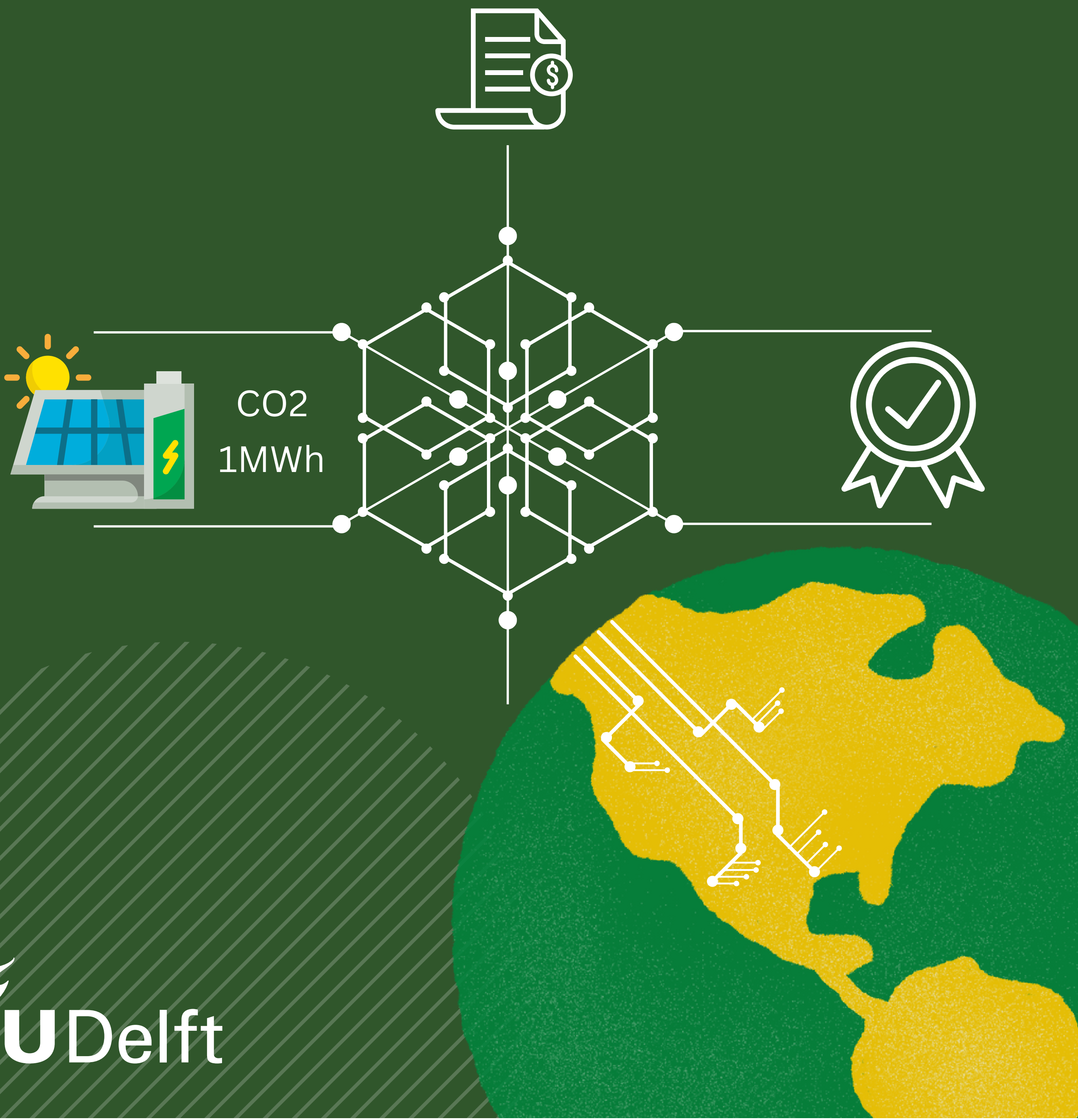
Is it Green?

Designing a Blockchain-based Certification System for Green Hydrogen.

Jonathan Schmid

Delft University of Technology



TU Delft

Is it Green?

Designing a Blockchain-based Certification System for Green Hydrogen.

by

Jonathan Schmid

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in partial fulfillment of the requirements for the degree of

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Jonathan Schmid
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Management summary

The severity of climate change impacts various aspects of human life today, with projections of up to six degrees of global warming by 2100 if significant changes are not adopted. (Intergovernmental Panel on Climate Change, 2021). Among others, the energy supply cannot be solely fossil-based but need to adopt alternative ways of generation, transportation, and storage. In response, politics worldwide stimulate the use of alternative energy sources, such as sustainable hydrogen. Hydrogen differs from conventional fossil fuels and gases. Since primary pollution arises from hydrogen production and the energy source to produce the hydrogen, **additional metadata** on the hydrogen is needed for successive parties in the hydrogen value chain. They depend on the **truthfulness** of the information for compliance with emission reduction targets and emission reporting obligations toward the public authorities. In the EU and worldwide, public authorities develop certification mechanisms to ensure the truthfulness of the information, ensuring the composition of the physical hydrogen. These certifications aid the information asymmetry between hydrogen sellers and buyers but are characterized by complicated administrative reporting efforts and regionally differing certification requirements. Questions remain on the **GHG emissions accounting, the boundaries of the reporting obligation, and the tradeoff between certification rigor and administrative reporting burden** for hydrogen producers (Abad & Dodds, 2020). Discrepancies among current certification standards lead to **opacity, incompatibility, and high auditing costs** for hydrogen producers and public authorities. Addressing the problem of truthful information throughout hydrogen value chains can help to establish a green hydrogen market, fostering green hydrogen production, and sustaining alternative energy supply in Europe (EU Commission, 2022a; IRENA & RMI, 2023; World Energy Council, 2022).

This thesis presents a blockchain-based artifact design for the European Union that addresses the requirements for reliable hydrogen certification, unifying European certification standards in one system while automating intensive reporting and certification processes. **Design Science Research (DSR)** helps to approach the research structurally. First, the complex hydrogen certification system is outlined, comprising the stakeholders, the institutional frame, and the technical certification processes. Second, the stakeholders contribute to the requirements engineering through semi-structured interviews. Third, a blockchain-IoT architecture framework is developed to translate the requirements of the hydrogen market into system design components. Fourth, the technical artifact is demonstrated in the complex hydrogen certification context. Last, expert interviews are conducted to evaluate the proposed design.

Concluding, blockchain-IoT can serve the requirements for **interoperable, automated, and reliable green hydrogen certification while complying with EU regulations** on sustainable hydrogen. However, the technical design aspects required to fulfill requirements are premature and costly. Blockchain can serve as a solution, but the **technological readiness** of specific design aspects such as Zero-Knowledge-Proof (ZKP), Oracles, and Non-fungible tokens (NFT) induce tradeoffs between costs and the effectiveness of the design. Blockchain introduces a paradigm shift from central to decentral systems, affecting technical architecture, governance, and institutions. **Governance** of the technological artifact is essential to guarantee a successful implementation in the market. Therefore, a decentral system maintenance council must align the physical hydrogen market with the digital blockchain infrastructure and enforce mutual functionality. The alignment with **institutions** is considered to address compliance with regulatory green hydrogen standards and interoperability with multiple Voluntary Schemes. The current hydrogen market is characterized by institutional fragility affecting the confidence of green hydrogen producers. The artifact can ensure trust in the information, but institutions determine the rules of the certification game, whether virtual or physical. Moreover, the evaluation found that considering only the European market is insufficient. **International trade** scenarios would increase the impact of the artifact in complex internationally entangled hydrogen value chains. For example, hydrogen producers outside the EU that comply with internationally accredited Voluntary Schemes could sell hydrogen in Europe. Hence, given the information trust issue in the hydrogen market, the artifact provides the first alternative to conventional centralized certification mechanisms benefiting researchers and practi-

tioners in the blockchain application environment.

The thesis contributes **socially, culturally, environmentally, and economically** to society. The artifact can guide European policymakers to new decentralized methods of addressing the trustful information-sharing issue in the hydrogen certification market (social impact). Conventionally, certification functions from top to bottom enforcing reporting to national authorities. Blockchain can reinvent public-private cooperation by decentralizing control and tasks (cultural impact). Deploying the artifact can help to facilitate the EU's plan to increase green hydrogen domestic production and import by 10 million tonnes by 2030 (EU Commission, 2023a). The blockchain artifact can guarantee environmental-benign hydrogen supply by ensuring trusted information on the emissions of hydrogen production (environmental impact). Lastly, the artifact can automate reporting processes for hydrogen producers and certification processes for public bodies and thus contribute to the economic capital of the EU. Public bodies and hydrogen buyers have enhanced trust in the information accompanying the hydrogen supply in the European market, and hydrogen producers have reduced market entrance barriers induced through administrative tasks (economic impact).

Methodologically, the thesis contributes to the green hydrogen certification economy: To the knowledge of this thesis's author, the potential of blockchain technology as a tool to facilitate hydrogen certification has not been analyzed yet. The thesis provides tangible design concepts for blockchain-based hydrogen certification systems. Scientific research and blockchain practitioners can develop upon this initial study. Secondly, partly outdated blockchain architecture modeling in combination with IoT infrastructures is addressed. A framework is developed based on existing scientific research to serve the peculiarities of the hydrogen certification market, which can serve as an ontology for future blockchain designs in energy systems. Third, the socio-technical embedment of the technical blockchain design gives insights into adopting such complex, paradigm shift-inducing information systems in society. Last, the evaluation methods of DSR are addressed in the underlying research project. Interesting insights from practitioners with energy and blockchain backgrounds are discussed. These can serve as recommendations for future amendments or extensions of the design. Hence, the artifact can contribute to the theory of DSR and practical blockchain implementation research.

The research is **limited** to the hydrogen market of the EU and distribution via gas pipelines, neglecting navel and road transport. The study covers the first design cycle of the DSR approach. Adding successive cycles with the gradual inclusion of more industry experts, various use cases, and new institutional changes can enhance the artifact's viability for the hydrogen market. Furthermore, different evaluation parameters could be added, such as the tradeoff between technical optimization and the costs of such interventions. Other use cases could entail considerations of the artifact's interoperability with hydrogen trade platforms, feasibility for different hydrogen trade scenarios (international trade, but also closed systems), and incorporation of additional requirements addressing hydrogen safety, hydrogen facility construction, and financial incentives. These complexities can test the artifact's applicability in the socio-technical context.

Contents

List of Figures

List of Tables

Nomenclature

Abbreviation	Definition
AFHYPAC	French Association for Hydrogen & Fuel Cells
AIB	Association of Issuing Bodies
BEIS	Department for Business, Energy & Industrial Strategy of the United Kingdom's Government
CBAM	Carbon Border Adjustment Mechanism
CCS	Carbon-Capture-System
CEN	European Committee for Standardization
CENELEC	European Electrotechnical Committee for Standardization
CG	Coal Gasification
dena	German Energy Agency
DLT	Distributed Ledger Technology
DP	Design Principle
DSO	Distribution System Operator
DSR	Design Science Research
EECS	European Energy Certificate System
EO	Economic Operator
ETS	European Trading System
EU	European Union
GHG	Greenhouse Gas
GO	Guarantee-of-Origin
HBE	Hernieuwbare Brandstofeenheden
IEA	International Energy Agency
IIoT	Industrial Internet of Things
IoT	Internet of Things
IPCC	International Panel on Climate Change
ISCC	International Sustainability & Carbon Certification
ISO	International Organization for Standardization
IT	Information Technology
LCFS	Low Carbon Fuel Standard
LoRaWAN	Long Range Wide Area Network
MRQ	Main research question
MS	Member States of the European Union
NEa	Nederlandse Emissieautoriteit (Dutch Emission Authority)
NFT	Non-fungible Token
PBFT	Proof-of-Byzantine-Fault-Tolerance
P2P	Peer-to-Peer
PoA	Proof-of-Authority
PoS	Proof-of-Sustainability
PoW	Proof-of-Work
PPA	Power Purchase Agreement
RED II	Renewable Energy Directive of the European Commission
REV	Dutch Registry for Energy for Transport
RFID	Radio-Frequency Identification
RFNBO	Renewable Fuels of Non-Biological Origin
RQ	Requirement
RTFO	Renewable Transport Fuel Obligation
SDG	Sustainable Development Goal

Abbreviation	Definition
SFT	Semi-fungible Token
SHA	Secure Hash Algorithm
SMR	Steam Methane Reforming
SQ	Subquestion
TAM	Technology Acceptance Model
TSO	Transmission System Operator
UDB	Union Database
UN	United Nations
UNFCC	United Nations Framework Convention on Climate Change
VS	Voluntary Scheme
WEC	World Energy Council
Wifi/WLAN	Wireless Local Area Network
ZKP	Zero Knowledge Proof
ZK-SNARK	Zero-Knowledge Succinct Non-Interactive Argument of Knowledge

1 Introduction

This master thesis project is conducted in collaboration with the TU Delft and CGI Netherlands - Energy and Communications. The thesis aims to shed light on the fragmented hydrogen certification field in the European Union. In this sense, it seeks to explore the opportunities and uptakes of emerging technology, such as blockchain, to facilitate tracking hydrogen provenance and composition. A design science research approach is utilized to build a blockchain-based hydrogen certification system architecture design for the hydrogen value chain to accomplish this. With this method, the right design decisions can be ushered to comply with the peculiarities of the hydrogen value chain and involved stakeholders.

The first chapter guides the reader toward the research topic and functions as a fine-grained outline explanation. In Section 1.1, the main problem is introduced as the decisive reason for the research project. In the subsequent section, the key concepts are introduced: *the complex hydrogen value chain, the certification schemes, blockchain as part of distributed ledger technology, and its potential for certification*. This is achieved through a literature review that shows the state-of-the-art knowledge of the key concepts and helps identify gaps in the green hydrogen certification and affiliated blockchain-based systems. These knowledge gaps are outlined in Section 1.3. The main research question can be defined based on the identified knowledge gaps in Section 1.4.

1.1. Problem introduction

Climate change poses one of modern society's most pressing challenges (Nasa, 2022). According to conservative projections by the International Panel on Climate Change (IPCC), global warming could exceed six °C by 2100 if no drastic energy consumption changes are pursued (Intergovernmental Panel on Climate Change, 2021). In response, politics worldwide, including the EU, adopted an energy transition plan to tackle the global societal problem of global warming, namely the European Green Deal (EU Commission, 2019). This EU strategy encompasses an action plan to achieve the EU's target of reducing 55% of Greenhouse gas (GHG) emissions by 2030 (European Environment Agency, 2022). Among others, the EU strategy aims at fostering hydrogen distribution, storage, and utilization across borderlines within the EU (EU Commission, 2020).

Hydrogen, one of the most abundant elements, has emerged as a viable energy carrier opening an additional pathway to a more sustainable and stable energy supply (Mould et al., 2022). Three main types of hydrogen conversion have gained prominence: sustainable electrolysis through green electricity (green), steam-conversion with carbon capture (blue), and lastly, the production from fossil fuels (grey). Green hydrogen accounts for only 2% of the EU's energy consumption in 2020, while the majority (96%) still relies on fossil fuels, contributing to about 70-100 million tonnes of CO_2 emissions (EU Commission, 2020). The EU Commission also points out that environmentally benign production of hydrogen, such as electrolysis, is still not cost-effective to be adopted widely, which is why mostly blue and grey production (from fossils) is executed (EU Commission, 2020). Out of the technology scarcity and current problems in hydrogen production, multiple endeavors are undertaken to support the transition towards clean energy, such as the Clean Hydrogen Alliance bringing together public, business, and civil actors to collaboratively push clean hydrogen production in the EU to reach the goal of two 40 GW electrolyzers by 2030 (Capurso et al., 2022; EU Commission, 2020). In collaboration with Gasunie, the Dutch government rolled out a plan to construct a national hydrogen distribution network with a connection, for example, to Germany, which is supposed to be used by 2025 (Gasunie, 2022b). Further, plans are pursued by the EU by establishing an EU-wide hydrogen backbone which partly comes into place by 2030 (Enagás et al., 2020). Hydrogen can serve for energy storage, heating, high-temperature production processes, and long-distance transport (TNO, 2022).

Differentiating between sustainable and non-sustainable hydrogen is a challenge. Due to the multiple, more or less polluting production methods of grey, blue, and green hydrogen, without significant compositional effects, additional information about the purchased hydrogen is needed to assess its sustainability. The required information is transparent information about the provenance and composition of hydrogen (Dawood et al., 2020; White et al., 2021). Conventionally this information is guaranteed by certifications of hydrogen producers. Out of the information needed, different certification schemes were developed regionally, such as Certifhy in the EU, TÜV Süd in Germany, Low Carbon Fuel Standard (LCFS) in California, and BEIS in Australia (Australien Government, 2021; California Air Resource Board, 2023; Certifhy, 2022). Scientific literature found that current standards deviate from a unified definition of 'green' hydrogen with uncertainty regarding GHG emission accounting, its boundaries, and trade-offs between accuracy and cost (Abad & Dodds, 2020). For example, Certifhy aims to facilitate green hydrogen production, so the main focus for emission accounting lies in hydrogen production. TÜV Süd, in contrast, proposes a more granular certification standard with system boundaries that reach from production to the end of life (White et al., 2021). This discrepancy leads to challenges in the conventional certification field, such as opacity, incompatibility, and high auditing costs (Collell & Hauptmeijer, 2022). Hydrogen producers are largely affected by these unclarities as market entrance costs rise and green hydrogen production costs are pushed. To stimulate a flourishing green hydrogen market, hydrogen producers require a transparent information system ensuring a reliable and unified hydrogen certification while complying with different hydrogen standards. As there are many different certification standards, the research of this thesis focuses on the European hydrogen market regulated by the RED II directive. In the RED II directive, the EU Commission sets binding renewable energy targets for the transport and heating sectors, driving the demand for low-carbon hydrogen and encouraging the development of analogous infrastructure to support green hydrogen production, distribution, and use (EU Commission, 2022b). The directive aims to facilitate the expansion of the green hydrogen market by creating a regulatory framework that promotes green hydrogen use and reduces GHG emissions in the EU.

To address the challenges of current certifications, this thesis explores the certification of green hydrogen within the frame of distributed information systems, specifically blockchain technologies/ distributed ledger technologies[1]. Through its tamper-resistant, transparent, and distributed character, it is exceptionally suited for supply chains with large spans and many involved stakeholders which rely on information up- and downstream (Mould et al., 2022). Existing research has demonstrated the potential of blockchain in increasing supply chain transparency for products like textiles, drugs, and food (Hastig & Sodhi, 2020; Tian, 2016). Furthermore, blockchain also has the potential to track emissions for bulky goods such as energy commodities (Silvestre et al., 2020). Cali et al. (2022) state that blockchain can facilitate large amounts of transactions in a cyber-secure manner while providing trustworthy information on the sustainability of electricity through the linkage of Renewable Energy Certificates (REC) to digital tokens. Hydrogen's bulky nature promises a similar solution as blockchain technology could digitize hydrogen certificates transparently for market actors in a tamper-resistant and confidentiality-preserving manner. Furthermore, hydrogen poses a physical commodity that requires tools to link it with the digital blockchain world in order to grasp the informational data-sharing benefits of blockchain technology. This can be done through the linkage of blockchain technology with the Internet of Things (IoT) which allows the sensing of physical processes and translation into digital data (Christidis & Devetsikiotis, 2016). Blockchain research on supply chain traceability with linkage to physical measurement devices, the IoT, is already advanced and multiple surveys in this field can be found (Christidis & Devetsikiotis, 2016; Fernandez-Carames & Fraga-Lamas, 2018; Kumar et al., 2022; Moin et al., 2019).

