frontiers | Frontiers in Blockchain

TYPE Original Research
PUBLISHED 09 December 2024
DOI 10.3389/fbloc.2024.1408743

OPEN ACCESS

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RECEIVED 28 March 2024
ACCEPTED 18 November 2024
PUBLISHED 09 December 2024

CITATION
Schmid J, Ubacht J, van Engelenburg S, van Oudheusden J and Chappin E (2024) Is it green? Designing a blockchain-based certification system for the EU hydrogen market.
Front. Blockchain 7:1408743.
doi: 10.3389/fbloc.2024.1408743

Is it green? Designing a blockchain-based certification system for the EU hydrogen market

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Energy production and consumption are major contributors to greenhouse gas (GHG) emissions, exacerbating one of the greatest challenges faced by modern societies: climate change. Thus, societies must switch to more sustainable energy sources. Green hydrogen has emerged as a promising alternative energy carrier, facilitating storage and utilization across various industries. However, amidst different production processes, solely sustainable electrolysis stands out as an environmentally benign production method. Hydrogen producers must prove provenance and sustainable production to regulatory bodies and hydrogen buyers to comply with the regulations for sustainable development. Blockchain provides a viable solution encompassing trustworthy and secure information sharing between untrusted partners. In this article, we employ a design science research approach to develop a blockchain-based certification system (BLC-CS) for green hydrogen. Through collaboration with experts to gather requirements and conduct evaluations, we design an artifact that streamlines the certification process for producers, regulators, and consumers. Our proposed solution facilitates information gathering, verification, and reporting, contributing to the advancement of sustainable energy practices. We provide a comprehensive discussion of the BLC-CS's feasibility for green hydrogen certification, including technical extensions, recommendations for practitioners, and directions for future research.

KEYWORDS

blockchain, sustainable development goal, hydrogen, energy transition, energy security, tokenization, energy certificate, internet of things

1 Introduction

Climate change is an omnipresent issue in every human's life today, with projections suggesting a temperature increase of up to 6 degrees Celsius if no significant measures are taken (NASA, 2022; Intergovernmental Panel on Climate Change, 2021). In response to this need, local and international governments are driving the development of multiple alternative energy sources and carriers, such as the Green Deal's action plan to reduce GHG emissions by 55% by 2030 (European Environment Agency, 2023; EU Commission, 2019).

One of the promising alternatives, green hydrogen, can serve as an energy carrier, storage, and source for various industries such as heating, high-temperature production processes, and long-distance transport (Mould et al., 2022). Hydrogen is produced through different methods, the most prominent being electrolysis based on green electricity (green), steam-conversion with carbon capture (blue), and gasification from fossil fuels (gray). Currently, only 2% of the hydrogen used in the EU is green, while 96% is based on fossil fuels, which accumulate up to 100 million tons of CO_2 emissions annually (EU Commission, 2020). The different hydrogen production methods increase the complexity of establishing an economically viable, sustainable, and stable green hydrogen market (Gale et al., 2024). Thus, buyers of green hydrogen depend on trustworthy information about the provenance of hydrogen. Tracking the production of green hydrogen with certificates can help establish suitable subsidies compensating for the price difference of other types of hydrogen. Moreover, certificates represent and ensure the value of green hydrogen compared to other production types to foster a green hydrogen market development.

Information on the GHG emissions of the hydrogen value chain is crucial to facilitate adequate sustainability reporting and documentation (Abad and Dodds, 2020). The information is currently collected manually by spreadsheets and in-person audits, increasing the complexity and effort to obtain green hydrogen certificates—Guarantees of Origin (GOs) (Gale et al., 2024). In the EU, multiple service providers issue such GOs for green/low-carbon production based on underlying standards/certification schemes such as CertifHy in the EU, TÜV SÜD in Germany, and Verticir in the Netherlands (Certifhy, 2023; TÜV SÜD, 2023; Gasunie, 2022). The literature highlights a lack of consensus in the current standards for defining "green" hydrogen, resulting in uncertainties on greenhouse gas (GHG) emission accounting, boundary delineations, and the trade-offs between accuracy and cost (Abad and Dodds, 2020). For instance, CertifHy seeks to streamline green hydrogen production, emphasizing emission accounting during hydrogen production. Conversely, TÜV SÜD proposes a more detailed certification standard, encompassing system boundaries from production to end-of-life considerations (White et al., 2021). This disparity presents challenges in conventional certifications, including opacity, incompatibility, and increased auditing costs (Collell and Hauptmeijer, 2022). The resulting uncertainties significantly impact hydrogen producers, leading to increased costs for market entrance and hydrogen production.

The current EU legislation, grounded in the Renewable Energy Directive (RED), requires the hydrogen value chain to provide fine-grained information on emissions at each step of the value chain (EU Commission, 2023d). However, current methods for energy certification are based on "book and claim" concept, whereas hydrogen regulation follows a mass balance principle, which requires a stricter connection between the actual hydrogen output and digital certificates (Abad and Dodds, 2020). This implies that current methods do not align with the institutional requirements for hydrogen certification.

Our motivation is underlined by the aforementioned hydrogen certification challenges. We investigate the certification of green hydrogen within the framework of distributed information systems, specifically focusing on blockchain technology. With its tamper-resistant, transparent, and distributed characteristics, blockchain technology is well-suited for supply chains with extensive spans and numerous stakeholders, relying on information both upstream and downstream (Mould et al., 2022). Prior research has demonstrated blockchain's potential in enhancing supply chain transparency for various products, including textiles, drugs, and food, as well as its ability to track emissions for bulky goods like energy commodities (Hastig and Sodhi, 2020; Tian, 2016; Silvestre et al., 2020). Blockchain technology offers a tamper-resistant means of facilitating transactions and providing trustworthy information on electricity sustainability by linking Renewable Energy Certificates (RECs) to digital tokens (Cali et al., 2022). Extending this concept to the realm of hydrogen, blockchain technology provides an opportunity to digitize certificates transparently while ensuring tamper-resistant and automated certification processes.

Moreover, the physical nature of hydrogen as a commodity calls for a direct linkage with data sources, achievable through integration with the Internet of Things (IoT). IoT enables the sensing of physical processes, translating them into digital data (Christidis and Devetsikiotis, 2016). Existing research on blockchain for supply chain traceability, incorporating physical IoT integration, is well-advanced (Kumari et al., 2020; Fernandez-Carames and Fraga-Lamas, 2018; Moin et al., 2019; Kumar et al., 2022). Building upon this knowledge, established architectures for cyber-physical blockchain-based IoT systems can be adapted for application in the green hydrogen certification market. The literature explored green electricity labeling and peer-to-peer energy trading with IoT data collection as blockchain applications in the energy sector (Gupta et al., 2021; Kumari et al., 2020; Sekar et al., 2024; Wongthongtham et al., 2021; Babel et al., 2022). Investigating the transformative potential of blockchain technology can contribute to European efforts to scale the green hydrogen market. By harmonizing diverse certification schemes into a single, transparent system, blockchain can foster interoperability, reduce discrepancies between national and regional standards, and support the secure and automated exchange of certification information. Such a system can increase trust in green hydrogen provision and contribute to a growing hydrogen market.

We address the challenges in the current hydrogen certification market by creating a blockchain-based certification system (BLC-CS) that addresses the market requirements of the EU hydrogen distribution system to provide a trustworthy and automated information system aligning the certification process and handling a growing green hydrogen certification market. With this research, we contribute to the literature regarding blockchain applications in the industry and provide an updated generic blockchain architecture framework. Furthermore, we contribute to the societal issues of hydrogen certification by providing an alternative certification system compared to traditional central databases and manual audits.

The remainder of this paper is structured as follows: in Section 2, we present our research methodology, followed by an overview of related work and the knowledge of the hydrogen economy in Section 3. In Section 4, we provide the requirements for the BLC-CS based on expert interviews. In Section 5, we present the BLC-CS design, which is evaluated by a combination of expert interviews and literature in Section 6. Lastly, we discuss the feasibility of the BLC-CS in supporting trustworthy, efficient, and scalable hydrogen certification, and we reflect on our research limitations and future research topics in the conclusion, presented in Section 7.

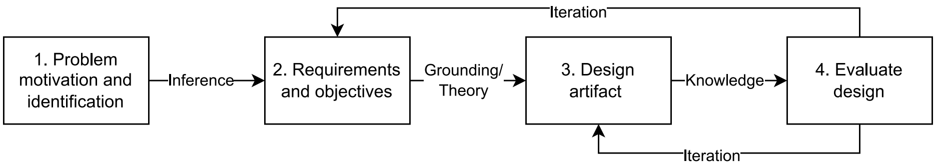

FIGURE 1
DSR process flow adapted from Peffers et al. (2007).

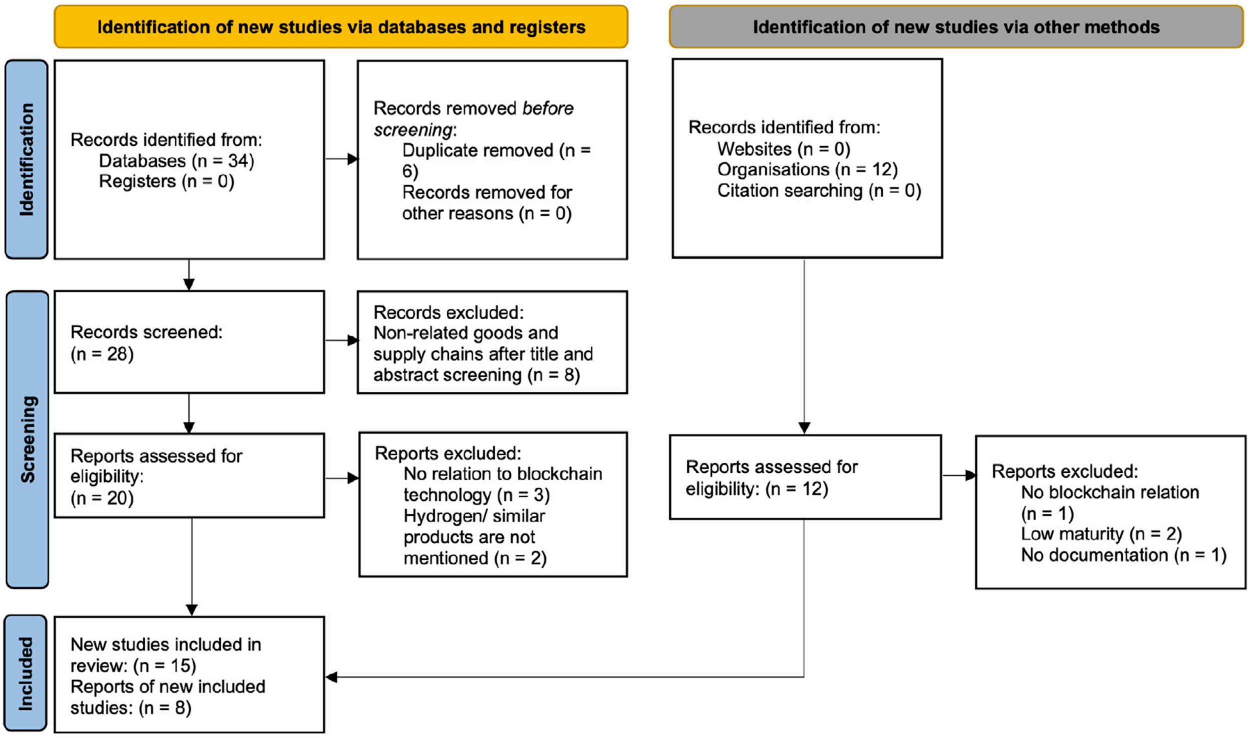

FIGURE 2
PRISMA diagram adapted from Page et al. (2021).

2 Methodology

In the research process, we followed the design science research (DSR). Hevner et al. (2004) first operationalized DSR as a method for designing effective information system artifacts. The authors introduced the pillars of design science, connecting the environment and existing knowledge base with the central design process through the gradual relevance and rigor cycles. Peffers et al. (2007) delineated the three pillars into an iterative process that we adapted to focus on data collection and artifact creation. In this research, we included only the first four steps and one cycle. Figure 1 shows this tailor-made process.

Adhering to the first step of the design cycle, we conducted a structured literature review to ground the problem statement in a scientific research gap. Scopus served as the underlying database to identify relevant scientific articles, resulting in 34 items. We used the following Boolean: *((“guarantee of origin” OR “proof of origin” OR “emission accounting”) AND “green hydrogen”))*. It resulted in six scientific articles. In the second round, a more generic research string was used to identify current blockchain-based applications in the hydrogen field: *(blockchain AND hydrogen)*. This yielded 13 results. In the last round, a more specified Boolean was used for identifying blockchain-based certification systems in the renewable energy domain: *(blockchain AND (hydrogen OR “renewable energy”) AND (certification OR “proof of origin” OR “guarantee of origin”))*. It resulted in 16 documents. After filtering and forward/backward snowballing, we identified a final set of 23 papers with adequate relevance to the hydrogen certification case based on blockchain. Furthermore, we searched the internet for current business endeavors, streamlining information technology for hydrogen certification purposes. This analysis resulted in eight relevant reports by industry actors in the field. Figure 2 shows the selection of sources. The results are presented in Schmid (2024).

