data innovation for sustainable energy solutions. *Proceedings of the 30th European Conference on Information Systems*. https://aisel.aisnet.org/ecis2022_rp/87/

Saberi, S., Kouhizadeh, M., Sarkis, J., & Shen, L. (2019). Blockchain technology and its relationships to sustainable supply chain management. *International Journal of Production Research, 57*(7), 2117–2135. https://doi.org/10.1080/00207543.2018.1533261

Salah, K., Nizamuddin, N., Jayaraman, R., & Omar, M. (2019). Blockchain-based soybean traceability in agricultural supply chain. *IEEE Access, 7*, 73295–73305. https://doi.org/10.1109/ACCESS.2019.2918000

Schlund, D., & Schönfisch, M. (2021). Analysing the impact of a renewable hydrogen quota on the European electricity and natural gas markets. *Applied Energy, 304*, 117666. https://doi.org/10.1016/j.apenergy.2021.117666

Schniederjans, D. G., Curado, C., & Khalajhedayati, M. (2020). Supply chain digitisation trends: An integration of knowledge management. *International Journal of Production Economics, 220*, 107439. https://doi.org/10.1016/j.ijpe.2019.07.012

Schultze, U., & Avital, M. (2011). Designing interviews to generate rich data for information systems research. *Information and Organization, 21*(1), 1–16. https://doi.org/10.1016/j.infoandorg.2010.11.001

Sedlmeir, J., Buhl, H. U., Fridgen, G., & Keller, R. (2020). The energy consumption of blockchain technology: Beyond myth. *Business & Information Systems Engineering, 62*(6), 599–608. https://doi.org/10.1007/s12599-020-00656-x

Sedlmeir, J., Völter, F., & Strüker, J. (2021b). The next stage of green electricity labeling: Using zero-knowledge proofs for blockchain-based certificates of origin and use. *ACM SIGEnergy Energy Informatics Review, 1*(1), 20–31. https://doi.org/10.1145/3508467.3508470

Sedlmeir, J., Buhl, H. U., Fridgen, G., & Keller, R. (2021). *Recent developments in blockchain technology and their impact on energy consumption*. Advance online publication. https://doi.org/10.48550/arXiv.2102.07886

Seo, S.-K., Yun, D.-Y., & Lee, C.-J. (2020). Design and optimization of a hydrogen supply chain using a centralized storage model. *Applied Energy, 262*, 114452. https://doi.org/10.1016/j.apenergy.2019.114452

Sezer, B. B., Topal, S., & Nuriyev, U. (2022). Tppsupply : A traceable and privacy-preserving blockchain system architecture for the supply chain. *Journal of Information Security and Applications, 66*, 103116. https://doi.org/10.1016/j.jisa.2022.103116

Shiva Kumar, S., & Lim, H. (2022). An overview of water electrolysis technologies for green hydrogen production. *Energy Reports, 8*, 13793–13813. https://doi.org/10.1016/j.egyr.2022.10.127

Someh, I., Davern, M., Breidbach, C. F., & Shanks, G. (2019). Ethical issues in big data analytics: A stakeholder perspective. *Communications of the Association for Information Systems*, 718–747. https://doi.org/10.17705/1CAIS.04434

Sonnenberg, C., & vom Brocke, J. (2012). Evaluations in the science of the artificial – Reconsidering the build-evaluate pattern in design science research. In Hutchison, D., Kanade, T., Kittler, J., Kleinberg, J. M., Mattern, F., Mitchell, J. C., Naor, M., Nierstrasz, O., Pandu Rangan, C., Steffen, B., Sudan, M., Terzopoulos, D., Tygar, D., Vardi, M. Y., Weikum, G., Peffers, K., Rothenberger, M., & Kuechler, B. (Eds.), *Design Science Research in Information Systems. Advances in Theory and Practice* (Vol. 7286, pp. 381–397). Springer Berlin Heidelberg. https://doi.org/10.1007/978-3-642-29863-9_28

Straubert, C., & Sucky, E. (2021). How useful is a distributed ledger for tracking and tracing in supply chains? A Systems Thinking Approach. *Logistics, 5*(4), 75. https://doi.org/10.3390/logistics5040075