[1]from now on the term blockchain technology will be used in this study.

Considering this knowledge base, existing architectures on cyber-physical blockchain-based IoT systems can be exaptated for application in the green hydrogen certification market.

Conducting research on the capability of blockchain technology as a nascent information system changing the semantics of information sharing fundamentally can contribute significantly to European developments in setting up a holistic hydrogen distribution network. The research can support energy production companies and end-users in sharing information on hydrogen grid injection and withdrawal transparently in a distributed and secure network that integrates data standards and ensures interoperability. The information can be uploaded and securely shared with the stakeholders involved in the hydrogen value chain. Users can trust the information about the hydrogen's provenance and composition provided by the blockchain's distributed information system and verify the information themselves. Further, the certificates for green hydrogen can be securely digitized in so-called digital tokens inspired by green electricity labeling (Babel et al., 2022).

Subsequently, an initial literature review is conducted to identify the current state of blockchain-based systems connected to Guarantees of Origin (GOs) and emission accounting along energy value chains.

1.2. Definition of key concepts

The following structured literature research has been conducted to analyze the state of the art in green hydrogen certification and blockchain's paradigm for the hydrogen supply chain. This approach helps to identify relevant and up-to-date scientific data. Further, it is essential to introduce the fundamental concepts pertinent to analyzing the hydrogen certification and blockchain field to guide the research process. The scientifically recognized PRISMA approach was followed to identify the relevant articles, including the three steps of identification, screening, and inclusion (Haddaway et al., 2022). Additionally, forward and backward snowballing was added to identify more relevant literature.

1.2.1. Literature review

Hydrogen is an emerging renewable energy alternative that recently received significant attention from politics and the private industry. However, scientific research regarding green hydrogen certification and emission accounting, particularly concerning the potential of blockchain technology, remains limited. In this literature review, the Scopus database was the primary source for identifying relevant scientific literature. The first literature review round involved examining state-of-the-art articles focusing on energy value chains, specifically emphasizing green hydrogen. The following Boolean was used: ((“guarantee of origin” OR “proof of origin” OR “emission accounting”) AND “green hydrogen”). It resulted in six scientific articles. In a second round, a more generic research string was used to identify current blockchain-based applications in the hydrogen field: (blockchain AND hydrogen). Here, 13 results could be found. 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 removing the duplicates and screening, 15 identified papers could be categorized as useful for the ongoing research. Further, a forward and backward search resulted in 5 more articles relevant to the study. The results can be seen in Table 1.1.

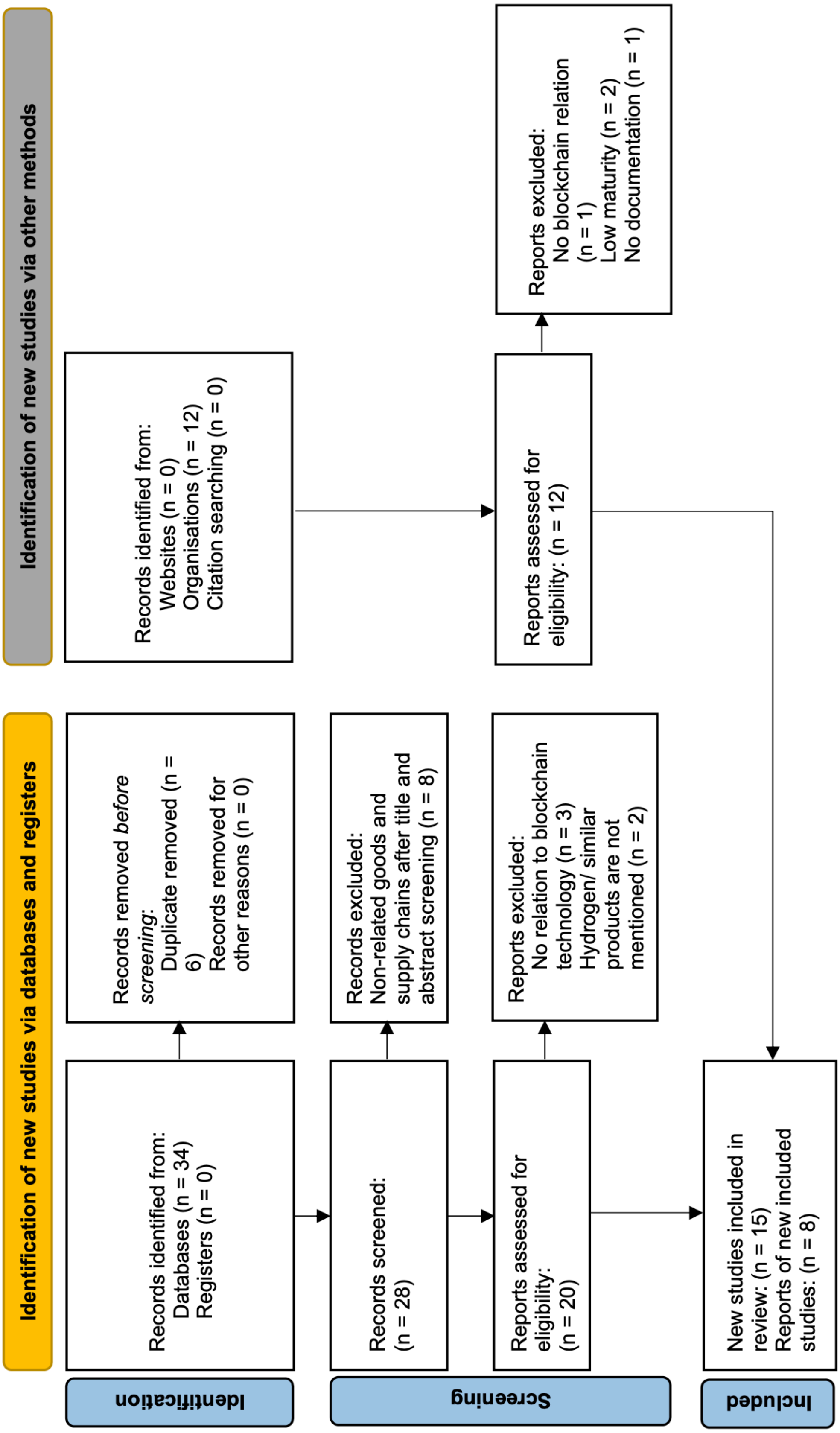

Figure 1.1: PRISMA diagram adapted from (Haddaway et al., 2022).

Table 1.1: Literature review results.

Source	Title	Date	Certification/GO related	Blockchain related	Identified by
(Abad & Dodds, 2020)	Green hydrogen characterization initiatives: Definitions, standards, guarantees of origin, and challenges	2020	✓		Scopus
(Barth et al., 2016)	CertifHy - Developing a European Framework for the generation of guarantees of origin for green hydrogen	2016	✓		Scopus
(Cheng & Lee, 2022)	How Green Are the National Hydrogen Strategies?	2022	✓		Scopus
(Mould et al., 2022)	A comparative analysis of biogas and hydrogen, and the impact of the certificates and blockchain new paradigms	2022	✓	✓	Scopus
(Dawood et al., 2019)	Power to gas energy storage system for energy self-sufficient smart cities development	2019		✓	Scopus
(Niya et al., 2018)	Design and implementation of an automated and decentralized pollution monitoring system with blockchains, smart contracts, and LoRaWAN	2018		✓	Scopus
(Nofuentes et al., 2022)	Blockchain-based Guarantees of Origin issuing platform	2022	✓	✓	Scopus
(Kim et al., 2020)	Seal-bid renewable energy certification trading in power system using blockchain technology	2020		✓	Scopus
(Castellanos et al., 2017)	Cryptocurrency as guarantees of origin: Simulating a green certificate market with the Ethereum Blockchain	2017	✓	✓	Scopus
(Zhang et al., 2022)	Study of Traceability System of Renewable Energy Power Trading Based on Blockchain Technology	2022	✓	✓	Scopus
(Cali et al., 2022)	Cybersecure and scalable, token-based renewable energy certificate framework using blockchain-enabled trading platform	2022	✓	✓	Scopus
(Zhao et al., 2020)	Individual green certificates on blockchain: A simulation approach	2020	✓	✓	Scopus
(Knirsch et al., 2020)	Decentralized and permission-less green energy certificates with GECKO	2020		✓	Scopus
(Finke et al., 2022)	A Distributed Ledger Based Ecosystem as an Approach to Reduce Greenhouse Gas Emissions for Shared Mobility by Incentivizing Users	2022	✓	✓	Scopus
(Gallo et al., 2022)	A Blockchain-based Platform for Positive Energy Districts	2022	✓	✓	Scopus
(Babel et al., 2022)	Enabling end-to-end digital carbon emission tracing with shielded NFTs	2022	✓	✓	Forward/ backward research
(Blasio et al., 2021)	Mission Hydrogen: Accelerating the Transition to a Low Carbon Economy	2021	✓	✓	Forward/ backward research
(Rioux & Ward, 2022)	A non-fungible token model for tracking emissions in the fuel value chain	2022	✓	✓	Forward/ backward research
(White et al., 2021)	Towards emissions certification systems for international trade in hydrogen: The policy challenge of defining boundaries for emissions accounting	2021	✓		Forward/ backward research
(Sedlmeir, Völter, et al., 2021)	The Next Stage of Green Electricity Labeling: Using Zero-Knowledge Proofs for Blockchain-based Certificates of Origin and Use	2022	✓	✓	Forward/ backward research

The most relevant articles for this thesis's research comprise recently published articles that concern blockchain research as a certification tool (cf. Articles with both checkmarks in Figure 1.1). These articles help to define the key concepts and identify the knowledge gap in Section 1.3. In the literature review, only 15 of the 34 identified scientific articles were helpful (not counting the forward/ backward snowballing). This observation suspects a lack of scientific research on hydrogen certification in combination with blockchain technology. Expanding the research scope to grey literature encompasses the entirety of hydrogen research, leading to numerous industrial and business projects that assert their ability to tackle the hydrogen certification issue through blockchain-based systems. Thus, the study analyzed multiple businesses to justify the research niche and newness. The cross-research on the internet and topic-specific newspapers and blogs resulted in Table 1.2.

Table 1.2: Business actors in the power certification field.

Company	Accounting	Boundaries	Conclusion	Status	Type of blockchain	Source
GreenH2chain	Segregated or Book and claim	Well-to-tank	Only one client and segregated accounting approach.	Development and testing	Private	(Acciona, 2021)
PowerLedger	Segregated	Cradle-to-gate	Only one client, they don't provide a scalable/ standardized information system.	Development and testing	Private	(Powerledger, 2023)
Nobian and Siemens Energy	Segregated	Cradle-to-gate	Only one client, they do not provide a scalable or standardized information system.	Piloting	Private for own green hydrogen production	(Nobian, 2023)
Circularise	Massbalance	not specified	Focus on supply chain traceability for tangible goods	Active	Private	(Konstantinov & Daphne, 2022)
PointTwelve	Segragated	Well-to-tank	Takes only production of green hydrogen into account	Development and testing	Private	(PointTwelve, 2022)
EnergyWeb	not specified	not specified	No hydrogen relation	Active and Testing	Private	(energy web, 2023)
Tymlez	Book and claim	Cradle-to-grave	No standardized GO Scheme compliant with EU regulation.	Active and Development	Private	(Tymlez, 2023)
GreenToken by SAP	Massbalance	not specified	Focus on RED2 and ISCC products, but no specification for the hydrogen market rather plastics and chemicals.	Development and testing	Private	(Kormann et al., 2022)

Eight significant industry efforts toward green hydrogen certification based on blockchain technology are found and included in identifying the knowledge gap. The Table further elaborates on the functioning of the concepts proposed by the identified companies. Chapter 1.3 provides an analysis of the practical feasibility of these business concepts to identify a practical knowledge gap.

1.2.2. The hydrogen economy

Hydrogen can be produced in different ways. Green, blue, and black hydrogen are the main categories indicating the energy consumption intensity: green is produced from only renewable energy with low-carbon intensity; blue is produced from low-carbon intense fossils or when CCS (Carbon-Capture-System) are deployed; and black is produced from carbon-intense fossils and nuclear power (Certifhy, 2022). As the hydrogen demand rises due to regulatory incentives, clear monitoring and auditing standards must be implemented to ensure a functioning and trustworthy hydrogen market where information is symmetrically distributed between producing, transmitting, and consuming entities. For now, hydrogen value chain participants have encapsulated data about their particular value chain process - so information is asymmetrically distributed. However, especially for hydrogen producers, it is vital to have clarity about the emissions happening along the supply chain up and downstream to comply with reporting obligations and receive the green certification.

In the hydrogen economy, three main production techniques exist, that is coal gasification (CG) or steam methane reforming (SMR), the same with carbon capture and storage techniques, and electrolysis through renewables with degrading GHG emissions (Dong et al., 2022). These three are grey, blue, and green hydrogen, respectively. According to the RED II directive, it also exits the definition of low-carbon hydrogen, produced through electrolysis and renewable energy, nuclear energy, and natural gas (turquoise) (EU Commission, 2022b). Table 1.3 entails the definition of hydrogen based on the emission intensity outlined by the RED II directive. The European legislation further denotes that country-specific laws should enforce and monitor hydrogen production to ensure a flourishing green hydrogen market.

Table 1.3: Hydrogen qualification according to EU Commission (2022b) and World Energy Council (2022)

	EU regulation definition	Energy Source	GHG intensity in (kg CO2/GJ H2)
Grey hydrogen	Fossils	Natural gas/ coal	82
Blue hydrogen	Fossils with CCS	Natural gas/ coal	11-54
Turquoise hydrogen	Low carbon	Natural gas	-
Green hydrogen	Clean/renewable	Green electricity	0 (excl. construction emissions)

The hydrogen value chain is a complex field of actors and processes, from hydrogen production to the consumer's usage of the hydrogen batch. It is also often referred to as a chain of custody. This chain is characterized not only by the complexity of production techniques but also by nature because hydrogen is a highly inflammable gas that requires strong safety standards, and there are multiple transportation, storage, and usage methods. Transportation can be executed through pipelines, trucks, or ships in compressed and liquidized forms. Each means of transportation causes different GHG emissions, thus introducing more complexities to the value chain. Further, hydrogen can be stored underneath the ground or in tanks above the ground. For the application possibilities, Li et al. (2023) state that hydrogen is a promising solution for transporting, storing, and using renewable energy in various sectors such as heating, heavy metal industries, transport, and fuel cells. Further complexities could be induced by institutional externalities such as the proposed CBAM (Carbon Border Adjustment Mechanism). The mechanism aims to incentivize environmentally-benign transformation of energy-intensive industries by taxing imported goods such as cement, steel, and electricity for energy consumption (European Commission, 2023b). It can be concluded that high bureaucratic effects can result in the green hydrogen certification market when linking it to taxation and emission trading infrastructures. From a hydrogen producer perspective, it has to be clear what the European standard is and what reporting obligations are required to sell hydrogen in the EU without facing market insecurities. The holistic value chain can be seen in Figure 1.2. In this thesis, an EU-wide pipeline distribution network is assumed to simplify the case for the artifact design and test it on one particular hydrogen value chain type. In this way, the particular case of the future hydrogen backbone can be tested as a case for the green hydrogen certification. Hydrogen storage is also not included as the state of the hydrogen does not change, nor is it consumed nor expanded. It can be assumed that the pipelines serve as temporary storage means. The application areas are referred to as hydrogen end users.

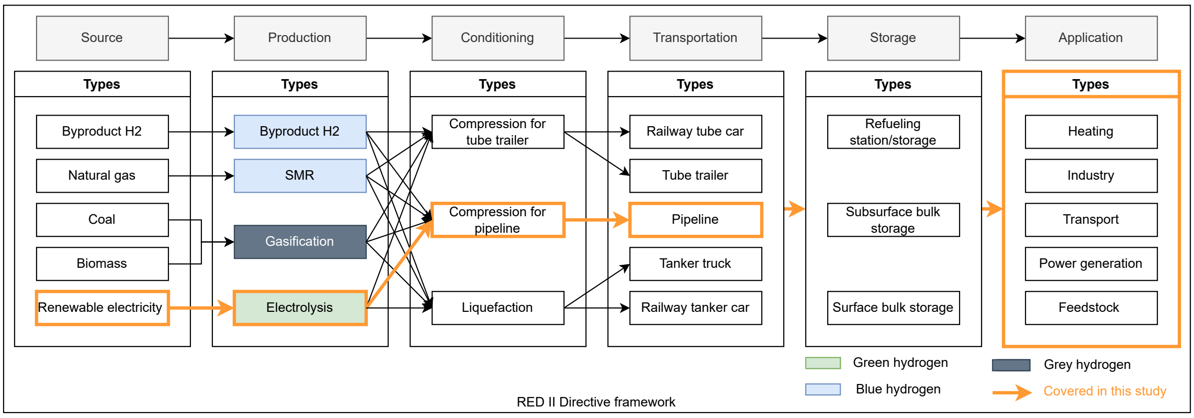

Figure 1.2: Hydrogen value chain adapted from Pale Blue Dot (2019) and Seo et al. (2020).

1.2.3. Hydrogen certification

Conventional renewable energy certification is based on GO claims that third-party auditors issue. The Association of Issuing Bodies (AIB) is the European instance to maintain a harmonized certification scheme for renewable energy among different issuing bodies and across borders (AIB, 2023). The fundamental legislation is in the RED II (EU Commission, 2022b). It defines the rules which outline the definition of green hydrogen in the EU and sets the framework for establishing the certification for all renewable fuels of non-biological origin (RFNBO), including hydrogen (Ministry of Economic Affairs and Climate Policy, 2020). The generic definition of a GO according to the EU law "[...] means an electronic document which has the sole function of providing evidence to a final customer that a given share or quantity of energy was produced from renewable sources" (EU Commission, 2022b). Particularly, 1 GO is equivalent to 1 MWh of energy (Nofuentes et al., 2022). To distinguish the renewable hydrogen certificate specifications from the renewable energy certificates (GOs), they are named Proof of Sustainability (PoS) (Sailer et al., 2021). The RED indicates further which data the certificate should entail, who is auditing and monitoring, and how it has to be reported and documented.

Each EU member state (MS) must follow the regulations delineated in the RED II directive and set out adequate measures to enforce the rules nationally. In the Netherlands, the Verticir cooperation is designated to establish a framework for issuing GOs for green hydrogen and the associated verification of emission data (Ministry of Economic Affairs and Climate Policy, 2020). Verticir is a publicly owned cooperation of Vertogas and CertiQ and is owned by Gasunie and funded by the Dutch Government (Gasunie, 2022a). Departing from the RED II directive, in other EU countries, different certification systems were established focusing on various aspects of the hydrogen value chain, with different boundary conditions and varying approaches depending on the country-specific governmental institutions. For example, TÜV Süd was elected in Germany, in France AFHYPAC, and Certifhy as an EU-wide certification entity for the hydrogen network (White et al., 2021). Predominantly book and claim technique is used. It is the most feasible solution to transfer certificates separately from the hydrogen batch and to allow for easier trading of such green energy certificates. A complete list of relevant certification mechanisms and types can be found in Table 1.4.

Table 1.4: Existing hydrogen certification standards, adapted from (Abad & Dodds, 2020).