In the second step of the methodology, we included requirements engineering. ISO 29148 (2018) provided the guidelines for obtaining and structuring requirements according

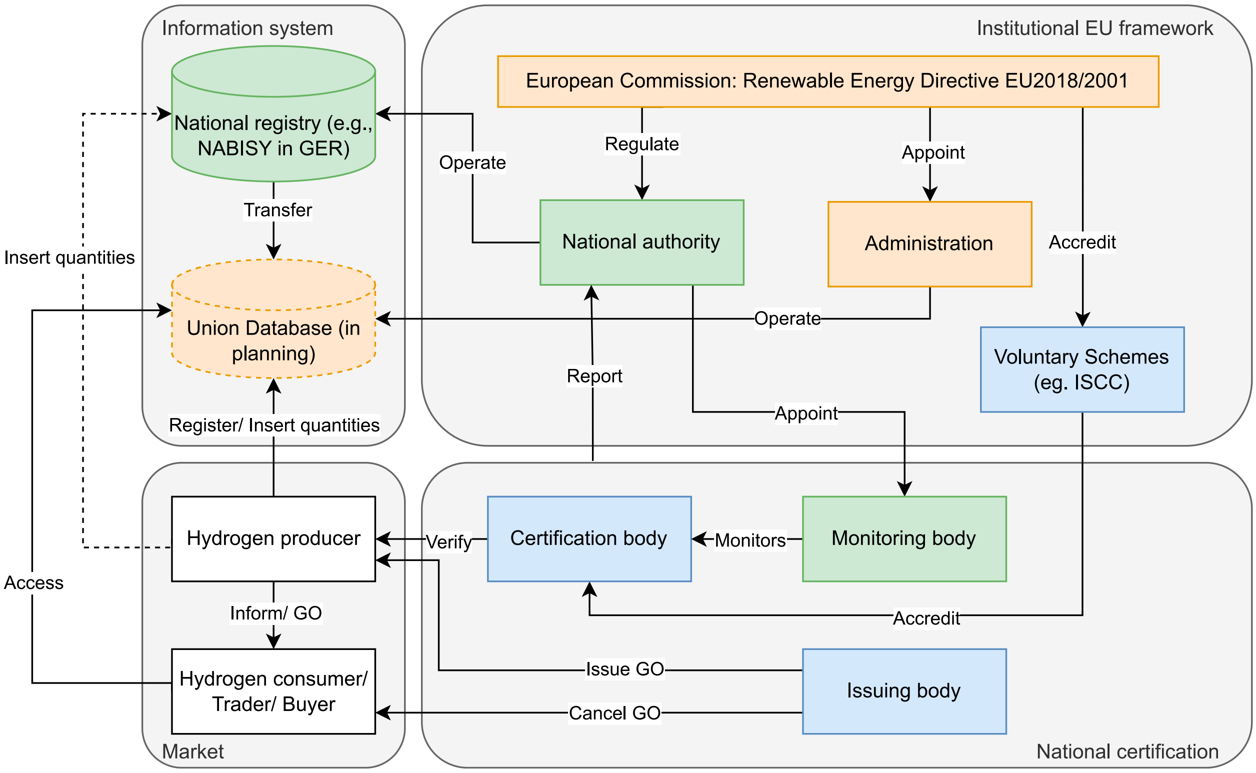

FIGURE 3
Overview of actors involved in hydrogen certification.

to sustainability reporting standards. An initial hydrogen economy analysis (presented in more detail in Section 3.1) yielded the design principles and initial requirements. We interviewed seven experts to gather data on current challenges and potential needs in the green hydrogen certification sector. We followed a protocol to gather structured information on the needs from the specific perspective of the hydrogen producer (cf. Database (Schmid, 2024): for each interviewee, we indicate their general contribution based on their background knowledge and a summary of the interview). We coded each of the information inputs to merge overlapping inputs from the interviewees. The results of the interviews are explained in Section 4.2. The requirements served as input to create the BLC-CS.

After finishing the design, we initiated a second round of interviews with different experts to receive evaluation feedback on the design. This evaluation round of the BLC-CS included 12 experts with different perspectives based on their experience and knowledge in the domains of hydrogen and blockchain. Schmid (2024) provided a detailed description of the experts and a summary of the interviews. The interviewees were industry experts, potential users of the BLC-CS, policymakers, and researchers. First, we asked the experts to reflect on the technical design choices. Second, the experts evaluated the governance of the BLC-CS and its institutional alignment. We categorize their feedback into adaptations/extensions of the BLC-CS, policy recommendations, and future research topics (see Section 6).

In the next section, we first provide an overview of related work and the fundamental functioning of the hydrogen economy.

3 Background and related work

The hydrogen economy is an emerging field. To understand the basics of hydrogen certification and the technical hydrogen field, we introduce the hydrogen economy in the subsequent sections.

3.1 Hydrogen economy

Hydrogen value chains are complex as they involve different hydrogen production technologies with different quantities of GHG emissions and, thus, different hydrogen colors. The GHG emission intensity of the associated hydrogen production technique defines these colors. The quantification of the hydrogen's emission intensity induced the fundamental change from a simple hydrogen transaction between the producer and buyer to a complex stakeholder entanglement. The complex certification system emerged from the need to regulate the documentation and validation of the different hydrogen production techniques according to emission reporting regulations and emission reduction objectives of the EU and its member states (MSs) founded in the EU Commission (2023d). Figure 3 provides an overview of the key actors involved in the hydrogen economy on the EU level as of December 2023.

The figure is divided into four components: the EU hydrogen certification framework, the national certification responsibilities, the hydrogen market, and the supporting information systems (which are partially in place and partially under development). In

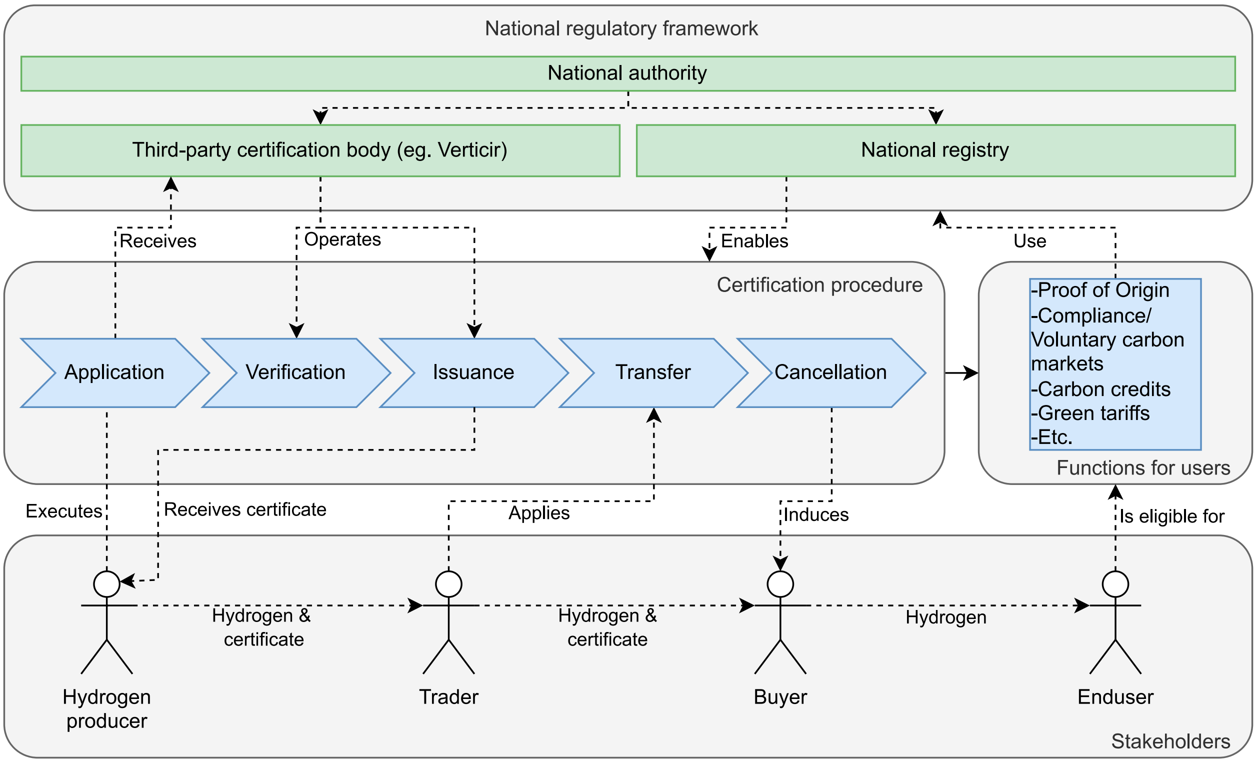

FIGURE 4
Certification process of hydrogen producers in the EU according to World Energy Council (2022) and Abad and Dodds (2020).

the figure, the orange boxes include the high-level EU entities, and the green boxes are the national execution bodies that delegate tasks to the blue boxes representing private third parties. The white boxes contain the market actors along the hydrogen value chain. The overall regulations are set by the EU Commission within the RED and its related delegated acts (EU Commission, 2023d; EU Commission, 2023c; EU Commission, 2023b). All data regarding green hydrogen transactions are registered in the Union Database (UDB) operated by an administration of the EU Commission and fed by the national registries of the MSs, if available (EU Commission, 2023d; EU Commission, 2023g). The MSs have the legal obligation of registering green hydrogen certifications and ensuring the truthfulness of the information, with regular reporting to the EU Commission. To control the tasks of the member states, the EU Commission accepts green hydrogen transactions only if registered and audited by third parties, following accredited certification schemes, namely, voluntary schemes (VSs) (Sailer et al., 2023; Gale et al., 2024). Issuing and certification bodies use the VSs as reference schemes for certifying the hydrogen producers and issuing the certificates. For example, Verticir is the authorized entity in the Netherlands (Gasunie, 2022).

Specifically, the hydrogen certification process currently deployed in the EU functions as displayed in Figure 4. The most interesting part of the figure is the interactions of actors with the certification procedure. There are several steps involved in the process of receiving the factual certificate of providing green hydrogen. Cheng and Lee (2022) emphasized the importance of balancing reporting rigor and administrative burden to enable smooth green hydrogen market integration while ensuring secure hydrogen certification and trade. Green hydrogen requires special treatment compared to other renewable energy certificates as information requirements exceed conventional electricity certificates: the electrolysis at the hydrogen production sites and the electricity supply must correlate temporally and geographically (EU Commission, 2022). This requires the adaptation of conventional book-and-claim GOs into mass balance-based proof-of-sustainability certificates (Sailer et al., 2021; World Energy Council, 2022; IRENA, 2022). The latter differs mainly due to its rigorous compliance with the RED II sustainability criteria and the actual consistency between green hydrogen production and consumption, while GOs are detached from the RED II regulation (EU Commission, 2023d).

The main contribution of Figures 3, 4 is a general overview of the opaque amount of connections between the actors and structures involved in the certification process. Each link indicates an information exchange and task that is to be performed to finalize the certification process. It involves many intermediate steps and actors until the certification process is finalized. Introducing a supporting information system that both maintains trustworthiness and complies with emission reporting obligations would significantly improve the certification processes.

The underlying RED II directive defines green hydrogen and the certification process with room for interpretation. Under this directive, each EU MS developed distinct certification schemes, resulting in an abundance of diverging schemes that are accredited by the European Commission (see Table 1). They differ in geographical and emission accounting boundaries, the tracking method, and the purpose (compliance (C) or voluntary

TABLE 1 International hydrogen certification landscape adapted from World Energy Council (2022).

Criterion	Regulation/standard	Region	Boundary	Tracking	Purpose
Regulation	LCFS	United States	Well-to-wheel	Book and claim	C
	RED II	EU	Well-to-wheel	Mass balance	C
	RTFO	United Kingdom	Well-to-wheel	Mass balance	C
Standard	TÜV SÜD	DE	Well-to-wheel	Book and claim	V
	AFHYPAC	FR	Cradle-to-gate	Book and claim	V
	Zero Carbon Certification Scheme	AU	Cradle-to-gate	Book and claim	V
	CertifHy	EU	Cradle-to-gate	Book and claim	V
	Vertogas	NL	Cradle-to-gate	Book and claim	V
	ISCC Plus	EU	Well-to-wheel	Mass balance	V
	Certification scheme	JP	Cradle-to-gate	Book and claim	V
	China Hydrogen Alliance's standard	CH	Well-to-wheel	N/A	N/A
	dena Biogasregister	DE	According to demand	Mass balance	C

(V) reporting). One can assume that different certification schemes per country are not vital for the hydrogen market. Considering the EU's ambitions of increasing the green hydrogen market to 20 million tons per year, with 50% domestically produced and 50% imported, hydrogen producers rely on smooth import and export procedures to facilitate trade and transport in these quantities (EU Commission, 2023e). Hydrogen producers, importers, and users require a standardized and harmonized system that allows smooth hydrogen trade to accomplish the ambitious green hydrogen objectives of the EU (White et al., 2021; Abad and Dodds, 2020). Coordinating different green hydrogen standards and certification schemes can help solve information asymmetries and build trust between hydrogen traders. The scientific literature proposes a modular certification system that enables the monitoring of emissions at each step of the hydrogen value chain (White et al., 2021). Hence, hydrogen producers can collect emission data on the hydrogen production process, and supply chain descendants can access the information required for emission reporting. However, scientific research lacks concrete design guidelines for such modular hydrogen certification systems, specifically on how to design such modular systems to provide value chain actors with equal access to information on the emission intensity of the hydrogen and track the issued certificates.