Tröger, R., & Alt, R. (2017). Design options for supply chain visibility services: Learnings from three EPCIS implementations. *Electronic Markets, 27*(2), 141–156. https://doi.org/10.1007/s12525-016-0231-4

Tsolakis, N., Niedenzu, D., Simonetto, M., Dora, M., & Kumar, M. (2021). Supply network design to address United Nations Sustainable Development Goals: A case study of blockchain implementation in Thai fish industry. *Journal of Business Research, 131*, 495–519. https://doi.org/10.1016/j.jbusres.2020.08.003

Valente, A., Iribarren, D., & Dufour, J. (2017). Life cycle assessment of hydrogen energy systems: A review of methodological choices. *The International Journal of Life Cycle Assessment, 22*(3), 346–363. https://doi.org/10.1007/s11367-016-1156-z

Velazquez Abad, A., & Dodds, P. E. (2020). Green hydrogen characterisation initiatives: Definitions, standards, guarantees of origin, and challenges. *Energy Policy, 138*, 111300. https://doi.org/10.1016/j.enpol.2020.111300

vom Brocke, J., Watson, R. T., Dwyer, C., Elliot, S., & Melville, N. (2013). Green information systems: Directives for the IS discipline. *Communications of the Association for Information Systems*, *33*. https://doi.org/10.17705/1CAIS.03330

vom Brocke, J., Simons, A., Riemer, K., Niehaves, B., Plattfaut, R., & Cleven, A. (2015). Standing on the shoulders of giants: Challenges and recommendations of literature search in information systems research. *Communications of the Association for Information Systems, 37*. https://doi.org/10.17705/1CAIS.03709

Walden, J., Steinbrecher, A., & Marinkovic, M. (2021). Digital product passports as enabler of the circular economy. *Chemie Ingenieur Technik, 93*(11), 1717–1727. https://doi.org/10.1002/cite.202100121

Walls, J. G., Widmeyer, G. R., & El Sawy, O. A. (1992). Building an information system design theory for vigilant EIS. *Information Systems Research, 3*(1), 36–59. https://doi.org/10.1287/isre.3.1.36

Wappler, M., Unguder, D., Lu, X., Ohlmeyer, H., Teschke, H., & Lueke, W. (2022). Building the green hydrogen market – Current state and outlook on green hydrogen demand and electrolyzer manufacturing. *International Journal of Hydrogen Energy, 47*(79), 33551–33570. https://doi.org/10.1016/j.ijhydene.2022.07.253

Westerkamp, M., Victor, F., & Küpper, A. (2020). Tracing manufacturing processes using blockchain-based token compositions. *Digital Communications and Networks, 6*(2), 167–176. https://doi.org/10.1016/j.dcan.2019.01.007

White, L. V., Fazeli, R., Cheng, W., Aisbett, E., Beck, F. J., Baldwin, K. G., Howarth, P., & O'Neill, L. (2021). Towards emissions certification systems for international trade in hydrogen: The policy challenge of defining boundaries for emissions accounting. *Energy, 215*, 119139. https://doi.org/10.1016/j.energy.2020.119139

Zampou, E., Mourtos, I., Pramatari, K., & Seidel, S. (2022). A design theory for energy and carbon management systems in the supply chain the quest for innovation in information systems research: Recognizing, stimulating, and promoting novel and useful knowledge. *Journal of the Association for Information Systems, 23*(1), 329–371. https://doi.org/10.17705/1jais.00725

Zeiss, R., Ixmeier, A., Recker, J., & Kranz, J. (2021). Mobilising information systems scholarship for a circular economy: Review, synthesis, and directions for future research. *Information Systems Journal, 31*(1), 148–183. https://doi.org/10.1111/isj.12305

Zhao, G., Liu, S., Lopez, C., Lu, H., Elgueta, S., Chen, H., & Boshkoska, B. M. (2019). Blockchain technology in agri-food value chain management: A synthesis of applications, challenges and future research directions. *Computers in Industry, 109*, 83–99. https://doi.org/10.1016/j.compind.2019.04.002