Regulation body	Region	Boundary	Type	Source
LCFS	USA	Well-to-wheel	Mass balance	(California Air Resource Board, 2023)
TÜV SÜD	Germany	Well-to-wheel	Book and claim	(TÜV SÜD, 2023)
AFHYPAC	France	Cradle-to-Gate	Book and claim	(France Hydrogène, 2021)
DISER	Australia	Cradle-to-Gate	Book and claim	(Australien Government, 2021)
CEN-CENELEC	Europe	Cradle-to-Gate	Book and claim	(European Committee for Standardization, 2023)
Certifhy	Europe	Cradle-to-Gate	Book and claim	(Certifhy, 2023a)
Vertogas	Europe/ Netherlands	Cradle-to-Gate	Book and claim	(Vertogas, 2023)

As can be seen in the table, different regions have different regulating bodies with various boundary conditions and different types of certification.

Mostly well-to-wheel emission accounting boundaries can be found, encompassing emissions along the entire hydrogen value chain. Other standards focus more on the main aspect of green hydrogen provenance, such as Certifhy's cradle-to-gate approach (Abad & Dodds, 2020). These standards exclude emissions emanating from hydrogen transportation, conversion, and storage.

According to Abad and Dodds (2020), three different chains of custody exist in the hydrogen economy: *segregated, book and claim, and mass balance*. The former considers segregated streams, which means green hydrogen is not mixed with other gases or production techniques. In the second approach, the goods stream is separated from the issuing of certificates. It links to the trading of certificates and seeks to incentivize the green production of hydrogen. The mass balance approach follows the idea that there cannot be an abrupt transition to exclusively green hydrogen supply, so compliant and non-compliant products can be mixed with regarding proportion indications (Department for Business, Energy & Industrial Strategy, 2021).

1.2.4. Issues of conventional GOs

Hydrogen induces a fundamental difference in emission accounting from conventional fossil energy sources because emissions occur at the point of production and not during consumption (Dhasarathan et al., 2021). For the end user, the emission intensity for consumed hydrogen can differ. Providing additional information on the origin and composition of the hydrogen can create awareness of the emissions. Conventional GOs for renewable energy cover aspects to comply with the emission reduction targets of the EU regulation but still need to cover temporary, geographical, and additional information required to qualify hydrogen (Sailer et al., 2021). Guaranteeing the trustworthiness of metadata about hydrogen emissions so that hydrogen end users and authorities can rely on it requires a credible certification. Upon this, the physical hydrogen must link with the digital certificate to ensure the sustainability claims correspond with the actual hydrogen production.

Volatile legislation characterizes the current green hydrogen certification field, leading to uncoordinated certification mechanisms. According to White et al. (2021), current efforts worldwide aim to launch adequate certification mechanisms to increase transparency in the hydrogen market. These standards must be aligned to serve international hydrogen value chains (Abad & Dodds, 2020). However, for example, Cheng and Lee (2022) notes that the Australian certification scheme does not specify whether hydrogen is produced 100% renewably. The same can be observed with the Certifhy scheme that focuses on the production procedure while excluding all downstream activities such as transport, usage, and end-of-life (Certifhy, 2023b). In contrast, LCFS follows more stringent documentation of all value chain steps through extended Life-cycle assessment studies (California Air Resource Board, 2023). This asymmetry of information among different schemes makes them incomparable. As a result, the lack of coordination hampers international trade and intensifies compliance processes for hydrogen producers that want to access new hydrogen markets such as the EU.

Thirdly, conventional certification induces monitoring and auditing to verify compliance. This process often causes a high monetary commitment and bureaucratic effort for governments and businesses (Cheng & Lee, 2022). European legislation tries to mitigate it by reducing reporting rigor. However, the credibility of the emission reporting decreases with lowering the reporting burden on hydrogen producers (Collell & Hauptmeijer, 2022; Schröder et al., 2021). Reducing reporting efforts can be achieved with industry averages, whose estimation is often conservative and obstruct market access for many potentially low-carbon hydrogen production variants (Abad & Dodds, 2020). These observations induce two drawbacks of conventional GO certificates: a cumbersome bureaucratic effort and a cost-intensive commitment for hydrogen producers. The trade-off between reporting rigor and reporting burden must be considered when implementing certification systems for green hydrogen. Hydrogen producers would welcome easy-to-use infrastructures for hydrogen certification facilitating the green hydrogen compliance process .

The issues of conventional GOs shed light on the problems hydrogen certification is facing. The above-mentioned issues strive for a solution that enables a flourishing future hydrogen market by addressing the hydrogen certification-specific data collection, mitigating the information asymmetry between hydrogen value chain parties, and balancing the trade-off between compliance and costs.

1.2.5. Blockchain technology and IoT

Blockchain technology emerged as a mechanism to conduct online payments without intermediaries such as banks but maintaining a high level of security, predominantly known as Bitcoin (Nakamoto, 2008). IBM defines blockchain as "[...] a shared, immutable ledger that facilitates the process of recording transactions and tracking assets in a business network." (IBM, 2023). The potential of blockchain technology quickly expanded to multiple industries, which are, among others, digital identities, E-Government applications, supply chain traceability, or energy certifications (Babel et al., 2022; Rioux & Ward, 2022; Sedlmeir, Smethurst, et al., 2021; Q. Wang & Su, 2020).

In global supply chains, data gathering, sharing, and analyzing play a more and more 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 an important role as the value of confidential information increases. Blockchain technology comes into play to save and share data transparently while keeping it secure through tamper-resistant cryptographic mechanisms, so-called hashes.

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

1.2.6. Prospects of blockchain for certification means

According to the literature review, Blockchain technology within the supply chain traceability field and as facilitating system for certification is not nascent. Blockchain technology is almost present in all supply chains as a tracking and transparent information distribution tool, such as the metal supply chain, the textile industry, or food logistics (Hastig & Sodhi, 2020; Tian, 2016). Further, Christidis and Devetsikiotis (2016), Kumar et al. (2022), and Moin et al. (2019) explore blockchain's potential for linking physical supply chain processes with a digital registry via IoT devices. The technology proved it could be a lightweight bookkeeping method for recording emissions along supply chains. According to Kaplan and Ramanna (2021), scope one emission can be recorded well and allocated to the right party in the supply chain with only a fraction of bureaucratic efforts and monitoring costs. Whereas the general supply chain traceability has multiple hits in the existing scientific literature, there is less focus on the prospects of blockchain technology for tracing emissions of intangible gases such as hydrogen. General research on Scopus [2] resulted in 505 documents that examine blockchain's application in supply chains. A scan of the headings and keywords showed that most articles examined supply chain traceability for compact goods, not bulky goods such as hydrogen. However, the advanced research of blockchain technology for supply chains provides a comprehensive picture of architectural design patterns that can be exaptated for the case of green hydrogen certification. Also, a similar field to green hydrogen is green energy information systems. Watson et al. (2010) introduces the connection of physical flows to digital information systems to increase the awareness of emissions and potential reactions based on the new information. The further development of such systems uses blockchain technology's potential to decarbonize the energy value chains and stimulate green energy through digital certificates, distribute transparent data about emissions, or optimize the energy grids for less energy consumption.

Ahmad et al. (2022) discuss within a survey the potential of blockchain technology in energy systems. The authors analyze applications of blockchain technology in the oil and gas value chains by testing features such as transparency, traceability, and auditability. The study shows how blockchain can support optimizing supply chains, detecting pipeline leakages, or tracing waste/ byproducts in the fuel value chain to optimize the value chain. The authors find, for example, that blockchain could facilitate data provenance to prevent fraudulent activities in the oil and gas trade and trace back the origin of non-compliant oil value chain actions to issue associated penalties. Ahmad et al. (2022) argue that the governance and enforcement of such penalties and non-compliant supply chain participants is one of blockchain's main benefits for the oil and gas industry. Linking it to tracing emissions in the hydrogen value chain, penalizing or rewarding non-compliant or compliant hydrogen producers can add value to the current hydrogen certification market.

To examine blockchain technology to stimulate and subsidize green energy markets efficiently, Castellanos et al. (2017) introduced a cryptocurrency-based GOs scheme that allows for additional monetary value when trading GOs. Enhancing such systems can serve the use case of certifying green hydrogen. For example, Knirsch et al. (2020) and Sedlmeir, Völter, et al. (2021) introduce the possibility of using blockchain and Zero-knowledge Proofs (ZKP) 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. Babel et al. (2022) introduce another blockchain application that is P2P energy trading to minimize electricity usage/ loss in smart grids. They link Non-fungible tokens (NFTs) with fractional ownership based on the attributed emissions of the supply chain actor. Further, they introduce Zero-Knowledge-Proof as a confidentiality-preserving mechanism that proves the provenance of green electricity but does not reveal the confidential data of the producer.

[2] search string: TITLE-ABS-KEY (("Supply chain" OR "Chain of custody" OR "Value chain") AND (tracing OR tracking OR "Guarantee of origin") AND (blockchain OR "distributed ledger technology"))

In sum, blockchain technology holds the following properties that make it especially suitable for tracing emissions along the hydrogen value chain to enable a credible and interoperable GO scheme.

1. *Decentralization*: No central authorities must govern and control data sharing and emission reporting. However, data can be extracted as authorized entities need from the distributed ledger infrastructure (Cali et al., 2022).
2. *Transparency*: Blockchain technology can solve principal-agent information asymmetries by providing reliable data between producer and consumer, thus stimulating green hydrogen trade (White et al., 2021).
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. *Traceability*: The blockchain stores emission data infinitely from the first entry to enable continuous tracking and verification possibility. It further denies fraudulent behavior, such as double counting, because the data no longer matches historical entries.
5. *Accountability*: Blockchain can tokenize 1MWh 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).
6. *Independence/ Standardization*: Blockchain technology is not bound to country-specific regulations but enables a self-regulated environment where participants can verify mutual transactions. Data is saved transparently and can be extracted for nation-specific reporting purposes (Mould et al., 2022).
7. *Trust*: The embedded code mechanisms in the blockchain can create trust without intermediary authorities verifying the credibility of the emission data. The blockchain enables verification through distributed mutual verification mechanisms.
8. *Tradability*: Tokenization/ Digitization of energy batches on the blockchain enables separate trading of these tokens/GOs to stimulate the green energy market (Castellanos et al., 2017).
9. *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.

These characteristics show significant potential to show the green, blue, and grey hydrogen mix in distribution networks and prove the origin based on tamper-proof data. Further, hydrogen producers benefit from decentralization which enables independence from national authorities and, thus, from complex regulations and cumbersome audits.

1.2.7. Integrating blockchain and IoT

The fundamental gathering of information 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) examine 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 point out potential challenges when using blockchain technology combined with IoT. Such a problem is, for example, 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, Völter, et al., 2021). Otherwise, the data collected through physical sensors are 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, according to (Novo, 2018).

Summarized, integrating IoT with blockchain technology cannot address data integrity due to the garbage in - garbage out problem. External verification methods are still required to ensure the compliance of the data sources. Also, complex IoT networks can overload blockchain systems. These are issues that need to be considered when setting up blockchain-IoT systems.

1.3. Identification of the knowledge gaps

Scientific knowledge gap: A structured literature review is conducted to determine the gaps in the literature related to hydrogen certification supported by blockchain-based information systems (cf. Chapter 1.2.1. The main research gaps are highlighted by Abad and Dodds (2020), Cheng and Lee (2022), Mould et al. (2022), and White et al. (2021).

As mentioned in Chapter 1.2.4, conventional renewable energy certificates do not suffice the **information requirements** for hydrogen certificates. Hydrogen certificates must adhere to the geographical and temporal correlation between electricity production for electrolysis and hydrogen production according to EU Commission (2022b). The complex restructuring of legislation regarding conventional GO regulations toward green hydrogen certificates tries to aid that issue, leading to the introduction of PoS (Sailer et al., 2021). However, research lacks alternative approaches to securely and transparently provide the required extra information to authorities and hydrogen end users. Blockchain can secure data and make it transparent. An investigation of blockchain's potential would provide valuable insights for scientific research.

As illustrated in Table 1.4, hydrogen certification standards are not aligned. For example, the TÜV Süd issues certificates based on extended life-cycle assessment studies, whereas Certifhy only focuses on hydrogen production, a cradle-to-gate approach (TÜV SÜD, 2023; Weeda et al., 2019). In particular, Abad and Dodds (2020) mention that certification schemes vary due to the following decision-making aspects: (1) the definition of green hydrogen, whether it aims at reducing the GHG emissions or if it shall incentive the production of renewables; (2) the system boundaries, starting from the production the usage, or the entire value chain; (3) the chain of custody type, predominantly mass balance or book and claim; (4) emission intensity thresholds; and, (5) the hydrogen pathways depending on production, transportation, and feedstock techniques. These aspects induce the **coordination issue** of differing certification schemes per nation (cf. Chapter 1.2.4). To mitigate such interoperability and comparability issues, White et al. (2021) proposes to construct **modular certification systems**, where emissions at each value chain stage would be certified. Henceforth, hydrogen producers could comprehensively collect data about the hydrogen production process, and supply chain descendants can access the information required for emissions reporting. However, scientific research lacks design guidelines on how to build such a modular hydrogen certification system and what information system can facilitate such asymmetrically distributed information distribution.

Cheng and Lee (2022), moreover, note that current certification standards always balance between **reporting rigor and administrative burden** for hydrogen producers. Too high market entrance barriers due to strict reporting obligations can obstruct a flourishing hydrogen market in the EU. At the same time, too lax enforcement opens up the gap for greenwashing and other fraudulent activities. The latter creates insecurities for the green hydrogen producers as they depend on the green hydrogen demand and fair competition with the fossil hydrogen market. Blockchain can aid the transparency and integrity of emission metadata with a secured, decentralized information infrastructure (Mould et al., 2022).

In the identified scientific literature, authors predominantly described blockchain-based certification mechanisms concerning renewable energy such as electricity or mentioned the traceability of tangible goods such as textiles, food, or drugs (Babel et al., 2022; Cali et al., 2022; Castellanos et al., 2017; Knirsch et al., 2020; Nofuentes et al., 2022; Sedlmeir, Völter, et al., 2021; Zhang et al., 2022). However, scientific literature did not mention **hydrogen-specific blockchain-based certification** yet. Only Mould et al. (2022) mentioned the potential of blockchain technology for certifying biogas and hydrogen. They claim that blockchain technology can help to aid the communication asymmetries caused by opaque information about hydrogen provenance and sustainability criteria. Further, they claim that blockchain can increase tradability and reduce hydrogen and GO trading transaction costs. The research lacks factual information or clear concepts on creating a blockchain-based certification artifact. It states merely the current state-of-the-art hydrogen and biogas economy and the alleged prospects of blockchain technology on renewable energy certification and emission accounting.

Practical knowledge gap: Many industrial businesses are trying to aid the information system requirements for green hydrogen certification and emission accounting for the hydrogen value chain (cf. 1.2). Companies such as FlexiDAO, Powerledger, or PointTwelve aim at facilitating hydrogen certification in a distributed data system while automating the issuance of certificates and managing their certificate portfolio (Acciona, 2021; PointTwelve, 2022; Powerledger, 2023). Other companies engage in blockchain-based green electricity labeling. For example, Siemens Energy is working with Nobian and Envia THERM GmbH, local green hydrogen and power producers in Germany, to establish a transparent and traceable distributed certification system for a fast transition towards sustainability (Beyer, 2022). However, most existing concepts are premature and entail limitations preventing wide adoption. Additionally, projects such as FlexiDAO are singular prototypes focused on certifying hydrogen in a segregated manner [3]. It opposes, according to Gasunie (2022b), the requirements of the future European hydrogen backbone that must be able to include all colors of hydrogen. Moreover, purely green hydrogen production relies on renewable electricity from fluctuating sources such as wind, solar, and water power plants. Fluctuating supply contradicts the customers' requirement for steady energy demand. The current segregated approach of tracing emissions is unrealistic for the green hydrogen certification. A multi-stakeholder approach can help identify the requirements of all hydrogen value chain actors to establish a standardized and reliable distributed information system for green hydrogen certification. Companies such as Circularise address this issue and offer mass balance-compliant GO mechanisms (Konstantinov & Daphne, 2022). However, they are mostly concerned with compact goods such as steel and fabrics that do not fit the specific hydrogen requirements.

The practical business concepts need guidelines on harmonizing such a system for the complex stakeholder field involving businesses, governmental bodies, and end users. These concepts prioritize businesses and need to pay more attention to integrating institutional infrastructures and compliance with the regulations.

1.4. Main research question

Upon the literature review, current research only problematizes hydrogen certification but needs more practical solution proposals. This thesis aims to aid the need for specific design guidelines for developing an information system architecture for certifying green hydrogen and how blockchain technology can play a role in reliably and automatically accounting for emissions along the hydrogen value chain. Thus, the thesis focuses on the requirements gathering for a reliable and automated certification system, the subsequent creation of a blockchain-based information architecture, and its evaluation to facilitate the green hydrogen certification process from the perspective of the hydrogen producer. The theory above and related cases of blockchain certification could be used and adapted to fulfill the necessity of closing the gap for certifying green hydrogen based on production methods and value chain trajectories. Furthermore, the scientific theory states that blockchain can safeguard data confidentiality and control and address data sharing across different certification boundaries. The following research question aims at investigating a transparent, interoperable, and automated green hydrogen certification blockchain system.

What blockchain-based IT architecture can support the requirements for reliable green hydrogen certification in the European Union?

[3] only green hydrogen can enter the grid, not blue or grey

2
Methodology

The methodology chapter describes the fundamental research approach to answer the main research question: *What blockchain-based IT architecture can support the requirements for reliable green hydrogen certification in the European Union?*. First, a general description of the chosen Design Science Research (DSR) approach is provided. Secondly, the subquestions (SQs) are delineated to guide the research process in answering the main research question and help the successive understanding of research steps. For each SQ, the specific research methods are described that help to address the underlying question. Eventually, a research flow is used to illustrate the research approach.

2.1. Research approach

The main research question targets a blockchain-based design to facilitate green hydrogen certification. To address this problem, a DSR approach for information systems is adopted. As inspiration, the generic DSR concept is used for creating a blockchain-based IT artifact to solve the data-sharing problem of existing hydrogen value chains. Hevner et al. (2004) pioneered operationalizing DSR as a feasible method for designing effective information system research artifacts. The authors introduced pillars of design science connecting the environment and existing knowledge base with the actual design process through the two crucial relevance and rigor cycles, as seen in Figure 2.1. Later, Peffers et al. (2007) refined this approach and outlined a guideline on developing and positioning DSR effectively as it is used in this thesis. The design steps include problem identification, the definition of objectives and requirements, design of the artifact, evaluation, and communication with respective iterations, illustrated in Figure 2.2. Figure 2.1 indicates which steps are undertaken to design an effective blockchain-based hydrogen certification scheme. However, the field's maturity denies field testing or technical dissemination to the application domain. Subsequently, the focus will lay on contribution to the knowledge base with relevant additions to blockchain architecture theory and implementation process.

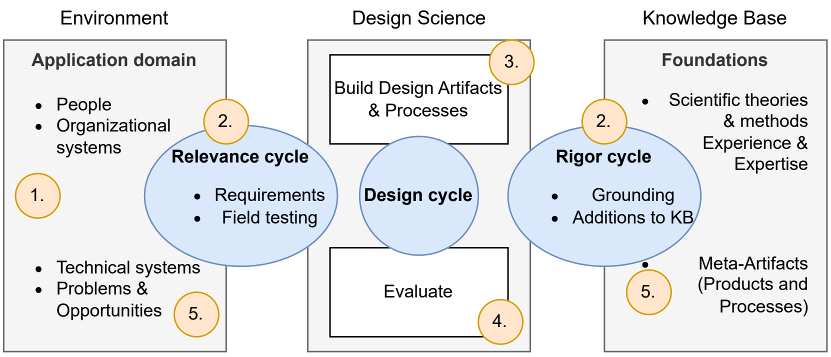

Figure 2.1: Design science theory based on (Hevner et al., 2004).