3.2 Blockchain and IoT-based energy certification

In this section, we describe the related work based on Schmid (2024). Blockchain technology emerged as a mechanism to conduct online payments without intermediaries such as banks while maintaining a high level of security, predominantly known as Bitcoin (Nakamoto, 2008). The potential of blockchain technology quickly expanded to multiple industries, which are, among others, digital identities, E-Government applications, supply chain traceability, and energy trading (Kumari et al., 2020; Babel et al., 2022; Rioux and Ward, 2022; Wang and Su, 2020; Sedlmeir et al., 2021a; Nofuentes et al., 2022).

In global supply chains, data gathering, sharing, and analyzing play an increasingly important role for optimization and efficiency purposes (Mould et al., 2022). IoT devices enable real-time data gathering and can couple physical supply chains with information systems. In this increasing data space, data integrity and security play important roles as the value of confidential information increases. Blockchain technology comes into play to store and share data transparently while ensuring security through tamper-resistant cryptographic mechanisms, known as hashes.

Blockchain–IoT systems have different strategies of implementation based on the functions that need to be fulfilled in the underlying business case. The scientific literature provides technical architectures of such information systems, among others, for blockchain applications in energy systems. Blockchain can manage information asymmetries in complex energy systems and secure data transfer, storage, and analysis (Sadawi et al., 2021; Kumari et al., 2020). Subsequently, a detailed description of blockchain's potential for hydrogen certification is provided.

3.2.1 Prospects of blockchain for hydrogen certification

Blockchain technology is not nascent in supply chain traceability and as a facilitating system for certification. It is used for tracking and distributing transparent information in the metal supply chain, the textile industry, or food logistics (Hastig and Sodhi, 2020; Tian, 2016). Furthermore, Moin et al. (2019), Kumar et al. (2022), Christidis and Devetsikiotis (2016) explored blockchain's potential for linking physical supply chain processes with a digital registry via IoT devices. The technology has proven to be a lightweight bookkeeping method for recording emissions along supply chains. Scope 1 emissions can be correctly recorded and allocated to the actor in the supply chain with only a fraction of bureaucratic efforts and monitoring costs compared to manual reporting (Kaplan and Ramanna, 2021).

To examine how blockchain technology can stimulate and subsidize green energy markets efficiently, Castellanos et al. (2017) introduced a cryptocurrency-based certification scheme that facilitates certificate trading. Furthermore, Sedlmeir et al. (2021b) and Knirsch et al. (2020) introduce the possibility of using blockchain and zero-knowledge proofs (ZKPs) to improve the credible qualification of green electricity. The authors conclude that these technologies can facilitate the verification process of utility providers, comply with the confidentiality premise of businesses, and create easier access to the certification system. Further research shows the potential of blockchain for energy trading to optimize electricity usage in smart grids, increase trust, and provide information transparency (Babel et al., 2022; Kumari et al., 2020). The former links non-fungible tokens (NFTs) with fractional ownership for binding digital certificates as assets maintaining the value of green electricity.

In summary, blockchain technology holds the following properties that make it particularly suitable for tracing emissions along the hydrogen value chain to enable a credible and interoperable certification system:

1. Decentralization: No central authorities govern and control data sharing and emission reporting. However, data can be extracted by authorized entities from the distributed ledger infrastructure (Cali et al., 2022).
2. Transparency/trust: Blockchain technology can solve principal-agent information asymmetries by providing reliable data between the producer and consumer, thus stimulating green hydrogen trade (White et al., 2021). The emission data are stored indefinitely and can be traced by the participating parties to prevent fraudulent activities and increase trust (Kumari et al., 2020).
3. Security: The tamper-resistant hash algorithms anonymize data and ensure compliance with corporate data standards and confidentiality of the captured data (Cali et al., 2022).
4. Accountability: Blockchain can tokenize 1 MWh of energy as a digital twin on the blockchain. Tokens allow for step-by-step documentation of emissions on each value-chain step to attribute emissions to the responsible actors (Babel et al., 2022).
5. Tradability: The tokenization of energy certificates on the blockchain enables separate trading of these tokens to stimulate the green energy market (Castellanos et al., 2017).
6. Automation: Blockchain connected to smart contracts enables the automatization of business logic (Cali et al., 2022). For example, canceling certificates when used or expired can decrease bureaucratic processes.

3.2.2 Integrating blockchain and IoT

Data gathering to allow adequate certification and emission accounting relies predominantly on sensor/meter data as the central source of information to share data along supply chains such as the hydrogen value chain. For example, Powell et al. (2022) examined the role of blockchain technology as a solution for showing information trustworthy to supply chain descendants while preserving the confidentiality of sensitive business data in the food supply chain. However, the authors also pointed out potential challenges when using blockchain technology combined with IoT, such as the garbage in–garbage out problem (Reyna et al., 2018). When collecting data to be stored in a trust chain based on blockchain technology, the data must be verified externally (Sedlmeir et al., 2021b). Otherwise, the data collected through physical sensors can be prone to fraudulent activities.

Another problem is that IoT sensors generate data continuously. Linking every sensor in every hydrogen production facility in Europe to the blockchain network would inject massive amounts of real-time data into the system. Current blockchain capabilities cannot cope with numerous simultaneous transactions as it would result in system breakdowns or long transaction queues (Reyna et al., 2018). Alternatively, predefined data collection points can be instantiated to gradually feed data into the system and thus prevent overloads, as explained by Novo (2018). Summarized, integrating IoT with blockchain technology cannot address data integrity due to the garbage in–garbage out problem. The literature addresses this issue with nascent technologies such as artificial intelligence-based information anomaly detection (Fadi et al., 2022). Nevertheless, external verification methods are required to ensure the compliance of the data sources. Moreover, complex IoT networks can overload blockchain systems. These issues need to be considered when setting up blockchain–IoT certification systems.

4 Design principles and requirements

4.1 Design principles

The analysis of the hydrogen economy in Section 3.1 illustrates that the current certification landscape faces major challenges obstructing the seamless development of the hydrogen market. First, current information requirements for complying with the RED regulations for qualifying hydrogen as green are opaque. Second, actors face a lack of standardization among existing certification schemes. Third, the process of reporting and verification is predominantly manual and requires automation for a feasible certification landscape that supports a flourishing sustainable hydrogen market. These observations lead to the five following design principles for a BLC-CS, which are the key design objectives for an artifact design according to ISO 29148 (2018):

4.1.1 (DP1) Compliance

A blockchain-based hydrogen certification system for the safe sale of green hydrogen in the EU can only be viable if it complies with the reporting and hydrogen qualification rules set out in the European regulations, as outlined in the RED II directive as of April 2023. Thus, the BLC-CS should be able to connect to EU reporting systems, be adaptive to the changing EU regulations, and be compliant with verification methods proposed by the European authorities.

4.1.2 (DP2) System modularity

Multiple certification schemes are accredited by European regulation. These schemes are developed on a national level and enforced through national independent authorities with varying local circumstances and reporting requirements. To comply with the mentioned information tools and the volatile certification market, the BLC-CS should be able to modularly connect to the required information systems of certification-related actors (White et al., 2021).

TABLE 2 Lower-level requirement structure for the BLC-CS.

Type	ID	Higher level	ID	Lower level	Source	Tracing
F	1	Granular monitoring	1.1	The injection interface point should be documented closely	L	DP4
			1.2	The hydrogen withdrawal interface point has to be documented continuously	L	
			1.3	The liquid transport should be documented	L	
			1.4	The BLC-CS should monitor the hydrogen storage	I4	
			1.5	The BLC-CS should be able to measure the hydrogen quality/ pureness	I3, I5	
			1.6	Metadata on the hydrogen batch should be shared gradually along the value chain, adding up emissions at each value chain step	L	
			1.7	The BLC-CS should monitor the electricity input	L	
F	2	Reliable data collection	2.1	Sensors should be verified by an external third-party	I2	DP4
			2.2	The BLC-CS should store the emission data reliably	I3	
			2.3	The data collection should directly be linked to the secure blockchain system	I4	
F	3	Traceability of emissions	3.1	The system should be able to lock proofs of sustainability	L, I1	DP4
			3.2	The system should link the virtual hydrogen certificate to the corresponding hydrogen batch	I5, I6, L	
F	4	Auditability/ verifiability	4.1	Automated verification of the injected hydrogen based on historical data	L	DP3
			4.2	The emission data should be verifiable by an independent third party	I5	
			4.3	The system should ensure the data quality of hydrogen emissions	L	
F	5	Confidentiality preserving	5.1	The BLC-CS should only transparently show metadata on hydrogen emissions, but identity and intellectual property-related sensitive data should not be revealed	I4	-
			5.2	The emission information has to be stored accessibly to authorized parties	I5	
F	6	Compatibility/ interoperability	6.1	The system should be compatible with the EU GO process	L	DP2
			6.2	The BLC-CS should be compatible with the renewable electricity certificates/GOs for green electricity	I5, I6, L	
			6.3	The BLC-CS should be able to synchronize with the different certification schemes/systems accredited by the EU	I3, I5	
			6.4	The BLC-CS should be able to connect to all hydrogen producers' information systems	I3, L	
			6.5	The BLC-CS should be compatible to account for emissions for all types of hydrogen	I3	
			6.6	The system should allow the tradability of certificates across national borderlines	I5, L	
F	7	Openness	7.1	The system should support fair and open standards for all users	L	DP5
			7.2	The system should be unbiased adaptively for domestic and international hydrogen producers	I5	
F	8	Allocation of roles and responsibilities	8.1	The BLC-CS should enable benefits and active roles for all parties involved in a transaction of hydrogen (incentives)	I2	DP5
			8.2	The BLC-CS should clarify the data collection control	I3, I4	
			8.3	The system should establish rules for data ownership	I4	
			8.4	TSOs should be utilized as the regulators for the hydrogen injection and withdrawal of the grid	I4	

(Continued on following page)

TABLE 2 (*Continued*) Lower-level requirement structure for the BLC-CS.

Type	ID	Higher level	ID	Lower level	Source	Tracing
			8.5	The BLC-CS should clarify the party responsible for data validation	I3, I4	
			8.6	The system should determine a system maintenance party	I3, I4	
F	9	Security	9.1	The system should ensure tamper-proof data collection (garbage in prevention)	I2	-
			9.2	The system should prevent fraudulent activities due to many varying certification systems	I3	
			9.3	The BLC-CS should be able to prevent double-counting	L, I5	DP1
F	10	Compliance with RED II	10.1	The system should comply with the additionality requirement	L	
			10.2	The system should be able to prove the geographical correlation	L	
			10.3	The system should be able to prove the temporal correlation	L	
			10.4	The system should be able to comply with mass balancing	L, I6	
F	11	Standardization	11.1	The system should clarify the emission influence factors and their calculation for producers and consumers	I3	DP1
			11.2	The BLC-CS should set clear data sufficiency criteria for the hydrogen qualification	I6	
			11.3	The BLC-CS should allow registration with the national responsible emission authority/registry	L	
NF	12	Flexibility	12.1	The system should be adaptive to volatile institutional reporting obligations and regulation	I2	DP2
			12.2	The system should be adaptive to changing roles and responsibilities in the volatile hydrogen certification market	I3	
			12.3	The BLC-CS should take local national/municipal varying emission-influencing difficulties into account	I6	
NF	13	Scalability	13	The BLC-CS should be scalable to many supplying hydrogen producers (as the hydrogen backbone evolves)	L, I4	DP2
NF	14	Stability	14	The BLC-CS should be robust according to the long-term electrolyzer use-phase (approximately 13 years)	I5	DP2
NF	15	Efficiency	15.1	The documentation, reporting, and verification process should be automatized	I5	DP3
			15.2	The system should be easy-to-use	I3	
			15.3	The system should facilitate the issuance, transfer, and cancellation of proof-of-sustainability	I6	

4.1.3 (DP3) Certification automation

Currently, most reporting processes for receiving a GO for green hydrogen are manually executed, as noted by Mould et al. (2022) and according to Interview I5 in Schmid (2024). Registration at the local issuing body, reporting documents, and audits are time-consuming and obstruct a flourishing hydrogen market as participants hesitate to enter a volatile certification market in the EU. Automating the data gathering, reporting, and auditing can facilitate a more efficient certification process.

4.1.4 (DP4) Traceability

The emission reporting obligations for companies in Europe increase continuously as the need for a transition toward lower carbon emissions increases. The first step toward cutting emissions is the granular traceability of the emissions' origin according to the emission scopes of the Greenhouse Gas Protocol (Barrow et al., 2013). In this regard, the BLC-CS should be able to fulfill the function of granular emission accounting, covering Scopes 1, 2, and 3 to help hydrogen production companies prove the provenance of the hydrogen emission to authorities and hydrogen buyers.