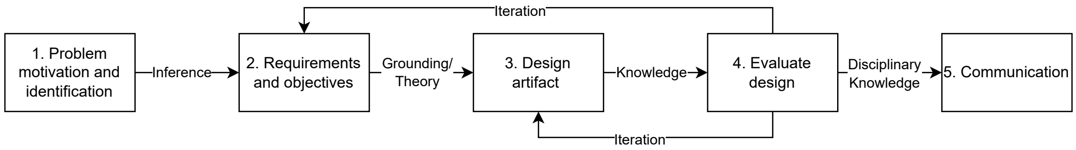

Figure 2.2: DSR process flow adapted from (Peffers et al., 2007).

To guide the answer to the main research question successively and structurally, a set of sub-questions is created and answered within the boundaries of the research flow diagram as seen in Figure 2.3. It visually shows the tasks for each chapter while following the design cycle of DSR. Each design process phase generates research output and the answer to one SQ, as indicated in purple boxes. The green boxes state the research methods used to accomplish the corresponding step. In general, the research steps/ SQs help to sequentially answer the main research question (MRQ).

1. What is the complex socio-technical hydrogen certification system in the European Union?

(a) Who are the stakeholders involved in the hydrogen value chain, and what are their roles?
(b) What is the institutional framework for green hydrogen certification in Europe?
(c) What is the technical certification system facilitating the European green hydrogen market?

The results of the first desk research on the hydrogen and green energy certification market will provide an overview of the most important concepts for the research. It will serve as the basis for analyzing the problems in the field and give a clear picture of the current state-of-the-art green hydrogen market. To answer the first sub-question, the guidelines of DSR are used (Peffers et al., 2007). To structurally identify the key characteristics of the hydrogen certification economy, a stakeholder, institutional, and process analysis is conducted based on supporting literature from European legislation, international associations, and relevant scientific literature. First, the stakeholders of the green hydrogen certification landscape are identified, and their roles and interactions with the key information systems are analyzed based on documents published by important organizations such as Certifhy (2023a), EU Commission (2022b), and IRENA (2022). Secondly, the institutional setting is analyzed. It is characterized by the institutional hydrogen certification framed by the EU regulation according to RED II (EU Commission, 2022b). Lastly, the technical functioning of the current certification processes is analyzed to understand the market of certificates for green hydrogen and how emissions are accounted for in the hydrogen value chain based on literature and supporting reports (Abad & Dodds, 2020; Albrecht et al., 2020; IRENA & RMI, 2023; World Energy Council, 2022). The stakeholder map, process diagrams, and institutional framework will be visualized in diagrams.

Next, an extensive qualitative data collection on stakeholder needs is conducted to identify core design principles and requirements for the to-be-design blockchain artifact.

2. What are the design principles and requirements for a blockchain-based information-sharing infrastructure for hydrogen certification?

The second research question addresses the second step of the design science research approach: requirements and objectives. Objectives in this research are phrased as design principles setting the scope for the artifact design. The design principles are based on the input from the system analysis, the output of the first research question. Semi-structured interviews with industry experts validate the system analysis as a source for framing the scope of system design principles. Seven semi-structured interviews are conducted to gather data from industry experts in the hydrogen market, blockchain application experts, and current practitioners in the market. The result of the interviews is a structured set of requirements according to ISO 29148 (2018) that give an outline of what a blockchain-based IT architecture requires to serve as an information-sharing tool for credible emission reporting and certification of green hydrogen producers in the European market. As scientific grounding, the requirements engineering approach of ISO 15288 and the NASA systems engineering handbook is followed (ISO 21840, 2019; ISO 29148, 2018; Nasa, 2022). They define system requirements as necessary, appropriate, unambiguous, complete, and singular. One drawback of interviews for information gathering is that experts might be biased toward the requirements for the blockchain-based design induced by their profession. To mitigate that issue, a preceding system analysis (cf. subquestion 1) was conducted to identify fundamental requirements. Subsequently, multiple experts from different professions were interviewed to enrich the information based on their backgrounds. The interviews were prepared with an interview procedure to address the questions to the interviewees structurally. Microsoft Teams is used to record and transcribe the interviews to review them and grasp the holistic information provided. The recordings and transcripts are then summarized and anonymized to be viable for the research of this thesis.

Upon the theoretical knowledge of the stakeholder analysis, the design guidelines and requirements guide the way for the subsequent artifact design.

3. What are the technical design components for a blockchain-based IT architecture for hydrogen certification?

The third subquestion concerns the third step of the design cycle: The design of the artifact. It aims to find a design taxonomy that can serve as a fundamental ontology to elect design decisions supporting the blockchain artifact for green hydrogen certification. As such, the identified requirements of the second sub-question will be translated into blockchain architecture design components meeting the identified taxonomy design aspects. Therefore, existing literature on blockchain architecture taxonomies and IoT infrastructure development is scoured to serve a reliable data collection and sharing blockchain architecture framework (Ahmadjee et al., 2022; Fernandez-Carames & Fraga-Lamas, 2018; Kumar et al., 2022; Moin et al., 2019; Tasca & Tessone, 2017; Xu et al., 2017). Based on that, a three-level architecture comprising perception, blockchain, and application layer was developed to serve as the three levels of design decision-making. For each level, design decisions were taken based on the requirements identified in the preceding chapter. The result of this chapter is a theoretical architecture model showing the important data collection methods, data structures, and data sharing rules for a reliable blockchain-based certification system for green hydrogen. The results are shown in diagrams and explained in textual form.

4. How can a blockchain-based IT architecture design be implemented in the socio-technical hydrogen certification industry?

The fourth sub-question also concerns the third step of the DSR, Particularly the implementation of the artifact in the socio-technical hydrogen certification field. The research targets an exaptation contribution to design science research defined in the design science contribution categories of Peffers et al. (2007). Exaptation means the translation of existing scientific innovations into different application fields. To adhere to the exaptation definition and to answer the fourth sub-question, scientific literature on blockchain implementation semantics for energy and emission tracking systems and existing implementation guidelines of blockchain-based systems will be used, for example, the scientific work of Babel et al. (2022), Castellanos et al. (2017), Knirsch et al. (2020), Novo (2018), Sadawi, Madani, et al. (2021), and Sedlmeir, Völter, et al. (2021). Scientific research on blockchain-based emission tracking systems and their application in the hydrogen sector is still developing, and a lack of knowledge on implementing such systems must be expected. Another drawback will be the rather theoretical structure of the implementation due to time scope and technological maturity issues. However, considering the feasibility of the artifact for hydrogen producers, the identified requirements will be utilized to visualize the design within a blockchain architecture framework combined with the integration into the socio-technical hydrogen certification infrastructure. First, the system's governance is addressed by allocating the roles and responsibilities of the artifact. Secondly, the embedding of the artifact in the institutional setting of European legislation is considered. And lastly, the process flow of the blockchain-based hydrogen certification is visualized in sequence diagrams. Sequence diagrams show the interrelations between processes and how specific functions of the artifact are executed. It shows how the artifact's functions interact with the environment when being implemented in the market. The finished artifact aligned with the socio-technical hydrogen certification economy lays the basis for the evaluation in the final step of the design cycle.

5. How feasible is a blockchain-based hydrogen certification system for the hydrogen production market?

To evaluate the viability of the artifact, ex-ante evaluation interviews are conducted. In the first part of Chapter 7, a relation to the system requirements by showing their fulfillment through the proposed artifact design. The only drawback is that the inductive method of concluding design decisions based on requirements leads to the inherent effect that almost all requirements are addressed. To enrich the evaluation, a qualitative expert validation was conducted to support the identification of practical value and flaws in the proposed artifact for successful adoption in the hydrogen value chain. In the thesis, the naturalistic ex-ante evaluation strategy of Venable et al. (2016) is followed to simulate the feasibility of the artifact in the socio-technical context. However, if not chosen right, expert interviews could emphasize one position and in this way induce biases in the evaluation of the artifact. Additionally, experts could be acting politely in their answers even though they might hold a different opinion of the design (Johannesson & Perjons, 2021). To prevent potential biasedness, a selection of experts with different backgrounds was taken and asked for their honest feedback on the artifact. The experts were asked to reflect on three aspects of the demonstrated artifact: technical design, governance and institutional alignment, and process. Additionally, the experts contributed feedback on the societal integration of the artifact.

Subsequently, the main research question can be answered, and a recommendation for practitioners of blockchain technology applications can be provided.

2.2. Research flow diagram

The following research flow shows the output/input variables to answer each SQ individually. The diagram logically follows the DSR steps of Peffers et al. (2007) and piles the content up to answer the main research question of the thesis (see Figure 2.3).

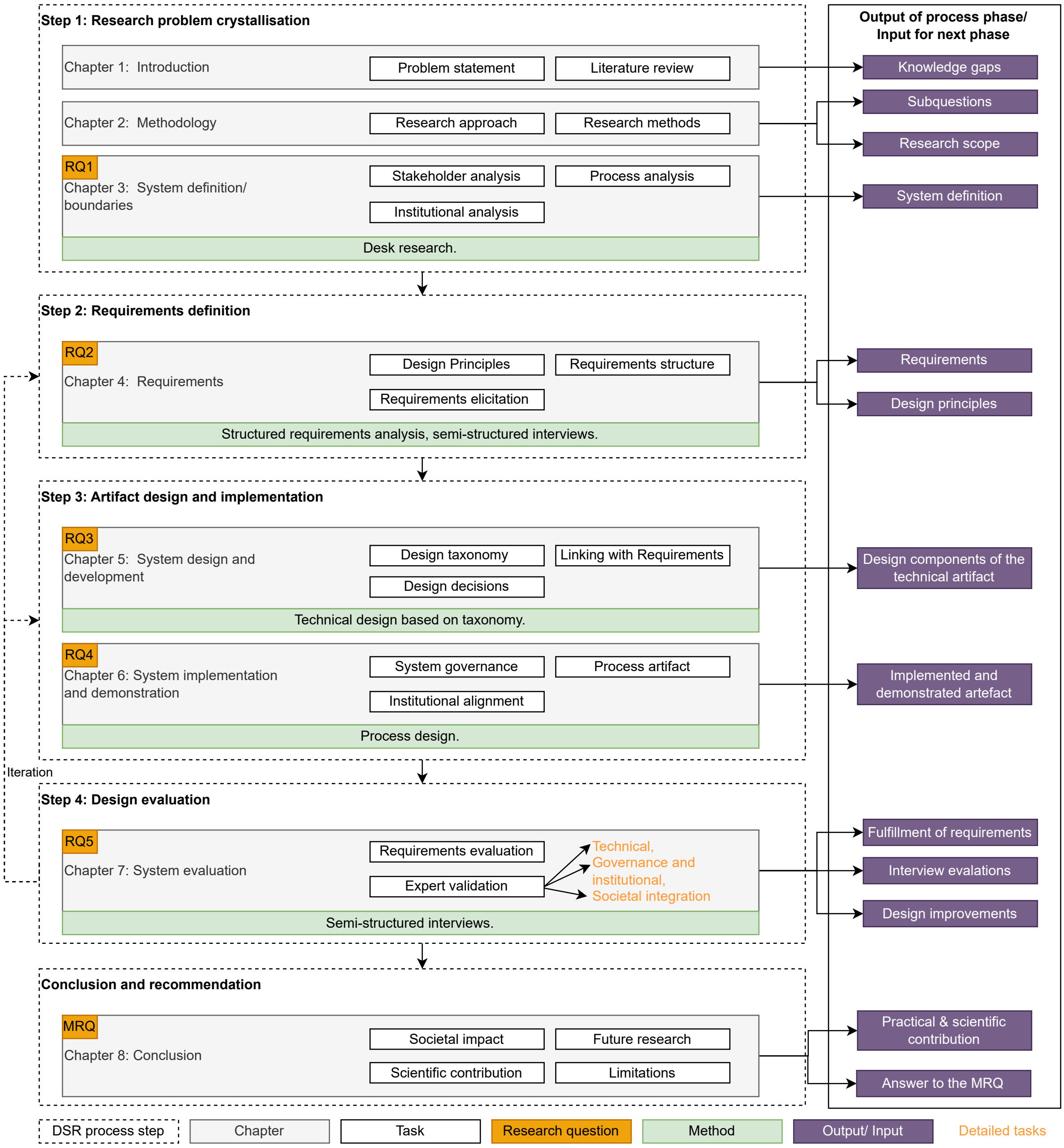

Figure 2.3: Research flow diagram.

3 The hydrogen certification economy

After introducing the problem and the course of this research work, an introduction to the socio-technical hydrogen value chain economy is examined in this Chapter. A stakeholder, institutional, and technical process analysis is conducted to give a structured overview of this field. This technique includes three steps: First, the stakeholder field and technical specifications of certification schemes define the system boundaries for this study. The next step describes the institutional environment of the current hydrogen certification. The third part characterizes the process description of the hydrogen certification process and the technical functioning of existing information infrastructures. All these steps are combined to answer the first research question: *What is the complex socio-technical hydrogen certification system in the European Union?* In particular, the first research question is structured through the following subquestions:

(a) Who are the stakeholders involved in the hydrogen value chain, and what are their roles?
(b) What is the institutional framework for green hydrogen certification in Europe?
(c) What is the technical certification system facilitating the European green hydrogen market?

3.1. Stakeholder analysis

The hydrogen value chain is a complex field of actors that constantly interact to bring the produced hydrogen to the consumer and comply with policy regulations. Stakeholder analysis can help to understand the behaviors, intentions, roles, and interests of such a complex actor field (Brugha, 2000). The stakeholder analysis helps to untangle the hydrogen actor field and brings light to the certification of low-carbon hydrogen. For this thesis, the analysis helps to understand the main requirements for coupling hydrogen certification to blockchain technology.

The main actors involved in the low-carbon hydrogen certification process are as follows. To visualize the relations and roles of actors and mutual dependencies, Figure 3.1 presents a diagram with the main actors, their interactions, and essential informational infrastructures.

The European Union represented by the European Commission

The European Commission sets out the institutional framework for certifying low-carbon hydrogen through the Renewable Energy Directive (RED II). The directive induces a couple of regulations to be adopted by the national governments that outline handling RFNBOs and how these renewable fuels must be reported with associated GHG emissions (World Energy Council, 2022). The directive states two ways of selling sustainable hydrogen: first, through Proof-of-Sustainability (PoS), which means the hydrogen was produced following the requirements for green hydrogen qualification; second, through purchasing GOs for green electricity as the main emission component for hydrogen production. It further prescribes the preference for certification schemes that utilize mass-balancing for emission accounting which can also be conducted by voluntary national certification schemes recognized by the EU regulation (EU Commission, 2022b). The EU regulation sets the legally binding boundaries for the

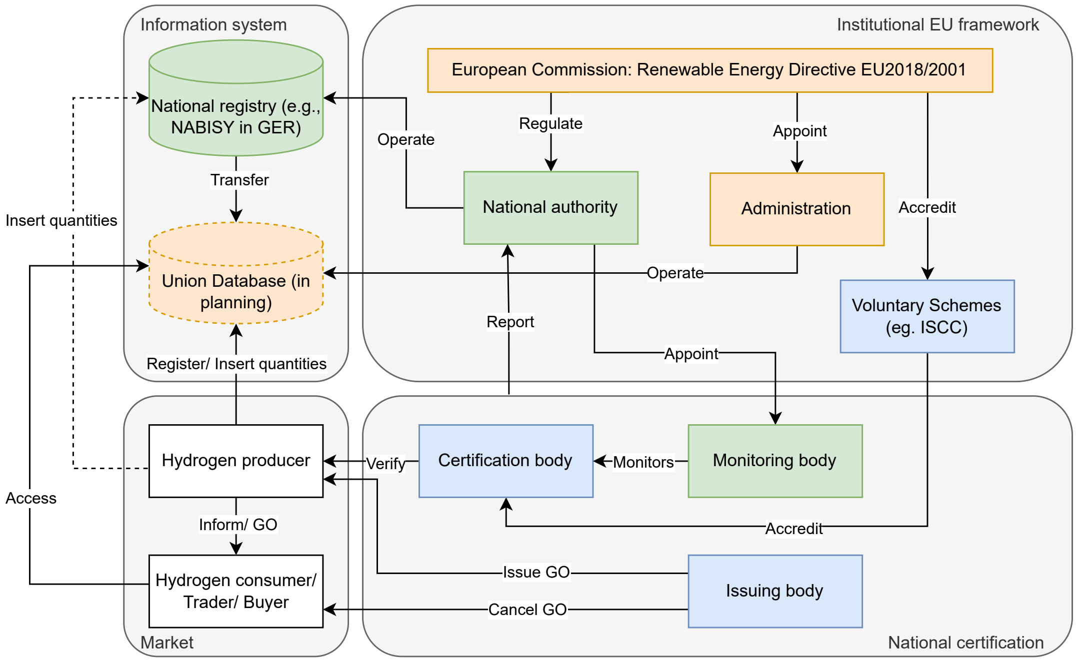

Figure 3.1: Overview of the EU hydrogen stakeholders.

national legislation of MSs and the business stakeholders acting in these fields. The administration of the European Commission oversees the enforcement of the EU-wide legislation; they are also in charge of managing the IT infrastructure. The RED II directive is followed up with two delegated acts still up to changes until July 2023 (I7, A.8). These delegated acts outline the regulation for the origin of the electricity for hydrogen production (Delegated Act 1) and the calculation of the emission reduction (Delegated Act 2) (for Energy, 2023a, 2023b).

The national authorities/ MSs

The national authorities are responsible for translating the European directive into national regulations regarding emission accounting. In the Netherlands, the Dutch Emission Authority (NEA) is responsible for monitoring and verifying the accounted emissions by hydrogen producers.

Voluntary Schemes (VS)

According to EU law, hydrogen producers can adopt voluntary certification schemes if they meet the EU's reporting obligations requirements. These certification scheme providers are, for example, ISCC, which is already responsible for issuing renewable energy certificates in the EU. The VS can apply for being accredited with European regulation. The hydrogen production companies need to mention the used scheme in the reporting document, and it has to be accredited by European legislation (World Energy Council, 2022).

Certification/Issuing bodies

Certification and Issuing bodies are illustrated separately in Figure 3.1; however, for hydrogen, they are the same entity. Only the connection of green hydrogen production with electricity GOs has to be considered and might induce separately involved parties (I7). In the Netherlands, the respective entity is Vertogas; in particular, certificates are issued in cooperation with CertiQ, namely Verticer (Vertogas, 2022). Verticer is a government-owned independent company ensuring the fairness of regulations to apply to every market participant similarly. The Dutch Ministry of Finance owns Verticer through the public organization of Gasunie (Gasunie, 2022a). The certification bodies such as Verticer are recognized under the VS and practically enforce the reporting obligations outlined by the EU legislation.

The Association of Issuing Bodies (AIB) represents the overall certification standardization entity. They work with national issuing bodies to ensure trans-border tradability and transferability through the European Energy Certificate System (EECS) (AIB, 2023). The certification authority might hire independent third-party auditors to execute the certification monitoring and verification. The audit entails the yearly inspection of the hydrogen production facility and observation of each hydrogen batch injected into the hydrogen distribution network/ hydrogen market through other transportation methods. The EECS certificate trading platform is not yet established for hydrogen certificates; however, the tradability of such certificates needs to be ensured.

National registry

The national registry is a centralized database where hydrogen production companies/ economic operators (EOs) are registered (European Commission, 2023d). For example, the Dutch Energy for Transport Registry (REV) is responsible for all gaseous liquids in the transport sector. The EOs insert the production quantities of each hydrogen batch injected into the distribution network. The data is then transferred to the union database as a central collection point for the holistic hydrogen market in the EU. The central national administration is set equal with the national authority. In the EU not all MSs possess national registries, but for example, the Netherlands and Germany do. These national registries have to be integrated with the Union Database (I7, A.8).