4.1.5 (DP5) Governance

Hydrogen certification is a complex field of interacting stakeholders bearing uncertain behavior. Hence, this design principle represents the required governance of the BLC-CS implementation to secure the system's reliability when implemented in the market.

4.2 Requirements

The DPs gave the overall scope for identifying the requirements for the BLC-CS. For the requirement analysis, we combined requirements engineering and design science as mentioned in the scientific literature (Braun et al., 2015; Peffers et al., 2007; Eekels and

Roozenburg, 1991). Requirements play a vital role in translating aspects from the environment cycle into system-specific design elements. They can be elicited from the system analysis and stakeholder needs through inductive methods according to ISO 29148 (2018). As introduced in the methodology in Section 2, we conducted seven expert interviews combined with preceding desk research to identify relevant needs for hydrogen value chain actors from industry, public authorities, and science. We structured these needs in a requirements structure that serves as the foundation to develop the BLC-CS. Table 2 shows the final results of the data collection. We found 15 higher-level requirements, divided into 11 functional (F) and 4 non-functional (NF) requirements. In total, we derived 49 lower-level requirements from the expert interviews. For each requirement, the source is indicated (L for literature and I for interview), and the last column indicates the assignment to the design principles (DPs). In Section 5, we explain the functional requirements in more detail and provide arguments for the resulting design choices. Non-functional requirements describe the quality of a system (Braun et al., 2015). We use the non-functional requirements for evaluating the performance of the BLC-CS, as described in Section 6.

5 BLC-CS design

With the requirements at hand, in the next step, we specify the technical design. Blockchain, in combination with the IoT, has been applied in multiple industries for supply chain tracking. We follow two generic blockchain architecture ontologies as the basic blockchain technology stack (Xu et al., 2017; Tasca and Tessone, 2018). Their approaches to identifying the appropriate blockchain semantics for the hydrogen certification are partly outdated and lack integration with IoT. Therefore, we extended the architecture taxonomy based on Ahmadjee et al. (2022). The authors surveyed blockchain applications in different contexts and derived design attributes for blockchain architecture. Furthermore, hydrogen is a physical molecule that must be measured to transform information on its state into digital form. Thus, we add a physical perception layer to the blockchain architecture model (Novo, 2018; Moin et al., 2019; Kumar et al., 2022; Fernandez-Carames and Fraga-Lamas, 2018; Kumari et al., 2020). Figure 5 summarizes the blockchain reference architecture model.

For each architecture level, various blockchain design choices are available. Based on the derived system requirements, we select the optimal design choice to fulfill the requirements of the BLC-CS.

5.1 Technical artifact design

In the BLC-CS, we consider eight design choices. The first six decision levels correspond to the reference architecture in Figure 5, designed from the bottom up (physical to application layer). Security and extensibility are considered separately in the technical design as they cannot be uniquely assigned to one of the architecture layers. In Figure 6, security and extensibility are highlighted in green and blue, respectively. Furthermore, we address the service layer in Section 5.2, where we describe the processes of the smart contract execution. In summary, the BLC-CS design combines the following decision-making levels: *1. perception layer*, *2. communication layer*, *3. data sublayer*, *4. network sublayer*, *5. consensus sublayer*, *6. incentive sublayer*, *7. security and privacy*, and *8. extensibility*. In the following sections, we present the rationale behind the design choices based on the requirement analysis.

5.1.1 Perception layer

For designing the perception layer, we align with Novo (2018) and suggest the implementation of a local IoT manager responsible for managing the data collection of the smart meters in a locally verified database. Such sensors can be set up in an edge computing setting to offload major computational power from the shared blockchain network and keep transaction data private on the user side (Gupta et al., 2021). As mentioned by Moin et al. (2019), hydrogen production facilities have a connected sensor network of smart meters that capture data on energy production processes and further aspects comprising the GHG emission intensity. According to the expert interviews, the system requires tamper-proof data collection and storage (RQ9.1). Furthermore, the system should safeguard intellectual property and other competitive advantages of hydrogen production when collecting and sharing data (RQ5). Each smart meter must also document the timestamp of the energy sources consumed for producing one batch of hydrogen (equivalent to 1 MWh) according to RQ3.1 and RQ10.4. To ensure correct and qualitative data collection and storage (RQ 2.2), each smart meter has to be verified individually (Moin et al., 2019). The sensors are verified as a prerequisite before the launch of the hydrogen production facility during the onboarding process in line with the suggestions of Sedlmeir et al. (2021b) and Knirsch et al. (2020).

5.1.2 Communication layer

The communication layer covers two types of communication, the mutual communication of sensors in the local facility and the communication with the blockchain. Typically, production plants operate as closed systems, omitting the need for long-distance connections. *Hence, there is no necessity to implement sophisticated communication protocols among the sensors.* The data communication must be secure according to the requirements (RQ9.1 and RQ9.3). In the design, the sensors are connected to near-field communication in a local sensor infrastructure that gathers data and stores it locally in a database, such as WiFi access points. The sensors are connected via the internet or other means like Long Range Wide Area Network (LoRaWAN) (Kumar et al., 2022).

Second, we propose that each smart meter device data transaction should be linked to producing one hydrogen batch (equivalent to 1 MWh of energy). Scalability is essential for the uprising green hydrogen market (RQ13). Infinitesimal transactions of each smart meter would amplify the transaction number and increase energy usage, which objects to the energy-saving information infrastructure and hamper data throughput (Fernandez-Carames and Fraga-Lamas, 2018). Furthermore, communication with the blockchain should be of quality and make information available to allow the verification service of the smart contracts and ensure the integrity of the transmitted data (RQ1, 2, 10, and 11). The local sensor network

FIGURE 5
Reference architecture for a BLC-CS.

setup must comply with the measurement points of the requirements RQ1.1–RQ1.7. Third-party sensor providers should be included in setting up this network, while auditors check the soundness of the data collection and compliance with the RED II regulation (RQ2.1). The set-up of explicit data collection points also addresses the standardization requirement RQ11. The WiFi communication needs to be secured locally with each sensor's public and private key pairs to ensure the integrity of the locally collected data.

5.1.3 Blockchain layer

5.1.3.1 Data sublayer

The data layer involves data storage, block configuration, and transaction management. Data storage is a fundamental decision to be made before building the information system as it influences the upper service layers and entails trade-offs such as costs, privacy, and data integrity (Ahmadjee et al., 2022). In line with Sedlmeir et al. (2021b), we propose that only the relevant metadata on the emission scopes and the encrypted hashes for identification be provided to the distributed, openly accessible blockchain structure. The design builds upon an off-chain–on-chain hybrid solution connected with oracles to enable communication (Pasdar et al., 2023). The emission data are encrypted in Merkle trees and then shared on-chain to ensure auditability (RQ4). These sensitive data should be only accessible to authorized auditing parties and potential monitoring authorities (RQ5). The on-chain data storage allows for data integrity, which can be accessed transparently by verification parties (RQ4.2 and RQ4.3). Furthermore, the automation of the process facilitates the emission reporting and complies with the efficiency non-functional performance requirement (RQ15).

The second part of the data sublayer is the block configuration. It defines the on-chain data storage and consists of the block header with the meta-encryption information and the block body containing the transaction data. *In the proposed design, the cryptographic encryption of the transactions through hashes provides unique identification and allows immutable storage of the emission data in the block body.* The block body contains all the

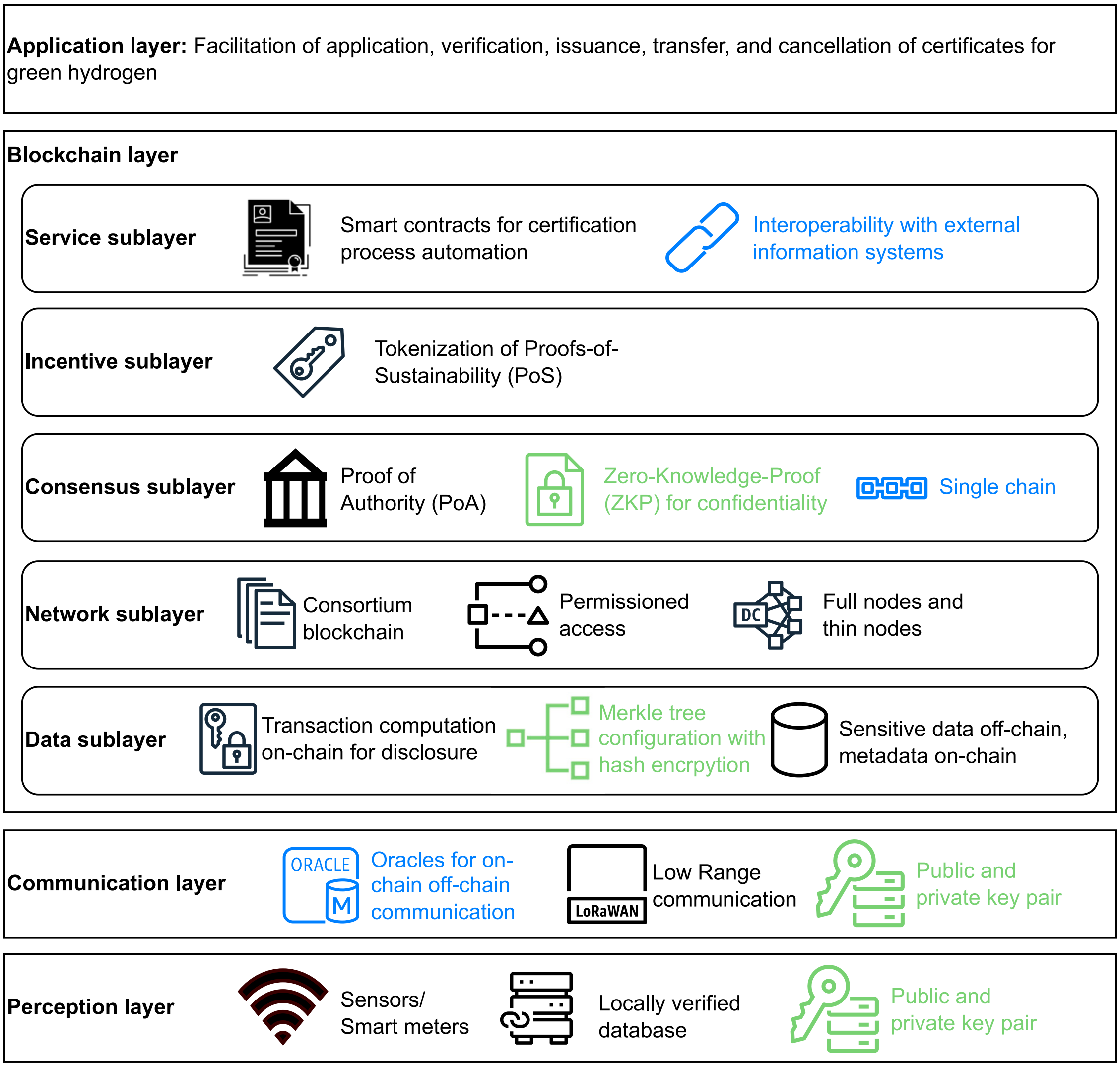

FIGURE 6
Overview of design choices.

emission data to verify compliance with the green hydrogen qualification requirements. The requirements prescribe that emission data should be traceable, granularly monitored, and reliable for reporting purposes (RQ1). Furthermore, the hydrogen certificates should be stored securely without double counting the renewable electricity input. They should prevent fraudulent activities due to data changes or retroactive changes to compliance requirements due to different certification systems (RQ9).

The transaction computation is the third part of the data sublayer, outlining the transaction process and storage on-chain or off-chain Xu et al. (2017). *In the BLC-CS design, we chose an on-chain transaction computation for the publicly disclosed emission metadata but off-chain storage of sensitive data.* Hydrogen producers require high interoperability because they work with legacy systems that need to be connected seamlessly to the BLC-CS. Furthermore, the legacy systems of the current GO process of the EU need to be integrated (RQ6.1–RQ6.4). Additionally, reporting obligations and the specificity of data provision require open sharing of emission data in on-chain transactions (RQ5). The consortium blockchain choice allows additional access and authorization mechanisms to unravel the confidentiality problem (cf. Section 5.1.3.2).

5.1.3.2 Network sublayer

On the network sublayer, design decisions entail decentralization and identity/access management. Decentralization entails the identification of the necessity for a decentralized or centralized architecture setting or a hybrid solution. *The requirements for a BLC-CS match best with an intermediate format addressing the heterogeneity of the hydrogen certification environment.* In the literature, these blockchains are defined as hierarchical network designs or federated-/consortia-governed blockchains (Dib et al., 2018; Tasca and Tessone, 2018). Considering the nature of the hydrogen certification system, two aspects support the consortia architecture: first, the hydrogen value chain is a complex system involving many actors that have different opinions regarding the state of the certification of hydrogen; hydrogen producers aim to sell hydrogen at the highest

TABLE 3 Access rights per blockchain type based on Christidis and Devetsikiotis (2016); Zheng et al. (2017).