Union Database

The union database serves as a central data log where all transactions of hydrogen will be registered and documented for administrative purposes (EU Commission, 2022b). The database is currently in a prototype version and has yet to be fully operational; it is just set up for hydrogen for the transport sector. However, a potential extension to other hydrogen sectors is planned. In the database, hydrogen producers and buyers will have personal accounts to view information on the hydrogen injection, extraction, and distribution and to check the proof of sustainability of the traded hydrogen. Such a database can serve as a central monitoring tool to keep an overview of the fractions of green, blue, and grey hydrogen in circulation, which is important to track the evolvement towards more green hydrogen.

Hydrogen production companies/ Economic operators (EOs)

Hydrogen producers (EOs) produce low-carbon hydrogen, such as renewable energy producers or industries that use electrolysis to produce hydrogen. Also, other production techniques are viable, but the thesis will focus on green hydrogen production and its certification.

Distribution system operators (DSO)/ Transmission system operators (TSO)

The DSOs/ TSOs are responsible for operating and monitoring the distribution network. TSO's main tasks include continuously monitoring gas grids' hydrogen injection and extraction points and ensuring all users' access and safety (I8, B.2). The World Energy Council (2022) points out that the distribution might have the least influence on the emissions of hydrogen apart from transport with trucks. The TSOs greatly influence the prospects of hydrogen distribution as large-scale pipeline networks such as the hydrogen backbone and other distribution means are evolving (European Hydrogen Backbone, 2023). These EU-wide distribution systems require clear coordination and governance from TSOs and scalable information system infrastructure to account for all hydrogen transactions. The DSOs for hydrogen distribution to consumers are not yet clarified, as the hydrogen market is developing decentrally in local hydrogen electrolyzers. The DSOs are responsible for knowing the hydrogen mix injected in the hydrogen grid. However, as there are multiple DSOs, they need to collaborate closely with TSOs to ensure the monitoring of the pipelines.

Energy provider

Various methods can be employed to generate hydrogen, requiring corresponding energy sources. For instance, green electricity can be utilized to produce green hydrogen through the process of electrolysis

(Osman et al., 2022). Energy providers play an important role as the electricity used for certifying green hydrogen must comply with certain requirements outlined in the institutional analysis in the Chapter below. Among others, green electricity providers must not offset the electricity on the voluntary carbon market before using it for the electrolysis as the carbon reduction would be counted double. The RED II regulation largely prevents double counting by restricting the geographical and timely correlation of hydrogen production and electricity source (EU Commission, 2022b). However, whenever borders are crossed in the electricity or hydrogen trade crosses borders, the information systems of corresponding nations need to be aligned to prevent double counting.

Users/ buyers of the low-carbon hydrogen

These actors hold certificates, such as energy consumers or energy traders. Certificate holders use them to demonstrate the environmental attributes of the low-carbon hydrogen they have consumed or traded so they can achieve other higher-level functions such as carbon credits, compliance with carbon accounting regulations, or application for green tariffs (cf. Figure 3.1). Consuming the hydrogen cancels the hydrogen PoS.

The roles and responsibilities of the hydrogen certification field are yet to be determined according to Erbach and Svensson (2023). Thus, they can be subject to change over the upcoming years due to the ongoing negotiations on the RED legislation for RFNBOs. The actor constellation, however, is most probably similar to the renewable energy certificate handling in the EU ETS and the bio-gas certificate functionality of Verticer. The subsequent analysis of the institutional field of interest gives insights into the current legislative landscape and interactions between vital actors for hydrogen certification.

3.2. Institutional analysis

On the international level, the International Energy Agency (IEA) plays an essential role in translating the global GHG emission reduction targets for the hydrogen economy. Internationally the Kyoto Protocol is the key incentive for reducing GHG emissions, and it was introduced in 1997 (United Nations, 2023). It serves as an execution incentive of the United Nations Framework Convention on Climate Change (UNFCC). Until now, hydrogen certification strategies lack global incentives and are primarily driven by national strategies (cf. Albrecht et al. (2020)).

On a European level, the main legislative incentive for the hydrogen economy is the Renewable Energy Directive (currently RED II). The main objective of the RED II directive is to support hydrogen production in Europe. In order to accomplish this, numerous initiatives are being pursued to define the parameters of low-carbon hydrogen and provide subsidies for the production of green hydrogen. Nevertheless, more than low-carbon hydrogen would be required to meet the demand for hydrogen in energy-intensive sectors like the steel industry, which currently necessitates approximately 95 million tonnes of green hydrogen for steel production (IRENA, 2022). Multiple production techniques with different levels of GHG emissions collaboratively will serve the great demand. The certification of such hydrogen production is important as its emissions need to be documented and reported to EU regulation and proved to predecessors in the hydrogen value chain. Two delegated acts supplementing the RED II regulation are relevant for the green hydrogen certification. According to the first delegated act of the RED II directive, RFNBOs certifications such as hydrogen are calculated based on voluntary GHG emission accounting schemes complying with the EU renewable energy framework that defines low-carbon hydrogen (EU Commission, 2023b). It is further elaborated that certification schemes should be harmonized to be easily adoptable by domestic or third-country hydrogen producers that import into the EU (EU Commission, 2022b). Certification systems are supposed to facilitate the proof of origin of low-carbon hydrogen to ease the production and trade of hydrogen in the market. The second delegated act informs hydrogen producers of the specific emission reduction targets for hydrogen production. However, both acts are in review until July 2023 and must be settled to become effective.

If a hydrogen producer wants to show transparent information about their hydrogen production techniques to consumers while complying with regulative emission reporting obligations, an easy-to-use information system that captures the necessary data and proves the origin and composition of the hydrogen is vital (World Energy Council, 2022). To facilitate that need, the EU outlines with the RED II an institutional framework for certification schemes to certify the origin of low-carbon hydrogen and stimulate the hydrogen market in the EU. Most schemes, such as Certifhy, are VS that allow tracking and documenting the origin of low-carbon hydrogen produced within the EU according to certain sustainability parameters outlined by the European Union. The scheme provides a framework for issuing, transferring, and canceling certificates, which entail environmental attributes of the produced hydrogen. The EU authorities accredit the VS if they comply with the framework outlined in the RED II directive (EU Commission, 2022b). The major certification schemes across Europe and in the rest of the world can be seen in the table below with different specifications. Generally, certification mechanisms aim to stabilize the hydrogen market and stimulate the production and trade of low-carbon hydrogen. However, regional legislative differences lead to varying reporting and documentation requirements for hydrogen sellers, which can avert the policies' engagements in the hydrogen market. From a high-level legislative perspective, an overarching institution per country sets the legislative framework for compulsive emission accounting and certification bodies, in Figure 3.1 displayed as LCFS, RED II, and RTFO. Per country, multiple organizations set up VS to certify hydrogen production as low-carbon; in Europe, six voluntary standards aim to be recognized by European regulation, according to the analysis. The Figure also indicates the purpose per row, whether compliance (C) or voluntary (V) reporting.

Table 3.1: International hydrogen certification landscape adapted from World Energy Council (2022)

Criteria	Regulation/standard	Region	Boundary	Tracking	Purpose
Regulation	LCFS	USA	Well-to-wheel	Book and claim	C
	RED II	EU	Well-to-wheel	Mass balance	C
	RTFO	UK	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

One of the vital differences is the aspect of the boundary conditions, which concerns the inclusion of emission parameters for the hydrogen value chain. Well-to-wheel accounting entails all emissions from hydrogen production energy sources to the point of use, including emission scopes 1, 2, and 3. Cradle-to-Gate, in contrast, focuses on the upstream emission until the point of production. The former targets granular emission accounting, while the latter aims to incentivize low-carbon hydrogen production. Subsequently, a short overview of the emission scopes is provided to connect to the calculation of emissions in the hydrogen value chain according to (Barrow et al., 2013).

Scope 1: Direct emissions from the hydrogen production site, including electrolysis, facility installation, and short-term storage.

Scope 2: Includes all the utilities needed for the hydrogen production site, such as electricity for the electrolysis that needs to be sourced somewhere off-site.

Scope 3: Includes all the indirect emissions occurring due to the hydrogen production facility, but the occurrence does not lie within the boundaries of the organization's control, such as transportation and distribution.

The exact composition of the emission scopes can be extracted from Figure 3.2. The hydrogen production and the required electricity for the electrolysis are the critical factors for the hydrogen emission intensity according to Majer et al. (2021). As such, the focus of the certification is the point of production (the first life-cycle stage). However, the means of transport may also significantly influence the value chain emission if pressure tank transport on trucks is used (part of the second life-cycle stage) (Wulf et al., 2018). Moreover, the use and end-of-life stage of the hydrogen value chain is the less decisive factor from a hydrogen producer perspective. To comprise all of these emissions, a granular framework for calculating the emission reductions is set out by EU regulation which needs to be followed to sell hydrogen labeled as low-carbon.

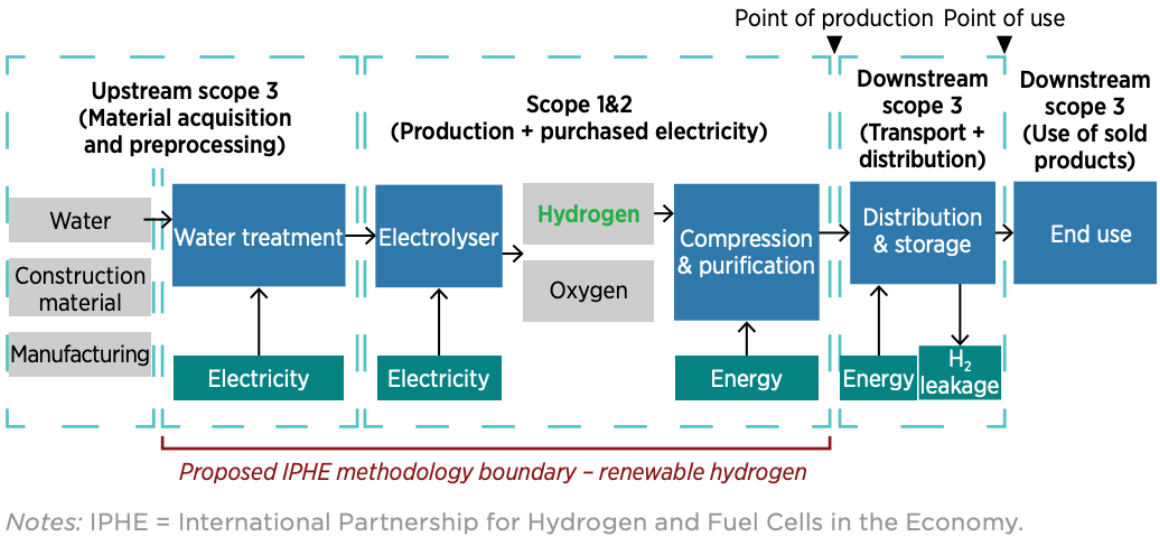

Figure 3.2: The composition of emission scopes in the hydrogen value chain (IRENA & RMI, 2023).

The second difference in the certification scheme landscape is the tracking/chain of custody. Two methods are followed by the identified certification schemes, which are book & claim and mass balance. **Book and claim** was initially introduced to prove renewable electricity is produced sustainably according to regulations. The producers would book the electricity produced in an information system, and the user could claim the provenance of the renewable electricity consumed (World Energy Council, 2022). The flow between the digital certificate and the physical hydrogen would then be separated. To ensure that the hydrogen is low-carbon, a temporal and geographical correlation is needed for the electricity/ energy consumed during the production (IRENA, 2022). The second model is called **mass balancing**. In this model of emission tracing, the certificate is traded together with the physical batch of hydrogen and accompanies the hydrogen along the value chain until being consumed. In this way, it is possible to feed different types of hydrogen into one pipeline while keeping track of the origin, trader, distribution, and consumption in one system (World Energy Council, 2022). It is the targeted method by RED II directive of the EU to be implemented in the national hydrogen legislations (EU Commission, 2022b). Table 3.2 describes the main differences between the mass balance-based PoS compared to the book and claim-based GO.

Table 3.2: Comparison of GO and PoS certification.

	GO	PoS
RED II affiliation	Art. 19	Art. 25-31
Scope	EU	Global
Purpose	Energy consumer	EOs that receive production support or have to meet regulations.
Application area	Disclosure of energy source to consumers. Independent from RED II sustainability requirements.	Proof of compliance with the sustainability criteria of RED II. GHG reduction has to be measured. Counting the actual production to sustainability targets (Art. 3).
Lifetime	12 months (transfer) and 18 months (cancellation)	Unlimited
Compliance	Book and claim	Mass balance

However, Sailer et al. (2021) mention that metadata about emissions has to be tracked along the entire supply chain, the data has to be saved in a transparent information system, the interface points have to be documented (injection and extraction points), and the liquid transport has to be registered. According to the World Energy Council (2022) some certification schemes also include additional factors such as the social impact of the facility, the water consumption, and the land use. The former considers factors such as safe working conditions, and compliance with human, and labor rights, the second considers excessive water usage to produce green hydrogen, and the latter considers factors regarding biodiversity, forestry, and land use changes. Further, certification schemes or regulations differ in the hydrogen definition (World Energy Council, 2022). Some classify based on qualitative criteria; for example, the usage of renewables qualifies hydrogen as green according to the RED II directive. TÜV Süd provides a stricter standard that classifies only hydrogen produced through electrolysis. However, the quantified classification gives a better insight into what can be certified as low-carbon hydrogen and what not according to the emission reduction objectives of the given regulation[1]. These differences problematize the current certification landscape and strive for a solution that comprises requirements of different certification schemes so that hydrogen producers can supply multiple markets without bureaucratic reporting outbursts.

Hydrogen can be classified as low carbon if it "[...] is derived from non-renewable sources and produces at least 70% less greenhouse gas emissions than fossil natural gas across its full life-cycle "(EU Commission, 2023b). That means, next to renewable energy sources, hydrogen production can also rely on non-renewable energy such as nuclear energy or natural gas as long as the GHG emission can be at least reduced by 70% through adequate methods (EU Commission, 2022b). Organizations have to document data about the production facility and the process's specifics to prove the produced hydrogen's low-carbon status. Figure 3.3 provides an overview of the data points that must be reported to the EU authorities to allow the commercial sales of low-carbon hydrogen.

Table 3.3: Description of certificate-specific data points for renewable energy sources adapted from Abad and Dodds (2020) and EU Commission (2022b)

Type of information	Detailed data points.
Information of the installation facility where the hydrogen was produced (Origin of the renewable energy source):	Unique identification number. Location. Type of installation. The capacity of the installation where the energy was produced. Start-up date (when the facility became operational). Kind and amount of investment support.
Information of the specific hydrogen batch (Qualifying aspects):	The energy source from which the energy was produced. Date of production (start/end energy of production) Specify whether the certificate relates to electricity, gas (including hydrogen), or heating and cooling. Country of issue. Benefits of the unit of energy from a national support scheme and type.

The information on the installation is needed to register the facility as a viable production place for low-carbon hydrogen production. It is just documented once to kick off the hydrogen supply. This type of information on the origin of the renewable energy source comprises several data points: The unique identification number allows for the unambiguous allocation of the production facility and gives the hydrogen batches produced from this space a low-carbon label. This identification also includes the location of the facility, what type of installation, and the facility's capacity. This information can determine which technology and infrastructure are involved in the production process, such as electrolysis, biomass gasification, or other emerging technologies. Also, the launching date of the plant is important as only plants that are not connected to the general electricity grid and have been in place for already three years are allowed as green hydrogen production plants (EU Commission, 2022b). Lastly, investment support is required to set up the installation.

The information on the origin of the hydrogen has to be enhanced by specific information on the qualitative aspects of the low-carbon hydrogen batch: First, the hydrogen producer needs to demonstrate the renewable energy source which was used to produce the low-carbon hydrogen, which can be solar, wind, or hydroelectric origin. Secondly, the date and time of the low-carbon hydrogen production need to be specified to ensure that it was produced environmentally benign. This specific information could also enrich the data used to determine the carbon intensity of the hydrogen batch. The last factor is the qualification of the hydrogen as low-carbon: It needs to be indicated whether the low-carbon hydro-

[1]for example, the RED II reduction goal is 70% (EU Commission, 2022b)

gen was produced in compliance with sustainability criteria, such as GHG reduction targets or other sustainability criteria outlining the benefits for the national energy support scheme. This calculation of GHG emission reduction includes all kinds of additional information, such as storage type, transport, and distribution infrastructure similar to the certification of renewable electricity (Abad & Dodds, 2020). In this way, the hydrogen is made comparable to other energy sources, transparency about the GHG emissions can be provided, and the tradability of the hydrogen can be facilitated.

The primary requirement for green hydrogen qualification is to prove that carbon intensity is reduced by at least 70% and supported by a recognized national certification scheme (EU Commission, 2022b). The EU regulation suggests a calculation method to determine the emission intensity of the generated hydrogen, which adheres to the standards for life-cycle assessment calculation (ISO14044) and product carbon footprint calculation (ISO14067) (European Commission, 2023c; ISO 14044, 2006; ISO 14067, 2018). The explanations of the parameters will be provided after presenting the formulas.

$$E = e_i + e_p + e_{td} + e_u - e_{ccs}, \tag{3.1}$$

where:

$$e_i = e_{ielastic} + e_{irigid} - e_{ex-use}, \tag{3.2}$$

comprises the emissions from the supply of inputs in $\frac{gCO2eq}{MJfuel}$. The parameters in this formula are defined as follows:

$$E = total\ emissions\ from\ the\ use\ of\ the\ hydrogen\ in\ \frac{gCO2eq}{MJfuel}, \tag{3.3}$$

$$e_{i\ elastic} = emissions\ from\ elastic\ inputs\ in\ \frac{gCO2eq}{MJfuel}, \tag{3.4}$$

$$e_{i\ rigid} = emissions\ from\ rigid\ inputs\ in\ \frac{gCO2eq}{MJfuel}, \tag{3.5}$$

$$e_{ex-use} = emissions\ from\ inputs'\ existing\ use\ or\ fate\ in\ \frac{gCO2eq}{MJfuel}, \tag{3.6}$$

$$e_p = emissions\ from\ processing\ in\ \frac{gCO2eq}{MJfuel}, \tag{3.7}$$

$$e_{td} = emissions\ from\ transport\ and\ distribution\ in\ \frac{gCO2eq}{MJfuel}, \tag{3.8}$$

$$e_u = emissions\ from\ combusting\ the\ fuel\ in\ its\ end-use\ in\ \frac{gCO2eq}{MJfuel}, \tag{3.9}$$

$$e_{ccs} = emission\ savings\ from\ carbon\ capture\ and\ geological\ storage\ in\ \frac{gCO2eq}{MJfuel} \tag{3.10}$$

The elastic emission factor (2.4) includes all elements that can be expanded to meet a fluctuating hydrogen demand, such as electricity. In contrast, the rigid components (2.5) are the ones that cannot be raised, such as municipal waste for biogas production, which is less critical for the production of hydrogen. The emissions from inputs' existing use or fate (2.6) are the factors that include carbon capture techniques where the captured carbon emissions are incorporated in the production process through diverse methods (compare RED II Appendix European Commission (2023c)). When having extracted the information to calculate the emission intensity, subsequently the emission reduction is calculated and needs to be compliant with the RED II regulation objective of 70% (European Commission, 2023c):

$$Savings = \frac{(E_F - E)}{(E_F)}, \tag{3.11}$$

where E_F is the average value of the fossil energy consumption and related emissions needed for the same amount of energy. However, other certification schemes worldwide consider different factors according to national regulations. As a result, companies that sell low-carbon hydrogen to multiple countries need to be aware of documenting all the parameters that comply with the specific target market institutions[2]. A compatible, self-regulating information system that could facilitate such a function

[2] for example, compare to emission calculation method proposed by the UK (UK Department for Business, Energy & Industrial Strategy, 2022)

would support global hydrogen production and trade, also when considering the background that the consumer side will be demanding more and more the sustainability of the hydrogen used due to emission accounting regulations (Dutch Blockchain Coalition, 2023).