		Access		
		Read	Write	Commit
Type	Public	Everyone	Everyone	Everyone
	Consortium	Everyone	Authorized users	Pre-selected authorized users
	Private	Authorized users	Pre-selected authorized users	Pre-selected authorized users

profit, while users need quality hydrogen, a secure supply, and compliance with their emission reporting obligations. Second, regulatory bodies want to stimulate hydrogen production bottom-up and regulate the greenness of the hydrogen in the market. The European Union is the fundamental instance for setting out the hydrogen certification rules; however, certification schemes and certification bodies that control the issuance and transfer of green hydrogen GOs differ per EU MS (RQ6.3). Per nation, an issuing body has the right to add blocks to the system, while hydrogen value chain participants can read the transactions to check on the provenance of the hydrogen (RQ4.2 and RQ5.2). Furthermore, transmission system operators (TSOs) can act as an additional instance of verification, and the national registries can be coupled with an updated version of the ledger to improve interoperability among MSs of the European Union (RQ6.6, RQ7.2). Moreover, it refers to RQ10 as the EU sets the institutional boundaries for the hydrogen certification space.

The blockchain type also depends on the decision regarding the identity/access management. Access management is closely related to the architectural choice of the node structure to set rules on the action space for each participant (Ahmadjee et al., 2022). *The design should entail physical identity management and additional proof of identity with the public–private key pair whenever transactions are pushed into the system.* Table 3 illustrates the design decision possibilities for access management. In the hydrogen certification use case, all registered system users are allowed to read transactions, authorized hydrogen producers can write transactions, and pre-selected and accredited certification bodies can commit blocks to the network (RQ4.2, 6.3, 6.4, 7.1, and 11.3). In this way, distributed tasks for each stakeholder and power division can fulfill the decentral benefits. Each EU MS keeps a bundle of enforcement rights as the head of a consortium. The system's control remains in the hands of the authorities through accredited bodies. However, hydrogen producers can access a transparent system to apply for certificates and report emissions, while the confidential data are securely protected. In other words, system users, such as hydrogen producers, operate as thin nodes, with the ability to read and write transactions. In contrast, auditors and certification bodies represent the pre-selected group of full nodes that have verification and block committing rights (Ahmadjee et al., 2022). Hydrogen producers input hydrogen production data and associated emissions automatically via the digital connection with smart meters; manual identity checks need to be executed as a prerequisite (RQ2.1), in accordance with Knirsch et al. (2020). Hydrogen producers provide their identity to the authority and hydrogen consumers to prove the integrity of the data; authorities require this identity for attributing the certificates to the correct entity.

5.1.3.3 Consensus sublayer

The consensus sublayer defines how the rules of interaction between users are enforced. This means that the consensus is the translation of existing rules of hydrogen certification into blockchain-based digital rules. There are different types of reaching a consensus, as listed in Table 4. *Based on the requirements, the most suitable solution for the BLS-CS is a proof-of-authority (PoA) consensus mechanism.*

This decision originates in the system requirements that imply specific control from the EU and national authorities regarding the reporting of emission data and compliance with institutions (RQ4.2, 5.2, and 11.3). As observed from Table 4, other parameters also play a role in choosing a suitable consensus mechanism. Energy consumption should be low as the blockchain architecture aims to facilitate green hydrogen production for sustainability objectives. The system's scalability is important considering an expanding future hydrogen market (RQ13). The BLC-CS should also not be subjected to unpredictable power distribution, which can be induced by finding consensus through computational advantage, system stake, or voting mechanisms. These mechanisms could obfuscate the hydrogen certification process and thus obstruct the green hydrogen market expansion (RQ14). Lastly, the system's efficiency is decisive (RQ15), which combines the throughput of validations and the confirmation speed of transactions (Dib et al., 2018). The number of transactions entering and being validated in the system is crucial for the BLC-CS[1]. Transaction validation requires a certain level of facilitation; otherwise, manual reports or other information systems would suffice.

5.1.3.4 Incentive sublayer

The incentive sublayer defines how digital rewards are handled when the transactions are validated and consensus is reached (Kumar et al., 2022). *The design decision on the incentive sublayer sees NFTs with fractional ownership as the optimal solution for the requirements.* Wang and Nixon (2021) distinguished different types of tokens: fungible tokens, non-fungible tokens, and semi-fungible tokens. Generally, the BLC-CS should be able to lock the certificates in the blockchain and provide value to it (RQ3.1), which means converting it into a digital asset. Each digital hydrogen certificate has to be linked indistinguishable from the belonging hydrogen batch to fulfill the mass balancing

1 The number of transactions covers the projected green hydrogen market of the EU, according to Odenweller et al. (2022), which will be 127 TWh by 2030.

TABLE 4 Consensus mechanisms adapted from Zheng et al. (2017); Ahmadjee et al. (2022).

	Proof of work (e.g., bitcoin)	Proof of stake (e.g., Solana)	Proof of byzantine fault tolerance (e.g., Hyperledger)	Proof of authority
Blockchain type	All	All	Consortium/private	Private permissioned
Energy consumption	High	Middle	Middle	Low
Scalability	Middle/low	High	Low	High
Security	Computational advantage	Stake in the system	Fault tolerance	Identity
Consensus criteria	Fastest computation	Highest stake	Voting-based	Predetermined authority
Efficiency	Low	High	Middle	High

requirement (RQ3.2 and RQ10.4). Non-fungible tokens can create such links as only one owner can be attributed to the token at a time. Deploying NFTs also complies with other requirements, such as gradually monitoring emission metadata along the hydrogen value chain (RQ1.6). In the current architecture, one certificate equals one transaction of 1 MWh of energy; however, hydrogen can also be sold in smaller amounts. To address this issue, Babel et al. (2022) introduced the fractional ownership of NFTs with the implementation of electricity GOs. Fractional ownership allows the system operator to request the Merkle tree entailing the transaction/ownership information of the green hydrogen batch while forwarding a fraction of the NFT (the certificate) to the buyer, corresponding to the amount of hydrogen used.

5.1.4 Security and privacy

Security and privacy pervade all architectural layers of the BLC-CS. *In the design, ZKPs are chosen to comply with the confidentiality requirements of the BLC-CS.* According to Schellinger et al. (2022), Merkle roots with SHA encryption provide sufficient security if only the data integrity of the transaction is to be ensured; however, whenever more complex business activities such as smart contracts are involved, the addition of ZKPs helps preserve the confidentiality of the data. In the hydrogen economy, an attacker could accumulate hydrogen production data of one specific address and reveal the GHG emission intensity of one specific hydrogen producer to infringe on its reputation and impair its profits. As such, the requirements prescribe data confidentiality and data-sharing security (RQ5 and RQ9). Sedlmeir et al. (2021b) addressed this problem by implementing ZKPs. Therefore, statements can be proven without revealing additional information or intermediate steps to reach the mathematical state.

5.1.5 Extensibility

Blockchain extensibility includes design decisions regarding chain structure, interoperability, and intraoperability, which influence the system's scalability. Generally, there are two types of chain structures: single chain and multiple chains (Ahmadjee et al., 2022). *According to the requirements, we choose a single-chain design with intraoperability properties.* One singular chain is easier to oversee and assures a high level of security. Intraoperability concerns the compatibility of different blockchains and the transferability of assets to another blockchain and is thus closely related to the chain structure decision (Tasca and Tessone, 2018). Digital hydrogen certificates must be linked persistently to the physical hydrogen batch and should not be transferred separately (RQ3.3 and RQ10.4). Thus, the BLC-CS should be capable of intra-operating other blockchains' information. Specifically, cases of hydrogen import require the blockchain to incorporate certificates of other blockchains to allow the certificate to travel with the belonging hydrogen batch.

The design element interoperability is a design element of the BLC-CS that allows the connection to external information systems (Tasca and Tessone, 2018). According to requirement RQ6, a connection to the information systems of different stakeholders has to be guaranteed and a stable connection to sensor devices measuring the emission data has to be ensured (RQ6.4). Requirement RQ6.5 points out that the BLC-CS should account for emissions from all types of hydrogen. Therefore, oracles connect each facility's local trusted data aggregation repository with the blockchain. These oracles enable the communication of smart contracts with the outside world (Ahmadjee et al., 2022). The interoperability allows smart contracts to work with data inbound from the physical world. This architectural component complies further with the automation design principle by automatically calculating the emission reduction, verifying the data, and transferring the certificate based on the hydrogen purchase agreement between producer and buyer (RQ4.1, RQ4.4, RQ15.1, and RQ15.3). Interoperability is complementary to the flexibility requirement. Whenever new participants enter the market, smart contracts can be adjusted to fit the local peculiarities of the consortium (RQ12.3); the same goes for institutional changes in the emission reporting (RQ12.1) and the potential changes of roles that might affect the verification control of smart contracts (RQ12.2). Accordingly, the interoperable design can support the open and fair standards for economic operators entering the market (RQ7.1).

5.2 Demonstration of the BLC-CS

After introducing the technical architecture, the question remains of how it is implemented in the context of green hydrogen certification. The DSR methodology by Peffers et al. (2007) suggests the implementation and demonstration of the BLC-CS in a socio-technical in the next step of the design cycle.

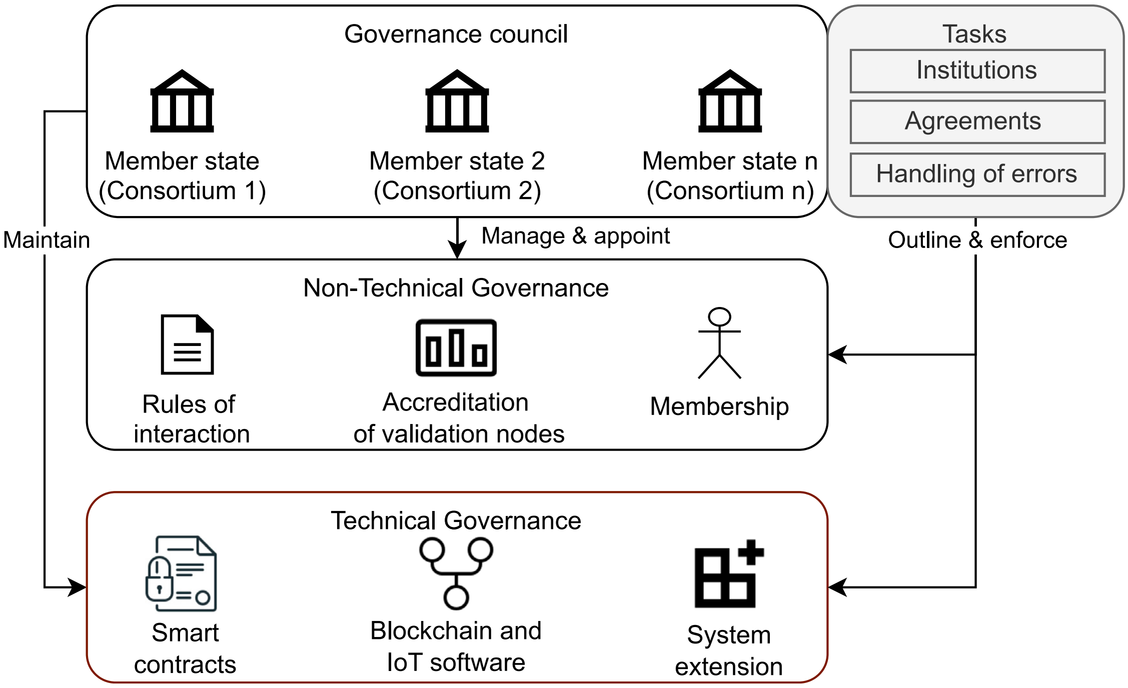

FIGURE 7
System governance and institutions for a blockchain-based hydrogen certification system.

Hence, we address the requirements regarding system governance and institutional alignment in Section 5.2.1 and introduce the certification process of the BLC-CS in Section 5.2.2.

5.2.1 System governance and institutional alignment

Governance is a broad term used for different purposes; in this research, we defined the term within the requirement for the appropriate allocation of rights and responsibilities to ensure smooth market integration and cooperation among the stakeholders. We found six aspects that comprise the higher-level requirement (RQ8: RQ8.1) beneficial and active roles for participants, (RQ8.2) control of the data collection, (RQ8.3) rules for data ownership, (RQ8.4) utilization of TSOs as grid operators, (RQ8.5) clarification of the data validation, and (RQ8.6) system maintenance. Furthermore, we found the requirement concerning the institutional alignment complying with the EU certification standard procedures (RQ10). Figure 7 illustrates the governance and institutions of the BLC-CS.