After giving an overview of the relevant institutions for the hydrogen certification economy, the technical functioning of certification processes are subsequently explained.

3.3. Process analysis of green hydrogen certification

The RED II legislation also defines the processes of registering a hydrogen production facility, conducting audits, and documenting transactions between hydrogen sellers and buyers. According to Erbach and Svensson (2023) the European regulation related to RFNBO certification is still in progress, and the EU MSs have not yet approved all aspects. However, certain procedures and prospected processes for handling the hydrogen market can still be derived.

In the first step, the hydrogen producer registers at the national registry and the union database with a certification body that is recognized by the European Union and uses an accredited certification scheme complying with the RED II regulation (World Energy Council, 2022). In this task, the general information of the hydrogen production facility is delivered according to the data points listed in table 3.3. Also, the designated certification scheme will be settled in consultation with the executing auditor.

Once the pre-registered, the manual audit process starts. It includes the responsible auditor's on-site inspection of the production facility. Afterward, the certification body will check the documented inspection for approval. The accreditation body might monitor the audit results as an additional verification instance, as seen in Figure 3.1. The hydrogen production process, the renewability-proof of the electricity source, the geographical correlation, and the temporary correlation are critical for the certification. In the current European GO system, the timely and spatial correlation of electricity generation was not of importance. Hence, the certificates need to be converted into a data file that provides a more granular proof of the electricity's origin (I5, A.6). Further, the electricity GOs were established in a book and claim format allowing separate trading of the electricity and the certificate. In this way, companies would comply with the EU regulation's emission reduction obligations with enough certificates. However, the certificate must be linked to the belonging green hydrogen batch for the hydrogen economy to ensure the value for hydrogen producers and traders (I5, A.6). That means the location of the facility and the location of the electricity source have to be correlated, and the time of the hydrogen production has to correlate with the electricity generation. Further, the commissioning of the hydrogen production plant has to be timely correlated to the commissioning of the renewable energy generation plant; they cannot be separated for more than 36 months (EU Commission, 2022b).

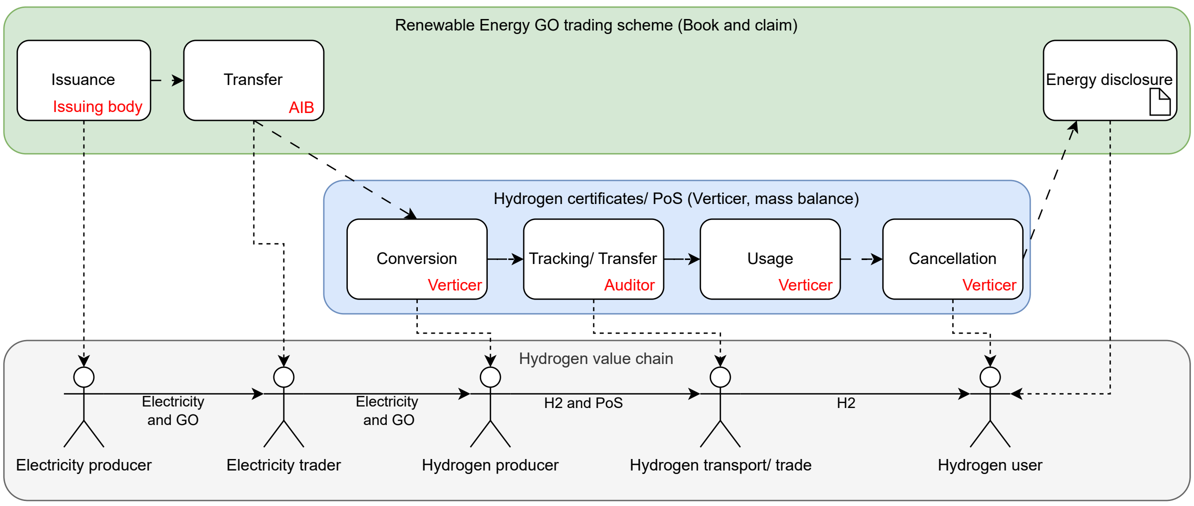

Figure 3.3: Conversion of renewable energy GO to hydrogen PoS.

Another factor that demands amendments to the certificates is that the RED II regulation requires an emission reduction of 70% along the entire hydrogen value chain until the hydrogen's end-of-life/ usage and not solely the point of production. The regulation requires the hydrogen producer to collaborate closely with supply chain descendants to ensure the certificate issuance. In this sense, it is of high importance for the hydrogen producer as the responsible stakeholder in the supply chain to ensure upstream and downstream coherence with the emission reduction targets of the European regulation. The linkage of the conventional electricity GOs and the PoS for green hydrogen is visualized in Figure 3.3 according to Interview I5 (A.6).

Suppose the initial auditing of the facility is approved for every hydrogen batch injected into the market. In that case, the hydrogen producer must report certain data points (cf. information of the specific hydrogen batch in Table 3.3). The production quantities of hydrogen must be recorded in the Union Database, which serves as the central log for all hydrogen transactions in the European market. This database provides transparent visibility to stakeholders involved in the green hydrogen economy, acting as a comprehensive tool for monitoring hydrogen movements from an institutional perspective. The Union Database is closely linked to the National Registries, serving as an intermediary platform for recording and verifying hydrogen transactions. The TSOs are crucial as administrative entities overseeing the practical injection and withdrawal of hydrogen into the grid (European Commission, 2023d). Consequently, the national authority and the TSOs serve as additional verification entities to ensure accurate tracking of the quantities of green hydrogen within the grid and the energy composition of the circulated hydrogen. Refer to Figure 3.4 for a visual representation of the comprehensive functioning of the Union Database.

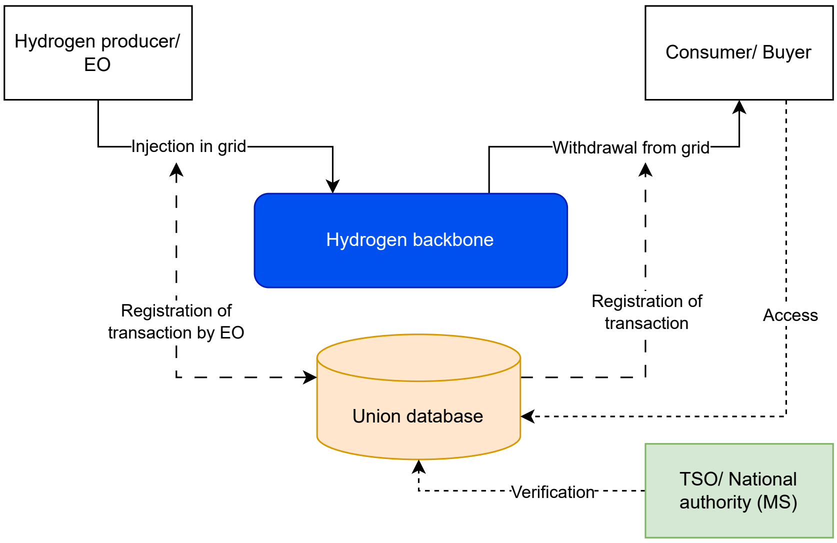

Figure 3.4: The union database (European Commission, 2023d).

The additional verification of hydrogen transactions through TSOs and national authorities is operationalized with regular monitoring of the registered hydrogen transaction in the database. According to Erbach and Svensson (2023), the eventual governance and roles distribution is not entirely determined; however, connecting the dots of different architectural elements that will be included in the system, such as the renewable energy GO process, the Union Database, and stakeholders of the hydrogen value chain provides a frame for assuming the technical system constellation.

In Figure 3.5, the interactions of hydrogen seller and buyer in connection to the proposed concept of the Union Database are visualized. The flow diagram provides an overview of future transaction flows with the Union Database. However, essential entities such as verification and monitoring stakeholders miss and need to be assumed according to the renewable energy GO system.

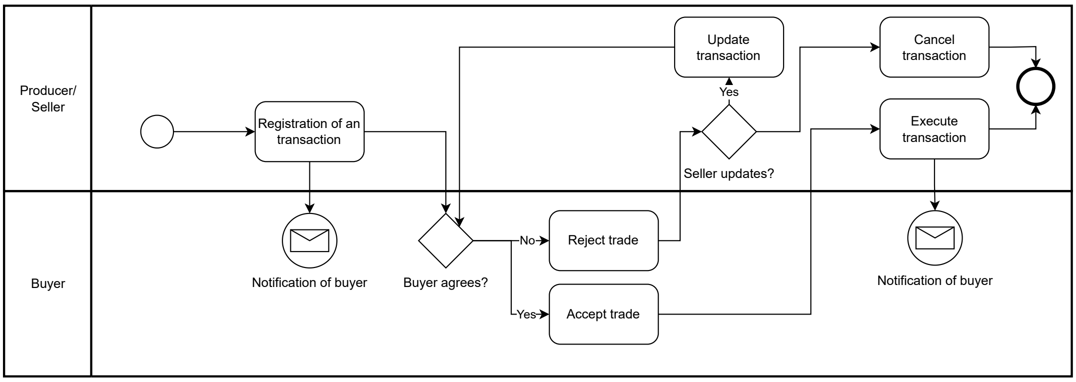

Figure 3.5: The transaction process of the union database based on European Commission (2023e).

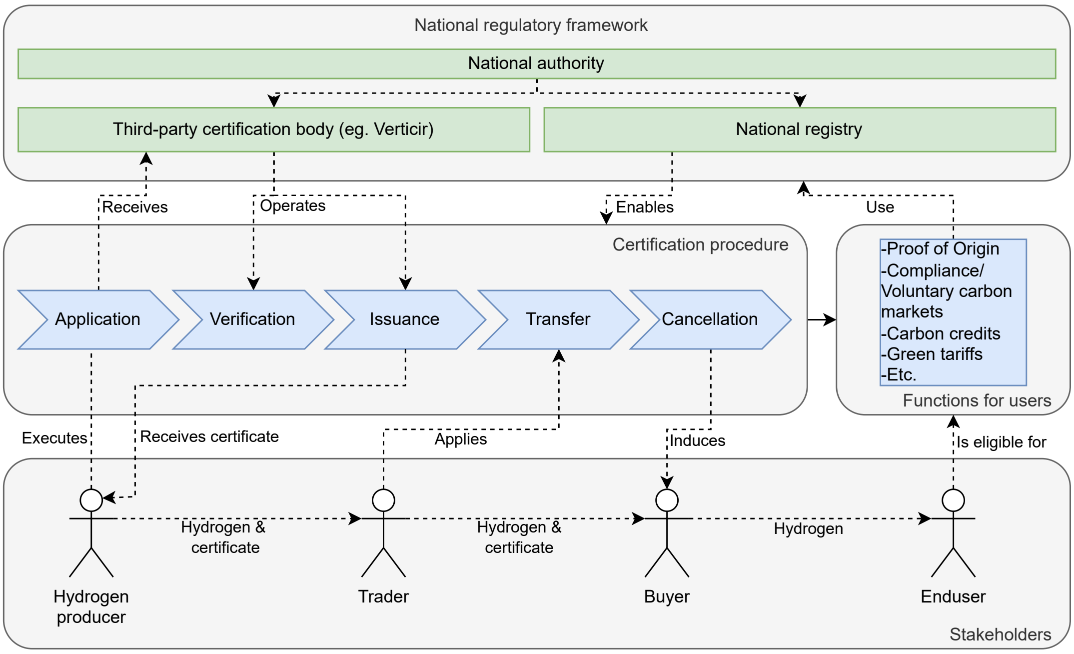

Figure 3.6: The EU GO process and associated actors adapted from (Abad & Dodds, 2020; World Energy Council, 2022).

In combination with the current system of certificate issuance that is used for biogas in the European Union and that is most likely to be adopted for the hydrogen certification, Figure 3.6 shows the complex constellation of government actors, the certification process, business stakeholders and the Union database as the central ledger for the hydrogen certification process. In the Figure, the green objects relate to national authorities and the blue boxes are certification process related. The process is based on the certification process introduced by Certifhy (Abad & Dodds, 2020; Weeda et al., 2019). Figure 3.6 shows how the actors of the technical system analysis interact with the GO process proposed by the European legislation and AIB as the main drivers for EU-wide harmonization of certification schemes. The application process for the hydrogen production plant can be seen as equivalent to the initial auditing by the issuing body to verify the facility requirements to produce green hydrogen. Once registered as a valid green hydrogen producer, the EO can enter transactions of hydrogen measured as batches[3] in the central database. These transactions are monitored regularly (Monthly and weekly) by the TSOs and national authorities (European Commission, 2023d). The TSOs report every month about the withdrawal of hydrogen from the hydrogen grid. The national registry can serve as a second level of truth accessed when doubts about the inserted quantities by the economic operators arise. However, the process is only an indication of how the system shall be looking like in the future. Indeed, specific steps

[3] 1MWh equivalent of energy

are still subject to change, for example, how digital certificates and physical hydrogen are being passed through the value chain and how it is controlled. Currently, hydrogen producers submit physical sheets documenting the emissions and pass them on to subsequent supply chain participants (I5, A.6).In this sense, one significant bottleneck will be the automatization and interoperability of information systems, as these certificates must be virtually transferred along the value chain, passing by actors with different information systems.

3.4. Conclusion

This Chapter provided the answer to the first research question: *What is the complex socio-technical hydrogen certification system in the European Union?* A structured analysis of the state-of-the-art hydrogen economy has been conducted to answer this research question. First, a stakeholder analysis of the hydrogen certification economy was conducted. The stakeholder interactions are visualized with the help of a stakeholder map that shows the institutional, facilitating, and business stakeholders and the fundamental information system infrastructures. The second part of the first research question analyzed the institutional context of the European certification system and the associated emission accounting and reporting requirements. The outcome shows that the RED legislation for RFNBOs entails some fundamental differences from the conventional electricity GO system, as temporal and geographical correlation and the linkage between the certificate and the physical hydrogen batch play a significant role in certifying green hydrogen. This difference is also given in the difference between PoS and GO. The institutional setting is still subject to changes as national authorities and major business actors must agree on a final version of the RED legislation for RFNBOs (state: April 2023). The last part of the research question analyzed the process of gathering data, applying for PoS, and its issuance and cancellation process. The process is still nascent as information systems such as the Union Database and the PoS issuing processes through Verticer are still in development and expected to be settled in the next two years (I5, A.6). However, certificates for biogas and GOs for electricity are supposed to be adjusted to facilitate the certification of green hydrogen. Especially as the electricity GOs are vital to ensure the greenness of the hydrogen.

The hydrogen certification field's stakeholder, institutional, and process analysis feeds the subsequent requirements engineering section as a basis for a blockchain-based architecture that allows reliable emission data collection for hydrogen producers to comply with European emission reporting obligations and provide credible certification for green hydrogen to end-users.

4 Requirements engineering

Based on the context analysis of the socio-technical hydrogen certification environment of the EU in Chapter 3, in this Chapter, a structured requirements analysis is conducted to identify the elements that a blockchain-based certification system needs. To accomplish this, semi-structured interviews are conducted as a method to speak with actors in the hydrogen certification field and identify their needs for credible and reliable hydrogen certification. In general, the structured requirements engineering approach of ISO 29148 (2018) 21840 and ISO 21840 (2019) 15288 is followed, interpreted by NASA and complex systems literature to value the importance of society in establishing socio-technically relevant systems (Arnold et al., 2002; Giuseppe et al., 2022; Nasa, 2022). This approach helps to answer the second research question: *What are the design principles and requirements for a blockchain-based information-sharing infrastructure for hydrogen certification?*

4.1. Design principles

During the analysis of the hydrogen certification landscape, it became clear that the current certification landscape entails major challenges and unclarities for the hydrogen producer that obstructs seamless access to the hydrogen market. The main challenge at the moment is the opaque information requirements for complying with the RED regulations for qualifying hydrogen as green. Secondly, multiple certification schemes and standards can be applied to report emissions and get verified, but currently, a lack of standardization among these exists. And lastly, the process of reporting and verification is predominantly manual and requires automation for a feasible certification landscape that supports a flourishing sustainable hydrogen market. The design principles serve as the expression of the main functions a feasible certification system from the hydrogen producer perspective needs when selling hydrogen in the European market. The design principles or objectives as referred to in ISO 29148 (2018) are the stakeholder needs for the to-be-designed system, which is represented from the hydrogen producer perspective in this thesis. Therefore, four main design principles are established as the scope for the blockchain-based artifact. Next to the design principles, governance is treated extra, as an important aspect of every complex system.

1. RED Compliance: *Companies that want to sell hydrogen in Europe need to comply with the EU regulation on green hydrogen, so the design should be compatible with the institutional framework of the EU.*

A blockchain-based hydrogen certification system to sell safely green hydrogen in the EU can only be viable if it complies with the reporting and hydrogen qualification rules of the European regulation, manifested in the RED II directive as of April 2023. Thus, the artifact should be able to connect to EU reporting systems, be adaptive to the changing EU regulation, and be compliant with verification methods proposed by the European authorities.

2. System modularity: *The system should be able to adopt different certification schemes that are accredited by the European Union and be compatible with central EU databases and multiple private* *information systems of relevant users.*

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 peculiarities and reporting requirements. To comply with the mentioned information tools and with the volatile certification market, the artifact should be able to modularly connect to information systems of issuing bodies and other systems that are still subject to change in the running EU legislation amendments of RED II. This was also acknowledged by scientific literature and addressed as one of the main issues in the current certification landscape (White et al., 2021).

3. Certification automation: *The system should facilitate the process of certification by automating application, issuing, transferring, and cancellation of GOs and reporting to relevant value chain actors.*

Currently, most reporting processes to receive a GO for green hydrogen are happening manually (cf. Interview I5 of Table A.6) (Mould et al., 2022). 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 and reporting, as well as the auditing would facilitate the process and in combination with the latter design principles round up a robust green hydrogen certification system that creates stability and security in the market.

4. Traceability: *The artifact should be able to guarantee the end-to-end traceability of the hydrogen value chain GHG emissions.*

The emission reporting obligations for companies in Europe raise continuously as the need for a transition towards lower carbon emissions increases. The first step towards 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 sense, the artifact should be able to fulfill the function of granular emission accounting covering Scope 1, 2, and 3 according to Figure 3.2 to help hydrogen production companies to prove the provenance of the hydrogen to emission authorities and hydrogen buyers.

Hydrogen certification is a more complex field, which cannot be reduced to four design principles that would facilitate the entire process, but these principles can be applied from the hydrogen producer perspective to enable an effective emission accounting and hydrogen qualification system compliant with the EU institutions. Further requirements were identified which couldn't be assigned to the fundamental design principles. These requirements are related to the **governance** of the artifact and system reliability when being implemented in the market. The former comprises the requirements concerning the handling of the artifact when being implemented, namely openness and allocation of rights and responsibilities (cf. Chapter 6.2. The latter comprises requirements concerned with preserving the confidentiality of shared data (RQ5) and system security (RQ9.), see Chapter 5.2.3.