The Governance Council consists of the n consortia participating in the blockchain. Each consortium is represented by the underlying MSs. These include the institutions, agreements, and handling of misconduct in the green hydrogen certification system. The Governance Council is divided into technical and non-technical responsibilities. The former implements the institutions of the EU green hydrogen certification regulations in smart contracts, maintains the functioning of the BLC-CS, and manages system extensions whenever new consortia, actors, or certification schemes are added to the system. The rules of interaction between the hydrogen economy actors, accreditation of new validation nodes, and membership in the blockchain-based certification system are managed by the non-technical Governance Council. These are the main tasks relevant to the EU hydrogen certification (Sailer et al., 2023). The Governance Council, thus, aims at sustaining fair system access and operating rules, the potential disclosure of system vulnerabilities, and mitigation actions for security risks. Governance is also important to ensure the security of the physical layers of the data perception; sensors need to be updated and regularly audited (Fernandez-Carames and Fraga-Lamas, 2018; Knirsch et al., 2020). The council, however, cannot sign and commit transactions, as that would concentrate the system's power and oppose the blockchain's decentral trust setup.

5.2.2 Certification process integration

Hydrogen certification comprises three main functions: onboarding the hydrogen production facilities, continuous data verification and issuance of proofs-of-sustainability, and tracking the trajectory of physical hydrogen and digital proof-of-sustainability until they reach the hydrogen end user in the EU. To demonstrate the implementation of the BLC-CS in the hydrogen market, we showcase a conceptual overview of both the data verification and token issuance processes (cf. Figure 8) and, second, the transfer and cancellation of the proof-of-sustainability token (cf. Figure 9).

As illustrated in Figure 8, the verified sensor network locally measures the emissions of the hydrogen production steps and all input variables, mainly electricity and water consumption, the electrolysis process, and hydrogen compression. This is the central local data collection point for the emission data obtained through smart meters. Before transferring the data on the blockchain, the local hydrogen producer creates a ZKP, which allows transferring only relevant metadata on the emission

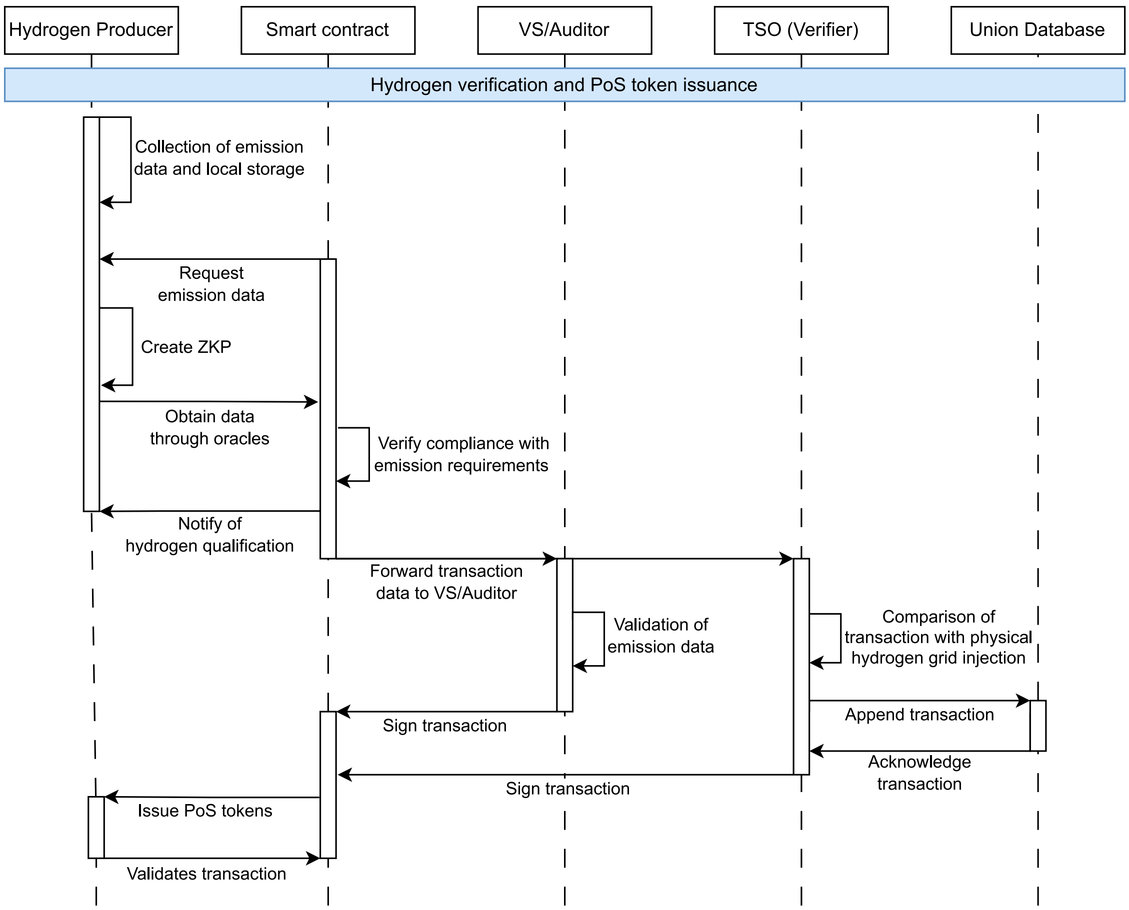

FIGURE 8
Hydrogen production process verification and proof-of-sustainability token issuance.

intensity to the blockchain without showing sensitive information such as hydrogen production efficiency, the quantity of available green hydrogen, or the individual hydrogen mix. A smart contract communicates through an Oracle with the off-chain data repository to verify the compliance of the emission data with the predetermined institutions embedded in the smart contract. These rules check the emission reduction of the hydrogen production process, the temporal correlation, the geographical correlation, and the additionality of the hydrogen production facility according to the RED II requirements (EU Commission, 2023d). Once verified, the hydrogen producer gets notified about the qualification of the produced hydrogen (green, blue, and black). The transaction is forwarded to the validation body (VS/auditor) for double-checking the hydrogen qualification. If positively validated, the transaction gets signed and appended to the blockchain. The smart contract will transfer the issued tokens to the personal wallet of the hydrogen producer. While the VS/auditor is validating the hydrogen qualification, the TSO serves as a secondary verification instance by comparing the hydrogen injection in the grid with the smart contract information. Once approved, the transaction gets appended to the Union Database (UDB), securing the token issuance redundantly.

The second and third functions of the system are displayed in Figure 9. Once the hydrogen seller and buyer agree upon a hydrogen delivery contract, the hydrogen producer requests the transfer of the proof-of-sustainability tokens according to the amount of energy the hydrogen entails. The smart contract automatically requests to verify the transaction of physical hydrogen at the TSO to transport the hydrogen through the distribution grid. Once the transaction is approved, the hydrogen producer gets notified, and the smart contract initiates the transfer of the proof-of-sustainability tokens based on the amount of hydrogen agreed in the Power Purchase Agreement (PPA). Referring to RQ1 in Table 2, the granular monitoring of grid injection and withdrawal points requires an immediate verification of the hydrogen producer's physical hydrogen injection and issued certificate balance. Whenever the proof of conformity is verified, the issuance of tokens does not need to occur in real-time, but rather when the reporting due date approaches. Moreover, the TSO appends the hydrogen grid injection information to the UDB to update the overview of green hydrogen volumes in the market. The smart contract automatically completes the transfer of the tokens to the hydrogen buyer's personal wallet. The third function is concerned with the cancellation of the proof-of-sustainability tokens. Based on the PPA, the hydrogen buyer withdraws hydrogen from the distribution grid. The sensors of the TSO trigger the smart contract to burn the tokens as the buyer consumes the hydrogen. The predetermined rules in the smart

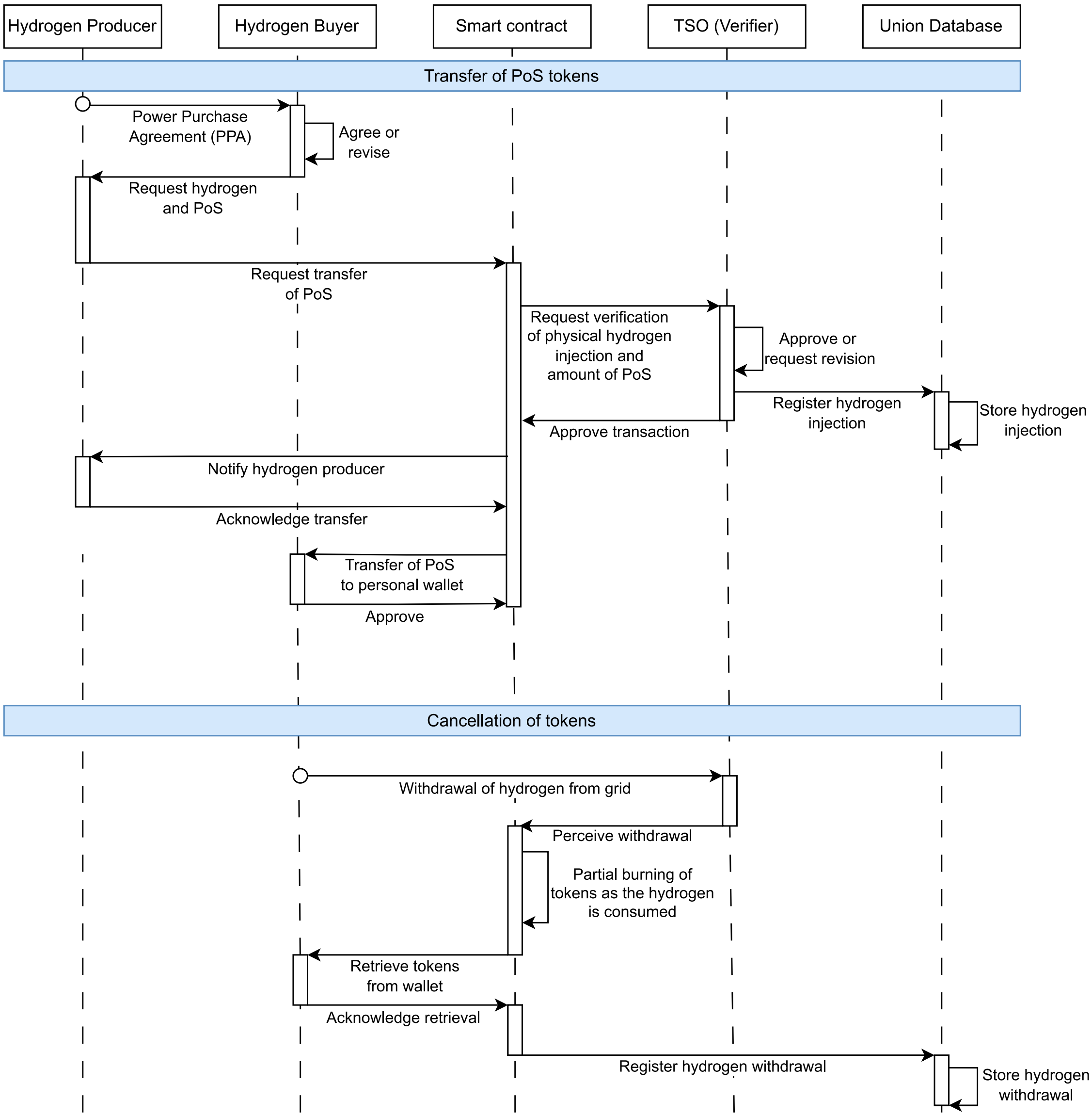

FIGURE 9
Proof-of sustainability token transfer and cancellation.

contract allow automatic access to the personal wallet of the hydrogen buyer to retrieve the tokens to be burned. Eventually, the UDB registers the withdrawal from the grid.

In a nutshell, implementing the design includes variable parameters that can change over time. Continuous updates to the BLC-CS implementation strategy are important for successfully applying the design in the socio-technical context.

6 Evaluation of the BLC-BS's feasibility

Hydrogen comes with multiple peculiarities that require unique treatments to ensure successful implementation in the market as a competitive alternative fuel. Current inefficiencies in converting electricity into hydrogen and *vice versa* lead to high energy losses in the short term and scaling uncertainties in the long term (Odenweller et al., 2022). These observations imply doubts about the market feasibility, particularly in terms of price competitiveness to electricity and fossil fuels. In this section, we evaluate the BLC-CS's feasibility in a sociotechnical context by consulting 12 experts. We thoroughly selected experts with different fields of expertise in hydrogen production/certification, blockchain programming, and their combination. A more detailed description of the experts and the interviews can be found in Schmid (2024). We translated their feedback into an adaptation of the design, future research topics, implications for the adaption and extension of the BLC-CS, and policy recommendations, as shown in Table 5, and we elaborate on the findings from the evaluation of the system performance, its technical feasibility, the system governance, and societal integration in Sections 6.1, 6.2, 6.3, 6.4, respectively.

TABLE 5 Implications from the evaluation for the design's feasibility.