4.2. Data collection and analysis

To identify the hydrogen producer's needs for hydrogen certification, seven interviews were conducted with experts operating in the hydrogen field. Before conducting the interviewees, the hydrogen certification system analysis of Chapter 3 brought up a couple of initial requirements related to the desk research results. Based on the initial list of requirements that can be found in Appendix A.2 and the defined design principles, an interview protocol was created to gather structured information about the needs from the specific perspective of the hydrogen producer. The protocol of the interview can be found in Appendix A. For each interviewee a general contribution based on the interviewee's background knowledge is indicated and the summary of the interview. Each of the information inputs has been coded based on overarching terms to merge overlapping inputs from the interviewees. From the identified relevant information per categorization, a condensed list has been created by reducing it to the essential information needed for the hydrogen certification system and deleting the redundant information. The outcome is the final list of requirements in Table 4.1 which is explained in the Chapter below.

4.3. Requirements elicitation

Requirements engineering and design science have a correlated approach as mentioned in the scientific literature (Braun et al., 2015; Eekels & Roozenburg, 1991; Peffers et al., 2007). 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). There are two types of requirements: functional requirements define the necessary tasks for the artifact to function in itself, and non-functional requirements describe the qualitative aspects of the functional features including the '-ilities' requirements (Braun et al., 2015; ISO 29148, 2018). The desk research of Chapter 3 in combination with the expert interviews resulted in a collection of 18 high-level requirements comprising functional, non-functional, human factor, and usability attribute types. A complete list of the requirements and their sources can be found in Table 4.1. Subsequently, the requirements constellation is explained based on Figure 4.1.

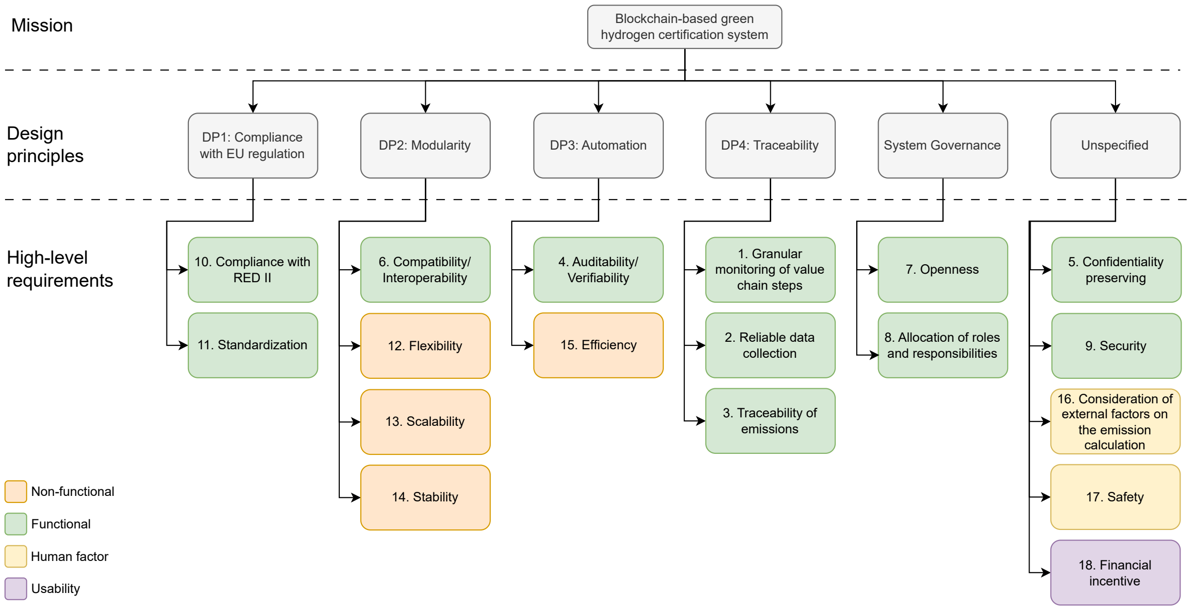

Figure 4.1: Requirements structure.

The requirements analysis resulted in 11 functional requirements on the higher level that are assigned to the design principles of the artifact. Additionally, non-functional and other requirements were identified framing to usability and performance of the artifact according to Braun et al. (2015). The lower-level requirements for the functional and non-functional requirements can be found in Table 4.1

Requirements assigned to the first design principle: The hydrogen producers need a blockchain-based system that complies with the EU regulation on renewable energy and the subsequent RED II regulation (RQ10). As can be seen in the more granular description of this requirement in Table 4.1, this implies preventing potential double counting (RQ10.1) of the emission reduction targets when the electricity input is produced and when the hydrogen itself is produced. Furthermore, the certification system should be complying with the additionality principle (RQ10.2), the geographical correlation (RQ10.3), the temporary correlation required by the RED II regulation (RQ10.4), and the ability to link the physical hydrogen flow with the digital certificate in a mass balancing (RQ10.5) setting (EU Commission, 2022b; World Energy Council, 2022). Standardization (RQ11) is the second functional requirement comprising the compliance principle. These requirement aims at the functionality of the artifact to clarify the composition and calculation of emissions of the hydrogen production process (RQ11.1), to set the sufficiency criteria for a green hydrogen qualification (RQ11.2), and to allow registration with the nationally responsible emission authority (RQ11.3).

Requirements assigned to the second design principle: The second design principle, modularity (DP2,) comprises one functional and three non-functional requirements. The functional requirement is related to the compatibility/ interoperability of the artifact (RQ6). The artifact should be interoperable with the issuance, transfer, and cancellation of the EU GO process (RQ6.1) (Abad & Dodds, 2020). Through interviews, it became apparent that multiple other aspects play into the compatibility requirement for example the compatibility with the renewable energy certificates/GOs for green electricity (RQ6.2) that need to be translated into GOs for green hydrogen without double counting (I5, I6). Further, the artifact should be able to synchronize with the accredited certification schemes in the European Union (RQ6.3), connect seamlessly to the information systems of hydrogen producers (RQ6.4), and account for all types of the hydrogen rainbow (RQ6.5). Lastly, the artifact should be able to trace emissions transparently even if certificates are traded across borderlines (RQ6.6). Additionally, three non-functional requirements were assigned to the second design principle. The artifact should be flexible (RQ12) which means it should be adaptive to the volatile institutional emission reporting environment (RQ12.1) that is still subject to changes in the nascent hydrogen market. Further, the roles and responsibilities of actors are not settled yet and can still change; the artifact should be able to incorporate these changes (RQ12.2). Also, there are not only legislative differences across borders but also within the EU, the system should acknowledge different local barriers to green hydrogen certification adoption into account (RQ12.3). For example, many closed systems are established or about to launch, these already have functioning consortia of energy source, production, transmission, and buyer/user such as NortH2 (Energy Industry Review, 2020). As such, they have different barriers to integrating a holistic blockchain information infrastructure than singular hydrogen production plants. Another performance indication of the artifact is the scalability (RQ13) of the system. The green hydrogen market currently makes up only 2% of the entire European hydrogen supply (EU Commission, 2020). However, the intense regulative and industrial efforts to support the market feasibility indicate an expanding green hydrogen supply such as the proposed hydrogen backbone or Hydrogen One project in Rotterdam Port (Enagás et al., 2020; Shell, 2022). Nevertheless, according to the interviews, the artifact doesn't have a time-critical availability constraint as the verification is not time-dependent but can be done independently of the data collection. That circumvents the computing objective dilemma of scalability versus availability (I2). Even though availability is not critical, the system should ensure stable (RQ14) functioning as hydrogen producers have committed high investments in electrolyzers and storage equipment. Such technical infrastructures have long lifetimes (electrolyzers roughly 13 years) and the system needs to be stable throughout the lifetime to ensure the profitability of switching to green hydrogen production (I5).

Requirements assigned to the third design principle: Automation of the process goes hand in hand with the verifiability (RQ4) of the green hydrogen certificate and associated GHG emissions. As identified by Sedlmeir, Völter, et al. (2021), the information on the hydrogen certificate needs to be verifiable by digital means and based on historical transaction data on the hydrogen value chain steps (RQ4.1). Through interviews and further research, it became apparent that the qualifying data should also be verified by independent third parties (RQ4.2) authorized to access the information transparently (cf. I5 and IRENA (2022)). Lastly, it comprises the qualitative storage of the data so it can be obtained fully by the verifying party (RQ4.3). Another important performance measure/ non-functional requirement assigned to the second design principle is the efficiency (RQ15) of the system. According to the interviewee (I5), current green hydrogen certification operates mainly manually. Producers regularly send Excel documentation about production emissions to authorities who verify the data on the accounted emissions based on physical audits. The processes of registration with the emission authority, emission documentation & reporting, and verification should be automized (RQ15.1). Also, the users should have access to an easy-to-use system contributing to the efficiency of the emission reporting (RQ15.2). And generally, the issuing, transfer, and cancellation of the PoS should be facilitated by the artifact (RQ15.3).

Requirements assigned to the fourth design principle: To accomplish the traceability principle of the artifact design, a function for granular emission monitoring (RQ1) should be established. Particularly, the research revealed that the hydrogen injection (RQ1.1) and withdrawal points (RQ1.2) of the grid should be monitored closely to allow continuous monitoring of the hydrogen volume and composition in circulation (Sailer et al., 2021). The data points that should be collected to calculate the appropriate emission reduction compared to the reference value are given by the RED II regulation and can be seen in Table 3.3. The calculation is then executed automatically according to Formula 3.11. Furthermore, the literature emphasized monitoring the liquid transport of hydrogen by trucks (RQ1.3). The interviews approved the requirement and added the monitoring of storage (RQ1.4), and the tracking of the hydrogen quality (RQ1.5). The metadata of the hydrogen batch should be gradually enriched along the value chain and its quality shall be continuously guaranteed (I6 and Sailer et al. (2021)) (RQ1.6). Specifically, the requirements analysis resulted in putting a specific eye on the electricity input (RQ1.7) as the most relevant emission factor. The second functional requirement concerns the reliability and trustworthiness of the data (RQ2) for the buyers of the hydrogen and verification bodies as they rely on correctness. This should be ensured by third-party sensor providers (RQ2.1) and secure data storage functions (RQ2.2). The reliability is accompanied by the willingness and incentive for transparent information sharing of value chain actors. The third functional requirement concerns the end-to-end emission traceability of the artifact (RQ3). That includes the ability to lock the PoSs as digital assets (RQ3.1) and as pointed out by one interviewee: *"If I have a contract with a company that sells hydrogen can he pinpoint me where the hydrogen is coming from to show them [the buyer] the hydrogen is green"* (I6). Aspects that are mentioned in the interviews are the location, time, and transportation specification of the electricity used for hydrogen production (RQ3.2), as well as the convertibility of electricity GO into the hydrogen certificate. Furthermore, the electricity GOs should be able to be converted to PoS for hydrogen (RQ3.3) while adding relevant additional information mentioned in Table 3.3.

Requirements assigned to the system governance: Some functional requirements couldn't be assigned to the design principles but were related to the governance of the system and are thus more implementation process related and less important for the technical architecture. The first requirement is openness (RQ7): it plays an important role in green energy-supporting information systems according to Sedlmeir, Völter, et al. (2021). Through fair and open standards the system should provide equal access to the European hydrogen market (RQ7.1). Furthermore to stimulate the green hydrogen market in the EU, green hydrogen producers should be able to register with the system regardless of institutional or legal barriers (RQ7.2) to sell hydrogen from a third country outside of the EU (I5). Another important requirement to accomplish a functioning system governance is a clear allocation of roles and responsibilities (RQ8). The interviews revealed that incentives to actively participate in a transaction can stimulate participation and thus contribute to an increasing user number (RQ8.1). A blockchain-based system doesn't necessarily change the responsibilities and roles of actors in the hydrogen certification fundamentally (I4). However, the specific allocation of actions such as the controlling of the data collection (RQ8.2), the rules for data ownership and usage (RQ8.3), the TSOs' responsibility of monitoring the grid movements (RQ8.4), the monitoring of storage capacities (RQ8.5), and accounting of emissions (RQ8.6) should be clarified. Lastly, the artifact needs to be maintained by a system operator that reacts to changes in the hydrogen market and during emergency cases can nudge change requests to the blockchain (RQ8.7).

Unspecified requirements: Lastly, two nonassignable functional requirements were found: confidentiality (RQ5), and security (RQ9). The former has to be ensured to stimulate companies to share the information along the value chain without having competitiveness, and intellectual property constraints (I4, I5). This includes the requirement to solely share emission metadata but no competitive data on the hydrogen production capacities (RQ5.1). The data has to be accessible, though, for auditors to verify the qualification of the hydrogen (RQ5.2). System security concerns the prevention of fraudulent activities such as tamper-proof data storage (RQ9.1) and prevention of fraudulent hydrogen trades (RQ9.2) due to confusion because of many certification schemes (I2, I4). The requirements concerning human factors and usability are not relevant to the technical construction of the artifact, however, they might be important to evaluate the feasibility of the artifact. To put it differently, a virtual information system for emission reporting entails not have the functionality to ensure the physical safety (RQ17) of the hydrogen transport, as well as the physical construction of the hydrogen plant (RQ16). The financial incentive (RQ18) of the blockchain artifact should be provided according to the interviewees' reactions, however, for the general functioning of qualifying hydrogen batches, it is not vital. The applicability of the human factor and usability requirements will be taken into account in the system evaluation, see Chapter 7.

Table 4.1: Lower-level requirements structure.

Type	ID	Higher level	ID	Lower level	Source	Tracing
F	1	Granular monitoring	1.1	The injection interface point should to 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 artifact should be monitoring the hydrogen storage	I4	
			1.5	The artifact 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 emission on each value chain step	L	
			1.7	The artifact should be monitoring 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 artifact 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 belonging 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 artifact should only transparently show metadata about hydrogen emissions, but no identity and intellectual property related sensitive data	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 artifact should be compatible with the renewable electricity certificates/GOs for green electricity	I5, I6, L	
			6.3	The artifact should be able to synchronize with the different certification schemes/systems accredited by the EU	I3, I5	
			6.4	The artifact should be able to connect to all hydrogen producers' information systems	I3, L	
			6.5	The artifact 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 as for international hydrogen producers	I5	
F	8	Allocation of roles and responsibilities	8.1	The artifact should enable benefits and active roles for all parties involved in a transaction of hydrogen (Incentives)	I2	DP5
			8.2	The artifact 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	
			8.5	The artifact should be clarifying the validation party of the data	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 artifact 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 artifact should set clear data sufficiency criteria for the hydrogen qualification	I6	
			11.3	The artifact 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 artifact should take local national/municipal varying emission-influencing difficulties into account	I6	
NF	13	Scalability	13	The artifact should be scalable to many supplying hydrogen producers (as the hydrogen backbone evolves)	L, I4	DP2
NF	14	Stability	14	The artifact should be robust according to the long-term electrolyzer use-phase (appr. 13 years)	I5	DP2
NF	15	Efficiency	15.1	The documentation, reporting, and verification process should be automized	I5	DP3
			15.2	The system should be easy-to-use	I3	
			15.3	The system should facilitate the issuance, transfer, and cancellation of PoS	I6	

4.4. Conclusion

In this Chapter, an analysis of the system design principles and requirements has been conducted to address the second step of the DSR: *requirements and objectives*. The Chapter aims to answer the second research question: *What are the design principles and requirements for a blockchain-based information-sharing infrastructure for hydrogen certification?* In the first step, four generic design principles are formulated, complemented by the governance of the technical artifact and unspecified requirements that cannot be assigned to one of the design principles or the governance as can be extracted from Figure 4.1. The second part of the research question entails the identification of system requirements. Seven experts were asked to contribute their knowledge in hydrogen certification and blockchain systems which can be found in Appendix A. From the interviews, 18 high-level requirements could be extracted which is visualized in Figure 4.1. Each high-level requirement comprises lower-level requirements as shown in Table 4.1. Notably, there was a significant divergence in the requirements provided by the interviewees. Experts hailing from various fields held distinct viewpoints regarding hydrogen certification. Intersections appeared in areas like emission monitoring, data reliability, compliance, and standardization. However, numerous requirements were mentioned based on individual needs, and these couldn't be definitively categorized under specific design principles. Thus, some requirements remained in the category *Unspecified*, as they did not crystallize during the system analysis of SQ1. These requirements serve as the essential input for the artifact design. Specifically, they serve as input for electing subsequent design decision parameters.

5
Design space for blockchain-based hydrogen certification

This Chapter will address the third research question: *What are the technical design components for a blockchain-based IT architecture for hydrogen certification?* According to Peffers et al. (2007) the next step of the DSR approach is creating the design artifact based on the design principles and requirements. In this thesis, a fundamental system analysis and expert interviews are conducted to accomplish this research step. These requirements offer different design options that can help to transform the hydrogen GO system into a blockchain-based information system for reliable green hydrogen certification. To this end, in the first part of this Chapter, desk research has been conducted to identify various design aspects of blockchain architectures. Based on the identified scientific articles, a blockchain-IoT architecture taxonomy is developed to structure the system architecture in different design layers, which can be considered independently. In the next step, different system design decisions are conducted on each architecture layer to best suit the identified requirements of Chapter 4. The result of the Chapter is a blockchain-IoT architecture taxonomy with design choices fitting the requirements analysis and associated rationals justifying the design choices.

5.1. Fundamental blockchain IoT taxonomy

To identify a blockchain-IoT taxonomy, this Chapter follows scientific approaches based on specific system peculiarities of the hydrogen certification environment. Blockchain, in combination with the Internet of Things, has been applied in multiple industries for supply chain tracking. As such, the following Boolean is applied to identify relevant architecture taxonomies relevant for developing a blockchain-IoT system: (blockchain AND IoT AND architecture AND design AND taxonomy OR patterns OR ontology). Two generic blockchain architecture ontologies have been found as the basic blockchain technology stack (Tasca & Tessone, 2017; Xu et al., 2017). However, their approaches to identifying the appropriate blockchain semantics for the hydrogen certification are partly outdated and lack a connection to the Internet of Things of the underlying hydrogen production sensing system. Therefore, the thesis additionally uses an extended architecture taxonomy by Ahmadjee et al. (2022). The authors surveyed modern blockchain-based application fields and condensed the information into different design attributes influencing architectural decisions. Further, hydrogen is a physical molecule that must be measured to transform information about its state into digital form. The thesis addresses this by modeling blockchain-IoT architecture and extending the architecture with a physical perception layer (Fernandez-Carames & Fraga-Lamas, 2018; Kumar et al., 2022; Moin et al., 2019; Novo, 2018). For example, Fernandez-Carames and Fraga-Lamas (2018) and Kumar et al. (2022) propose a general ontology for blockchain-based Industrial Internet of Things (IIoT) based on a survey of multiple industry applications. Figure 5.1 summarises the architecture layers used for the blockchain-based IoT system in this thesis.