Design aspect	Actions	Implications
Flexibility	Included in the design	Flexibility represents the system's response to the heterogeneous hydrogen market.
Scalability	Included in the design and future research	Privacy and security have to be weighed against scalability.
Reliability	Included in the design and future research	The combination of nascent IoT–blockchain technologies and blockchain types provide a robust and reliable green hydrogen certification system.
Efficiency	Included in the design	The hydrogen market requires a robust, scalable, and quickly developing certification system.
Technical design (oracles)	Future research	Decentralized oracles can enhance the BLC-CS by preventing single-point-of-failure vulnerabilities.
Technical design (ZKPs)	Adaption of the BLC-CS	ZKPs can improve anonymity but adds costs and complexities. Its cost development should be closely monitored.
Technical design (tokenization)	Future research	Further research can shed light on the benefits and drawbacks of tokens versus traditional identification of ownership through hashes.
Institutions and governance (governance dimensions)	Extension of the BLC-CS	Extending the governance council according to the mentioned dimensions can help strengthen the BLC-CS's system governance.
Institutions and governance (roles and responsibilities)	Extension of the BLC-CS	The role and responsibility distribution have to be compliant with the current capabilities of hydrogen certification actors.
Institutions and governance (on-chain and off-chain alignment)	Future research	Governance has to be determined off-chain and on-chain to clarify beneficial roles for all participating parties and the interaction rules.
Institutions and governance (institutional market barriers)	Recommendations	Setting low market entrance barriers but effective rules of certification is the optimal balance to facilitate a flourishing market.
Institutions and governance (business-government alignment)	Recommendations	Monitoring hydrogen production needs to be aligned with business needs to benefit reporting effectiveness and the hydrogen market development.
Societal integration (stakeholder interactions)	Future research	Future research should entail potential stakeholder interactions with the BLC-CS to test the real-world applicability.
Societal integration (hydrogen trade scenarios)	Future research	Future research should investigate the feasibility of the BLC-CS for different hydrogen trade scenarios.

6.1 Performance of the BLC-CS

Braun et al. (2015) emphasized the integration of DSR and requirements engineering. This proposal allows for the evaluation of a DSR design's quality based on non-functional requirements. In Section 4.2, we identified four non-functional requirements that indicate the performance prerequisites for a viable BLC-CS: flexibility, scalability, stability, and efficiency.

Flexibility resonates as one of the main market-induced obstacles for a harmonized one-system solution. In an ideal world, we would have one standardized system aligning with all standards and countries to facilitate fluent trade. Since a human factor is involved in the certification system, reality shows us that flexibility, competition, or simply the fact that humans do not always agree results in various certification systems that match the requirements of individual purposes (I19, (Schmid, 2024)). One all-encompassing certification standard system would likely be too complex and could create more problems than it resolves. In the hydrogen economy, the EU Commission only provides objectives and guidelines to reach them, but the execution is delegated to the MS or private parties. This not only opens room for flexibility but also increases progressiveness due to competition among different certification bodies. Every country needs different certification specifications as do import versus export market constellations. The BLC-CS can address this flexibility by setting strict rules according to RED II while allowing the consortia the freedom to set regional specifications.

Since the EU only prescribes the directions and limits for certification systems but allows the MSs freedom to choose their implementation path, it is advisable to start with national development and gradually expand to other countries (I17, (Schmid, 2024)). In the BLC-CS design, *flexibility* (RQ12) is addressed through the decentralized Governance Council that can adapt to changing standards and institutions. If the council agrees, the smart contracts can be adapted whenever changes in the RED II regulations appear. Furthermore, the consortium blockchain allows for the deployment of private channels that can be adapted to the specifics of the associated MS consortium. *Flexibility is required by the individual certification needs for different hydrogen production, transformation, or trade scenarios. The individual needs or human factors should therefore be acknowledged in the design, and processes should not be standardized for everyone.*

The second performance indicator is *scalability* (RQ13). Scalability is the ability to change the level of parameters that capture the performance measures of a system (Ross et al., 2008), such as the number of users or the volume of data. Scalability often arises in blockchain designs in the trilemma with decentralization and security (Wongthongtham et al., 2021). Sustainability comes into play in environmentally benign applications (Friedman and Ormiston, 2022; EU Commission, 2023a).

One benefit of decentralized systems is that they have a higher fault tolerance. Because data are replicated on many nodes, if some nodes fail, the other nodes can continue to operate. Furthermore, data stored in a blockchain are highly immutable, largely due to how they are stored in linked blocks and secured by the consensus mechanism (Nakamoto, 2008). The benefits that are offered by this decentralization and the security of the data, however, often come at a trade-off with scalability. It is important to consider these trade-offs for the design choices we made for the BLC-CS.

To evaluate the scalability of a blockchain-based application, several parameters can be considered, viz., the number of transactions the system handles per second, the number of nodes or users in the network, the storage space required to store the transactions, the consensus mechanism, and the number of nodes involved with consensus and validation (I18, (Schmid, 2024)). In the context of the BLC-CS, Sedlmeir et al. (2021b) noted that the expected user numbers have to be estimated during the initialization of the blockchain as the Merkle tree depends on it. First, the size of the Merkle tree should match the number of expected users in the system to comply with the scalability requirement. For the BLC-CS, this can be estimated based on the number of MSs in the EU. The projected European hydrogen market size is 127 TWh by 2030 (Odenweller et al., 2022). Under the assumption that one hydrogen batch[2] is equivalent to one proof-of-sustainability token on the blockchain, 127.000 transactions would be required per year by 2030. This estimate excludes considerations for blue and gray hydrogen transactions and fractional transactions. By 2030, the entire global hydrogen production[3] could reach up to 700 TWh per year (Bermudez et al., 2022).

Considering the potential number of nodes and transactions, it is important to ensure that the volume of data stored is manageable and proportionate to the required fault tolerance and data immutability. This is especially important because data storage and sharing require, e.g., hardware and electricity, which could also affect sustainability. To do so, data storage is facilitated in off-chain and on-chain parts. The data, i.e., the certificates, are stored off-chain at local data repositories. Only the roots of the Merkle trees built from the hashes of batches of the data are stored on-chain. The Merkle roots can then be used to verify the data and determine whether it has been changed in the off-chain database (Merkle, 1988). This reduces the required storage space and the transactional volume. In addition, BLC-CS will have thin node capabilities. This means only the full nodes (certification nodes and auditors) save a copy of the blockchain, whereas the local nodes (hydrogen producers) share only the headers to keep a record of the chain's validity. As explained by Nakamoto (2008), this type of reduction in redundancy might reduce immutability as fewer nodes participate in validation. However, in the BLC-CS, thin nodes are only required to read the validation results but not to validate transactions themselves.

In terms of choosing the right consensus mechanism, practitioners face the challenge of balancing decentralization and trust with the blockchain system's scalability (Sanka and Cheung, 2021). This approach is well-suited for permissioned consortium blockchains since authorities can sign transactions in batches (Zheng et al., 2017). In our case, they can do so by including the Merkle root of a batch of off-chain data (i.e., certificates) in the signed transaction. This makes it possible for users to not only verify whether a certificate has been changed but also to confirm that it was signed by an authority—by checking whether its hash is part of the Merkle tree of the Merkle root signed by the authority. As the system scales, more authorized parties can be installed for transaction signing to cope with the increasing transaction numbers. Using PoA results in less decentralization. However, in our case, the authorities ensure the security of the system as independent verifies. Random nodes signing transactions would not add value as the certification has to be done by authorized parties. *Recapitulating, the trade-off between advanced security and privacy mechanisms has to be weighed against larger transaction throughput and thus better scalability.*

Third, *reliability* is mentioned as a performance indicator by the experts for the requirement (RQ14). The financial commitment for an electrolyzer is high and long-term, as mentioned by the expert, approximately 13 years (I5, Schmid (2024)). The blockchain certification infrastructure should support this long-term investment by creating a robust information-sharing infrastructure around the physical hydrogen trade. Green hydrogen production is not yet profitable for hydrogen producers. Longden et al. (2022) stated that the green hydrogen price strongly depends on the fluctuating price of green electricity and thus contributes to a volatile and insecure cost structure. According to the authors, the average price for fossil-based hydrogen is stable, approximately 1.60$ per kg, whereas green hydrogen prices fluctuate between 1.86$ and 3.64 $ per kg (Longden et al., 2022). The fluctuating hydrogen price increases the importance of a cost- and effort-reducing certification system to maintain low long-term administrative costs. Abad and Dodds (2020) stated that fees for GOs for green energy range between 0.15 and 0.30 £/MWh in the United Kingdom. The major fluctuations result from the unsteady green energy supply and supply–demand discrepancies.

Blockchain-based energy trading has been introduced to balance the supply and demand and thus also the price (Kumari et al., 2020). Similar concepts can be transferred to the hydrogen sector to stabilize the green hydrogen costs. In the BLC-CS, the PoA-powered consortium design can also cut administrative transaction costs significantly. For the hydrogen producer, the infrastructure investment, audit costs, and transaction fees remain. In the designed artifact, the decentral system governance council can adapt the system's software so that the hardware can rely on long-term software support. *Nascent technologies such as peer-to-peer energy trading and secure data collection in smart meters can increase reliability and stabilize green hydrogen prices. In combination with the PoA consortium setup, the BLC-CS provides a robust and reliable green hydrogen certification system.*

Performance can also be measured in system *efficiency* (RQ15). All certification process steps are cumbersome but necessary. Is blockchain really capable of revamping the process to make it simple

2 equivalent to 1 MWh of energy.

3 in the net zero by the 2050 scenario.

or is it merely an underlying system change with limited improvement in efficiency (I15, I16, (Schmid, 2024))? The single-chain design facilitates the effectiveness of the system's Governance Council and the overseeability of the system. Avoiding transactions between multiple chains can preserve the efficiency of the artifact. Multi-chains would require synchronization efforts, increasing the artifact's complexity and energy consumption (Ahmadjee et al., 2022). Furthermore, smart contracts ensure that emission reporting is conducted automatically (RQ15.1 and 15.3). The automation reduces the resource commitment for hydrogen production companies, requiring only the management of the sensors and the locally verified data repository. The interoperable design of the system allows adapting the application interfaces for users to their personal needs. It makes the front-end system easy to use (RQ15.2), while data collection and sharing facilitate the compliance process with green hydrogen standards, mass balancing, and secure information sharing. The slimming process can be achieved in multiple ways, but blockchain is not the ultimate solution (I16, (Schmid, 2024)). *Nevertheless, as the hydrogen market grows rapidly, it requires a robust, scalable, and rapidly developing certification system to streamline the fluid hydrogen market* (I17, (Schmid, 2024)).

In summary, we expect the BLC-CS to outperform the cumbersome processes of green hydrogen certification as currently executed. The artifact can match user flexibility requirements, scale faster than manual certification processes, increase reliability with nascent technologies, and fasten the certification and inspection process.

6.2 Technical feasibility

Following the order of the design aspects in Table 5, we present the implications for the BLC-BS. We evaluated the technical viability of the BLC-CS to serve as a hydrogen certification system in the EU. The experts formulated three technical remarks. First, experts mentioned that secure transmission of information from sensors to the blockchain requires certain middleware such as oracles. They introduce a central point of data processing and thus pose a potential risk to blockchain security (I12, (Schmid, 2024)). Adverse behavior includes writing wrong transactions or manipulating input data. The challenge is to incentivize good behavior and effective governance mechanisms to deal with imposters (I13, (Schmid, 2024)). This means that decentralization must pervade all architecture layers from data collection to validation; otherwise, the system becomes prone to fraudulent activities. If every sensor is individually connected with the blockchain, a single point of failure of the central data repository connected with the oracle can be prevented. Since sensors are resource-constraint, the sensors cannot save the entire copy of the ledger, and vis-a-vis unstructured transaction data would spam the blockchain system. In the scientific literature and blockchain applications in supply chain management, the oracle problem has already been widely addressed. As mentioned by Mastando (2023) and Al-Breiki et al. (2020), there are different types of oracles for different purposes and security levels. Fadi et al. (2022) introduced artificial intelligence (AI)-based anomaly detection to prevent fraudulent activities on blockchains as another mechanism to identify attackers with financial gain intentions such as double-spending. Enhancing security always comes with drawbacks in scalability and decentralization. *Decentralized oracles are particularly relevant for balancing decentralization, data processing efficiency, security, and scalability. Nascent technologies such as decentral oracles and AI-based anomaly detection shall be closely tracked for potential future applications in the next design cycles.*

Second, through ZKPs, parties can prove a specific state of the information without revealing the data. It is most commonly used in privacy-constrained environments whenever one's identity should stay hidden (Fiege et al., 1987). Interviewee I12 (Schmid, 2024) responded that ZKP is not necessarily needed to comply with the confidentiality requirement identified in the design. ZKP likely introduces another complexity through one more level of data exchange. In other words, ZKP can not only provide more security but also increase computational complexity and reduce scalability. As mentioned by Sedlmeir et al. (2021b), the verification through ZK-SNARKS[4] costs approximately 50$. The deployment of this technology would increase the transaction costs, considering that every hydrogen batch equivalent to 1 MWh corresponds to one transaction, whereas the actual goal of the blockchain system is to reduce administrative efforts and certification costs. Recent technological developments could soon make ZKPs competitive with hardware prices and allow scalable computational processing (Sedlmeir et al., 2021b). *We recommend monitoring ZKP closely until scalability and costs are competitive for market application.*

Third, in the BLC-CS, we proposed a token-based digital asset management to assign property to green hydrogen certificates. Tokenization allows the unambiguous identification of ownership (Sunyaev et al., 2021). Blockchain inherently entails the identification of transactions based on hashes to identify a transaction with a certain address. Tokenization can add useful properties to the design, such as the fractional ownership of proof-of-sustainability tokens to allow smaller hydrogen transactions. Interviewee 13 (Schmid, 2024) mentioned composable NFTs that entail a bundle of property rights. These can be individually sold or bundled again, which corresponds to the hydrogen market depending on the used volume of hydrogen. However, it induces additional complexity. Other means, such as identity management and smart contracts, can similarly address the digital identification of property. When the system evolves and the user numbers increase, the costs of setting up tokens can be distributed among users. *Hence, tokenization remains a relevant concept in future research.*

Our overall conclusion based on the evaluation of the technical design is that each technical design choice induces additional complexities and costs. Considering the development of an initial prototype, simpler technologies can serve as an alternative. More sophisticated tools, like decentralized oracles, ZKPs, and tokens, can be implemented once the system is up and running.

4 SNARKS are a form of ZKP on the Ethereum platform.

6.3 System governance and institutional alignment

In this section, the second part of the design is addressed: the implementation of blockchain architecture in the ecosystem of hydrogen certification, considering the governance of such decentralized architecture and the institutional setting. Throughout the evaluation interviews, it appeared that governance plays an essential role because blockchain introduces a paradigm-changing decentralized system structure (I10, I12, and I13 (Schmid, 2024)). We discuss the two main subjects that were addressed by the interviewees in the following sections: the development of responsive governance mechanisms and institutional alignment.

6.3.1 Determining responsive governance mechanisms

The interviewees discussed the proposed task disposition between existing actors to validate the BLC-CS's feasibility. According to interviewees I10 and I12 (cf. Schmid, 2024), governance is the most critical challenge in developing a decentralized hydrogen certification system. Either one central party is responsible for pushing it into the market and getting everyone on board, or a collaborative approach is implemented, but no one will feel responsible (I10, (Schmid, 2024)). Considering the restrained commitment of hydrogen value chain actors, the scientific literature shows that blockchain can benefit the cooperation and coordination of organizations (Lumineau et al., 2021). Through automating transactions, blockchain can prevent opportunistic behavior in contractual agreements between hydrogen producers and buyers and stimulate a trusted trade environment. Moreover, deliberate or unintentional misbehavior can be allocated and automatically notified by smart contracts.

Governance can be fundamentally changed by decentralized systems. Several scientific articles examined the topic of governance in distributed systems; for example, Beck et al. (2018) and Pelt et al. (2021) identified six governance dimensions: formation, roles, membership, decision rights, accountability, and incentives. van Engelenburg et al. (2020) discussed blockchain governance rights in the context of business and government information sharing and analyzed them under blockchain design aspects. Based on this, the interactions of stakeholders mentioned in Section 5.2 can be structurally aligned with the technical design choices and reconciled with governance dimensions described by Beck et al. (2018) and Pelt et al. (2021). TSOs are colorblind to the hydrogen mix in the market and cannot monitor the distribution grids (I8, (Schmid, 2024)). Thus, TSOs require additional investment to equip the sensors for the distribution grid with the functionality of time-conform measurements. *Generally speaking, it is necessary to synchronize existing actor roles with suggested governance mechanisms for the BLC-CS.*

Governance spans contractual agreements on-chain and off-chain (cf. I12 in Schmid (2024)). Thus, the BLC-CS needs to ensure cross-level decentralized governance mechanisms. Pelt et al. (2021) stated three governance layers are essential when designing the BLC-CS: off-chain community, off-chain development, and on-chain protocol. Off-chain governance is related to the establishment of a Governance Council that not only engages in the development of fundamental system rules and agreements for smart contracts but also takes responsibilities for changes to the operating system if externalities affect the codified rules on-chain.

6.3.2 Institutional alignment

The expert evaluation also addressed the institutional alignment. The institutional hydrogen market is in a volatile state as the market's maturity is still in the beginning. According to the interviewees, it is important to set the institutional direction right upfront so that market participants have space to establish hydrogen business models. Interviewees I7 and I8 (cf. Schmid, 2024) mentioned that some institutions affecting the development of the green hydrogen market are still subject to change, such as the unclear distinction between proof-of-sustainability and GO. While the former relates only to hydrogen production and its sustainability as in the delegated act of the RED II regulation, the latter covers the entire energy production, including electricity and alternative sources classified as sustainable (EU Commission, 2023d). The regulation targets a gradual transition toward the proof-of-sustainability system by 2030, at which point all hydrogen producers will be required to match their green hydrogen production with the electricity supply (EU Commission, 2023f). EU policymakers need to acknowledge the hydrogen market's competitiveness and its volatility. Hydrogen producers can choose where to sell their hydrogen based on prices, implying that the hydrogen market's success is dependent on the regulations steering it. If the public authorities set high market barriers, hydrogen producers can choose to sell their hydrogen in non-EU countries. *An extensive cost-benefit analysis of the BLC-CS provides deeper insights into how the BLC-CS can influence the volatility of prices affecting the green hydrogen market development.*

Furthermore, hydrogen certification in EU facilities might be feasible, but countries outside the EU that are able to produce low-cost hydrogen may face higher risks of corruption (I8, (Schmid, 2024)). New institutions such as the Carbon Border Adjustment Mechanism can align lower international hydrogen production costs with the EU sustainability-compliant production prices (EU Commission, 2021). Cheap hydrogen from companies in low-cost countries that are allegedly less environmentally benign than EU companies would have the same price as RED II-compliant hydrogen. The trade-off between enforcing compliance with green hydrogen standards without expelling international suppliers to sell hydrogen in Europe is significant. *We recommend balancing reporting rigor with the free development of the hydrogen market as the BLC-CS cannot compensate costs associated with strict emission-reporting regulations.*

6.4 Societal integration

Lastly, the interviewees reflected on the societal integration of the BLC-CS. A steady, secure, and sustainable energy supply, such as green hydrogen, is on top of the current political agenda worldwide. In this regard, the discussions with the interviewees resulted in considerations on how the BLC-CS can support the green hydrogen developments in connection with society nowadays. According to Peffers et al. (2012), illustrative scenarios can support testing the applicability of the BLC-CS in the societal context. In discussion

TABLE 6 Implications of the scenarios for the BLC-CS.

Trade scenario	Implications
Case 1: Intra-Europe trade and transport	Case one represents the initial case chosen for the design of the BLC-CS to facilitate European green hydrogen trade and certification.
Case 2: Domestic usage	Whether the hydrogen is distributed within the country or between European countries, both are potentially feasible with the BLC-CS at hand.
Case 3.1: Closed system onsite	Green hydrogen certificates are needed for the user to prove emission intensities to the EU authorities. If the producer is the same entity as the user, the blockchain system still needs to be used although the closed loop cycle would not require certificates.
Case 3.2: Closed system separated	Separated closed systems function through contractual arrangements among trusted consortium partners, for instance, NorthH2. They have distinct information systems, ensuring their autonomy from the EU hydrogen grid. Despite this autonomy, it remains crucial to include their needs in developing the BLC-CS. The hydrogen valleys are important in efficiently shaping the hydrogen market. In the future, these independent clusters could be connected through corridors, paving the way for the creation of an EU-wide hydrogen grid (Armijo et al., 2022).
Case 4: Import from outside the EU	Importing hydrogen plays an important role in the EU's hydrogen strategy. The import restricts strongly the influence of European hydrogen monitoring. In this case, blockchain as a non-country-specific information system can play an important role in ensuring trust across EU borders. It is to be considered in future research.

with interviewee I11 (I11, (Schmid, 2024)), we found different trade scenarios imaginable in a future hydrogen market. For each scenario, we evaluated the utility and viability of the BLC-CS. Considering the institutional difficulties when it comes to monitoring the provenance of imported goods, the scenario plays an essential role in evaluating the BLC-CS. The implications of each scenario for the BLC-CS are summarized in Table 6.

In case one, we follow the EU's plan to successively develop hydrogen distribution in gas pipelines, which can be measured at injection points and withdrawal points to verify the data on green hydrogen circulation. The second case covers the domestic trade and usage of hydrogen. Blockchain technology can prevent double-counting when hydrogen moves across borders. Case three considers two scenarios: an onsite closed system and a closed system with separated owners. The former could be a steel plant installing a local electrolyzer to feed the steel-making process with green hydrogen instead of fossil gas (Schmid, 2024). The latter could be so-called hydrogen valleys/consortia such as NorthH2, including electricity producers, hydrogen producers, processors, distributors, and users (NortH2, 2023). In the fourth case, hydrogen is imported from countries outside the EU. Import will play a significant role in the hydrogen strategy of the European Union, accounting for approximately ten million tons of hydrogen by 2030 (EU Commission, 2023e).

7 Conclusion

In this research, we introduced a system design to address the trust issue in the hydrogen economy by focusing on the certification of green hydrogen and transparent data sharing. This study analyzed blockchain technology's potential to facilitate secure and automated certification while handling scalability with a growing demand for hydrogen certifications. Out of the need for a credible hydrogen certification system, we conducted an exhaustive requirements analysis. We implemented the requirements in the BLC-CS artifact to facilitate reporting, data verification, proof-of-sustainability token issuance, and cancellation in compliance with the RED II regulation on green hydrogen. The volatile institutional setting and the far-ahead expansion of the hydrogen market (2030–2040) induce uncertainties such as the magnitude of the hydrogen market and the costs of green hydrogen. However, technological advancements in blockchain and the permissioned consortium setup can accommodate a scaling hydrogen market and increasing user numbers. Hence, hydrogen supply chain actors can rely on blockchain for trustworthy and automated green hydrogen certification. The contributions of the research can be summarized as follows.

First, we found that blockchain research has not addressed the implementation of blockchain to ensure trustworthy hydrogen certification. Related work only problematizes the trust issue in information on hydrogen provenance but does not provide specific solutions. This research combines a comprehensive analysis of the market need for reliable green hydrogen certification with the technical capabilities of blockchain technology to aid challenges in trustworthy and efficient green hydrogen certification. Particularly, our research shows that green hydrogen certification is fragmented due to multi-actor and institutionally induced complexities. The connection to blockchain showed that decentralized information systems can unite fragmented stakeholder interests, facilitate coordination, and maintain monitoring in a trustworthy way.

Second, we extended research on blockchain architecture design, IoT system architecture, and their intersection. We developed a generic blockchain–IoT architecture framework that can serve as an ontology for future blockchain design applications in the energy sector. Vis-a-vis other use cases, this can contribute to the framework for future certification/emission accounting applications.

Third, we applied the theoretical blockchain–IoT framework to the hydrogen certification environment, considering societal and institutional externalities that influence the design. Information systems have a mutually dependent impact on the embedded context. We explored the implementation of the technical BLC-CS in the social and institutional context, contributing to the foundations of DSR in information systems by creating awareness of the socio-technical embedment of blockchain-based applications. Aligning technological opportunities with resilient governance and clear institutions can set a smooth pathway for green hydrogen certification.

In our research, we set some conscious limitations to the research scope and the methodological approach. We limited the research to the geographical area of the EU. The purpose was to limit the complexity of institutional and societal integration and limit the broadness of the experts to balance between the specificity and inclusiveness of the artifact design. The experts consulted in this study are limited to the mid-European regulation and green hydrogen context. Expanding the involvement of international stakeholders can increase the BLC-CS's validity. Second, the research focuses solely on the theoretical hydrogen use case, contributing to the broader field of supply chain transparency and tokenization of physical assets. Testing the BLC-CS in a proof-of-concept with real-world data would add to the practical feasibility of the design.

The artifact's evaluation suggests some directions for future research. First, oracles connecting on-chain and off-chain data and tokenization of proof-of-sustainability certificates face practicality issues in terms of security and costs, respectively. Second, off-chain governance strongly depends on the current actors in charge of green hydrogen certification. We recommend working closely with these actors to integrate the artifact successfully with stakeholders and institutions. Lastly, we found the artifact is dependent on its compatibility with society using the hydrogen system. We suggest running all hydrogen trading scenarios to ensure the comprehensiveness of requirements for a global green hydrogen market. Future research can use the qualitative information on designing the BLC-CS for creating a proof-of-concept in the market. This would allow testing the feasibility of blockchain for green hydrogen certification in a real-world setting.

Data availability statement

The datasets presented in this study can be found in online repositories. The names of the repository/repositories and accession number(s) can be found in the article/Supplementary Material.

Ethics statement

Approval for this study was received from the Human Research Ethics Committee (HREC) of Delft University of Technology, dossier number 2966.

Author contributions

JS: conceptualization, data curation, formal analysis, investigation, methodology, resources, validation, visualization, writing–original draft, and writing–review and editing. JU: conceptualization, methodology, project administration, resources, supervision, validation, and writing–review and editing. Sv: writing–review and editing, supervision, formal analysis, and validation. Jv: conceptualization, resources, supervision, validation, and writing–review and editing. EC: conceptualization, supervision, validation, and writing–review and editing.

Funding

The author(s) declare that no financial support was received for the research, authorship, and/or publication of this article.

Conflict of interest

Author Jv was employed by CGI Nederland B.V.

The remaining authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Supplementary material

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fbloc.2024.1408743/full#supplementary-material

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