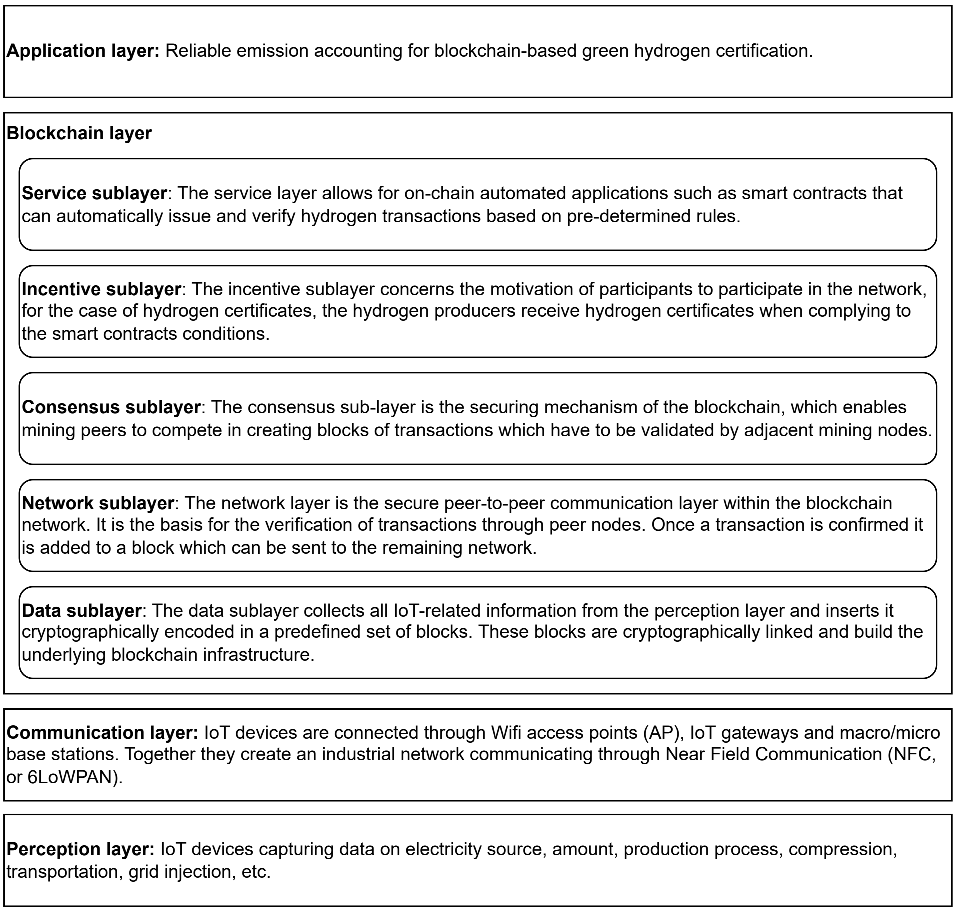

Figure 5.1: Blockchain IoT architecture layers adapted from Kumar et al. (2022) and Moin et al. (2019).

Different design options are possible for each layer depending on the requirements needed for the blockchain application. Subsequently, the different design choices for each IoT architecture layer are explained and justified based on the requirements and system analysis. Even though this thesis mainly focuses on identifying the blockchain layer design to ensure transparent and trustworthy data sharing for credible green hydrogen certificates, it also addresses the data perception layer and communication layer to provide a comprehensive architecture model. Further, the physical layer of the hydrogen value chain is vital for an effective design proposal.

The blockchain layer owns another division of design choices depending on the inherent properties of blockchain, such as decentralization, encryption, and storage type (Ahmadjee et al., 2022). Blockchain is by now an intensively researched and applied emerging technology. Many different use cases of blockchain technology design aspects appeared due to the research, such as different consensus mechanisms, access management mechanisms, security levels, and governance mechanisms. To find a fitting solution, a holistic ontology of blockchain architecture design is used as a reference to find the optimal artifact for the use case of green hydrogen certificates. To accomplish this, we adhere to the fundamental blockchain design frameworks and patterns established by Ahmadjee et al. (2022), Tasca and Tessone (2017), and Xu et al. (2018), Xu et al. (2017). A technical artifact for the blockchain-based hydrogen certification is created with the blockchain IoT architecture proposed by Fernandez-Carames and Fraga-Lamas (2018) and Kumar et al. (2022). The use case and the IoT data collection outline the design components; eight design choices are considered. The first six decision levels correspond to the blockchain IoT taxonomy from Figure 5.1. Security relates to the data and consensus sublayer but is a pivotal design component and is therefore considered separately in the design analysis. Extensibility cannot be uniquely assigned to one of the architecture layers, as it relates to external systems and internal communication to other blockchains. Subsequently, security and extensibility are considered separately in the design decision analysis. As they span multiple layers, they are indicated in green and blue in the design choices overview (cf. Figure 6.1), respectively. Further, the service layer is not addressed in the technical architecture design but in Chapter 6.4, where the processes of the smart contract execution are described.

1. Perception layer
2. Communication layer
3. Data sublayer (Data storage, block configuration, and transactions)
4. Network sublayer (Decentralization and Identity & access management)
5. Consensus sublayer
6. Incentive sublayer (Tokenization of certificates and Tradability)
7. Security and privacy (Key management, cryptographic primitives, confidentiality)
8. Extensibility (Chain structure, Interoperability, Intraoperability)

5.2. Blockchain architecture design

Based on the eight identified design levels above, an overview of the components of the blockchain IoT framework is provided. Each design step is described to feed successively in the holistic architecture model.

5.2.1. Perception layer

The perception layer is the fundamental layer gathering the data for the certification process. As mentioned in Moin et al. (2019), each hydrogen production facility has a connected sensor network of **smart meters** that capture data on energy provenance and usage, hydrogen production processes, and further aspects that play into the GHG emission composition of the hydrogen production process according to Table 3.3. The requirements analysis shows that the system should be able to collect and store data tamperproof (RQ9.1). Further, the system should comply with the competitiveness requirement to 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 1MWh) according to RQ3.1 and RQ10.4. The correct and qualitative data collection and storage also coincide with requirement RQ2.2. Therefore, each smart meter has to be verified individually to contribute to the emission factor calculation of the hydrogen production plant (Moin et al., 2019). Public key management or local cryptographic encryption identifies each IoT device unambiguously. The sensors are verified as a prerequisite before the launch of the hydrogen production facility during the onboarding process (cf. 6.4) in line with the suggestions of Knirsch et al. (2020) and Sedlmeir, Völter, et al. (2021). Novo (2018) suggests the implementation of a local manager for a set of IoT devices deployed in the specific production facility instead of registering each IoT device. This manager is responsible for managing the data collection of the smart meters in a locally verified database. This design decision supports legacy information infrastructures and heterogeneous infrastructures as API gateways (oracles) can connect the off-chain data with the blockchain. Figure 5.2 shows the design choices for the perception layer.

Figure 5.2: Perception layer.

The major challenges in the perception are the data collection's reliability and the sensor communication's security. The former is addressed by the external verification of the IoT devices and the local responsible data manager of the hydrogen production facility according to Knirsch et al. (2020). In this way, a specific range of hydrogen production capacity is defined based on the facility's capabilities. Sensor communication security is a problem related to the security of the sensor network's intracommunication protocol; cyber attacks such as Denial-of-Service can threaten the protocol (Moin et al., 2019). Every device is uniquely registered under the supervision of its respective manager to mitigate significant cyber threats to the local IoT network and enhance data integrity. Given the heterogeneous nature of the devices, each device receives a private and a public key pair. This key pair not only establishes the identity of the smart meter but also facilitates secure data gathering and transmission to the blockchain network, as highlighted (Moin et al., 2019).

5.2.2. 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**. The data communication must be secure for the former type, specified in requirements RQ9.1 and RQ9.3. However, local communication is less critical for the blockchain-based certification system. For this thesis, it is assumed that the sensors are somewhat 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) (cf. Kumar et al. (2022)). The installation type depends on the sensors' security aspect, the sensor network's costs per hydrogen production facility, and the communication range. Typically, production plants operate as closed systems, omitting the need for long-distance connections. Hence, there is no necessity to implement sophisticated communication protocols.

More importantly, the communication with the blockchain should be of quality and make information available to allow the verification service of the smart contracts and to ensure the integrity of the transmitted data (RQ1, 2, 10, 11). As addressed in Chapter 5.2.1 the local sensor network has to be set up according to the measurement points of the requirements RQ1.1-RQ1.7. The third-party sensor provider is included in setting up this network, while auditors check the soundness of the data collection RQ2.1. The audit includes the compliance requirements with the RED II regulation according to RQ10. 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 pair to ensure the integrity of the locally collected data. Also, scalability is essential for the uprising green hydrogen market (RQ13). Infinitesimal transactions of each smart meter would amplify the transaction number and increase the energy usage, which objects to the energy-saving information infrastructure and hamper data throughput (Fernandez-Carames & Fraga-Lamas, 2018). Accordingly, each smart meter device data transaction should be linked to producing one hydrogen batch (equivalent to 1MWh of energy). The local IoT network manager collects and stores the data in an off-chain registered database. The communication with the blockchain itself happens through oracles which serve as secure communication middleware between the locally verified computer and the blockchain. The final architecture choices for this layer can be seen in Figure 5.3.

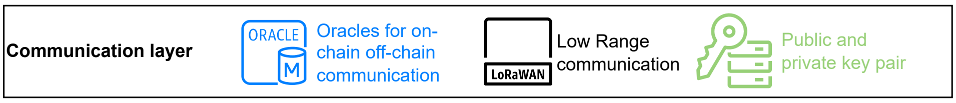

Figure 5.3: Communication layer.

The locally verified data registry introduces one drawback as the central server induces a single point of failure vulnerability to the architecture. The production facility turns into a centralized node that could oppose the decentralized nature of blockchain technology, which aims at serving a decentral sensor system (Fernandez-Carames & Fraga-Lamas, 2018).

5.2.3. Blockchain layer

In this Section, the inherent blockchain architecture layer is considered. The blockchain architecture layer is important as it denotes the main focus of the thesis's artifact design. It contains the data, network, consensus, incentive, and service layers.

Data sublayer

The data layer concerns data storage, block configuration, and transaction management. **Data storage** is one fundamental decision to make 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). Particularly, data storage poses a critical component concerning the confidentiality of potentially sensitive business data and the ability to store data by the blockchain capacity. Also, public blockchain models must have financial incentives, while other forms can host non-monetary incentives such as certificate issuance. In sum, Xu et al. (2017) summarizes that it is important to clarify which data and computation aspects of the blockchain architecture operate off-chain and what on-chain to ensure flourishing participation in the blockchain-based system.

The raw data on the hydrogen production perceived by the smart meters might contain confidential business data (RQ5). In line with Sedlmeir, Völter, et al. (2021), only the relevant metadata about the emission scopes and the encrypted hashes for identification are provided to the distributed and openly accessible blockchain structure. A solely on-chain blockchain storage approach is costly due to the requirement of each node/sensor to store a copy of the ledger. Therefore, a more suitable solution combines off-chain and on-chain data storage. Smart contracts rely on the integrity of the data layer as the primary interaction triggering point for business logic. By utilizing the emission metadata from the data layer, the calculation of emission reduction targets by the RED II regulation is facilitated. Additionally, the smart contracts verify compliance with the data requirements of hydrogen certificates, as illustrated in Table 3.3, see requirement RQ4.1). Storing data off-chain induces an extra middleware layer between the off-chain data storage means and the blockchain, allowing the real-world data to be shared with the blockchain participants. Oracles enable the connection of the off-chain data with the blockchain network (Pasdar et al., 2023). The automated sharing of the relevant data on-chain is necessary to ensure the auditability of the emissions (RQ4). This sensitive data is only accessible by authorized auditing parties and potential monitoring authorities. The on-chain data storage allows for data integrity which can be accessed transparently by verification parties (RQ4.2, RQ4.3). Further, the automation of the process facilitates the emission reporting and complies with the efficiency non-functional performance requirement (RQ15).

The critical component is data reliability, as off-chain data cannot be verified by the distributed properties of the blockchain itself. Still, the artifact deliberately needs to store raw data off-chain to ensure the information confidentiality of hydrogen producers. Another problem is the single point of failure drawback induced through off-chain data storage. Once the off-chain device is breached or malfunctions, the data cannot be restored by the encrypted hashes on the blockchain (Al-Breiki et al., 2020). Hydrogen producers and their local data managers have to ensure the reliability and availability of the data to receive the hydrogen certificates persistently.

The second part of the data sublayer is the **block configuration** as the on-chain data storage definition. The block header's structure usually consists of a unique hash that allows data transformation into transactions stored in a fixed-sized, cryptographically secured block. The block's hash entails information on the previous block's hash, a timestamp, a Merkle root, the unique block version, a nonce, and the block body (Iqbal & Matulevicius, 2021). The hash is said to be tamper-proof as retroactive changes would unmatch with the previous block hash. It further acts as the validation of the transactions of the last block and describes other capabilities of storing transactions' information in the block (Tasca & Tessone, 2017).

The unique hash function of the new block is created by using the previous block's hash and calculating a new hash function based on this input (Iqbal & Matulevicius, 2021). The timestamp entails the information on the block creation. Each hydrogen transaction is passed to a hash function to encrypt it and facilitate verifying the transaction as an infinitesimal transaction change outputs a completely different hash value (Liang, 2020). The Merkle tree is the cryptographic compilation of the transactions' hashes in a binary tree attached to the block header. The root of the tree is thereon attached to the block header. The nonce is an arbitrary value the creator of the block might alter when launching the block. The block body contains all the emission data to verify compliance with the green hydrogen qualification requirements.

The requirements analysis found that emissions should be traceable and, in that way, granularly monitor all emission steps and provide reliable data for reporting authorities and supply chain descendants (RQ1). Further, 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 cryptographic encryption of the transactions provides unique identification and allows immutable storage in a block.

Storing data on a blockchain is not executed conventionally, such as on a central database, but via transactions. That means that between two nodes in a network, there is a mutual imbalance expressed in the transaction. The **transaction computation** is the third part of the data sublayer. According to Xu et al. (2017), transactions can be automated on- or off-chain. The former provides higher interoperability as everyone uses the same transaction model and higher security for erroneous or malicious data. Hydrogen producers require high interoperability because they work with legacy systems that need to be connected seamlessly to the artifact. Also, the legacy systems of the current GO process of the European Union need to be connected similarly according to RQ6.1 - RQ6.4. Sedlmeir, Völter, et al. (2021) propose storing the entire transaction Merkle tree off-chain to ensure the confidentiality of the emission data. For the requirements of the artifact, though, reporting obligations and the specificity of data provision requires open sharing of emission data in on-chain transactions (RQ5). These requirements lead to on-chain transaction computation for the publicly disclosed emission metadata but off-chain storage of sensitive data. The consortium blockchain choice allows additional access and authorization mechanisms to unravel the confidentiality problem (cf. Network sublayer). The transactions trigger smart contracts, which automate hydrogen certificate verification, issuance, transfer, and cancelation. The detailed processes are explained in Chapter 6.4.

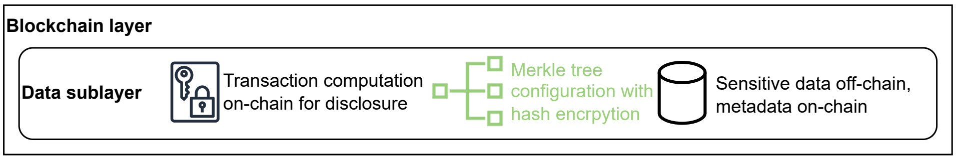

Figure 5.4: Data layer.

Network sublayer

The fundamental decision regarding **decentralization** is undertaken on the network layer. That entails the identification of the necessity for a decentralized architecture model or a centralized setting. Central systems are defined top-to-bottom, where one central authority can manipulate the system's functioning (Xu et al., 2017). Such systems need a defined central information system with transparent institutions clarifying the rules of interaction. However, considering the nature of the hydrogen certification system, there are two aspects opposing this architecture: first, the hydrogen value chain is a complex system involving many actors that have different opinions about the state of the certification of hydrogen; hydrogen producers want to sell hydrogen most profitable, while users need good quality, secure supply and compliance to their emission reporting obligations. Second, regulatory bodies want to stimulate hydrogen production bottom-up but ensure 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 European country (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, RQ5.2). Further, 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 MS of the European Union (RQ6.6, RQ7.2). Also, it refers to RQ10 as the EU sets the institutional boundaries for the hydrogen certification space.

The asymmetric nature of the hydrogen economy fits the decentralized nature of blockchain. Fully decentralized systems, on the opposite, allow new users to join at any time without access restrictions and any authorization rights such as reading, writing, and validating (Xu et al., 2017). Centralized systems, as the opposite extreme would not be fitting, as not all entities have the same role in the hydrogen economy. The hydrogen actor analysis of Chapter 3 reveals a federated set-up of the underlying actor relations. Subsequently, an intermediate format can best serve the inhomogeneity of the hydrogen certification environment. Tasca and Tessone (2017) define semi-decentralized blockchains as hierarchical network designs. In the literature, these blockchains are also called federated- or consortia-governed blockchains (Dib et al., 2018). The consortium architecture design choice can be seen in Figure 5.5. Per MS, a national authority controls the specific rules of the consortium and the accredited authorized nodes feeding the data into the blockchain network. For each reporting stream from the business actor to the auditing authority, a private information channel can be set up to comply with the confidentiality of the business actor. The data is kept confidential in the channel of the consortium until validated and revealed to the entire blockchain network. In this way, the national regulations can be applied but a European hydrogen certification network can be facilitated.

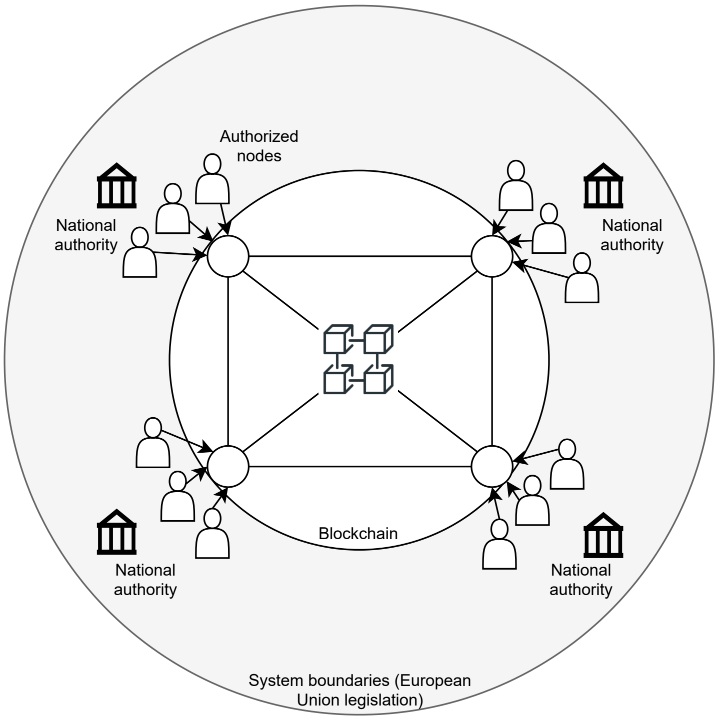

Figure 5.5: Federated/ consortium architecture.

The blockchain type also depends on the decision regarding the **access management**. Access management is closely related to the architectural choice of the node structure to set rules on the action space of each participant (Ahmadjee et al., 2022). Figure 5.1 denotes the design decision possibilities for access management. Reading rights include insight rights into transactions, writing rights allow the nudging of transactions, and committing rights authorize for validation and adding blocks to the system.

As mentioned in the prior paragraph, a permissioned consortium blockchain where registered users can read, authorized hydrogen producers can write transactions, and pre-selected and accredited certification bodies can commit blocks to the network is the most suitable solution (RQ4.2, 6.3, 6.4, 7.1, 11.3). In this way, distributed tasks for each stakeholder and power division can fulfill the decentral benefit. Each EU MS keeps a bundle of enforcement rights as head of a consortium. The system's control is still in the hands of the authorities through accredited bodies. However, hydrogen producers have a transparent system that can be accessed to apply for certificates and show their emissions to supply chain descendants and authorities while the confidential data is secured. To put it differently, system users, such as hydrogen producers, have the capabilities of thin nodes, that is, reading and writing transactions. In contrast, a pre-selected group of full nodes have verification and block committing rights (Ahmadjee et al., 2022). The artifact's detailed allocation of roles and responsibilities is addressed in Chapter 6.2.

In the network layer of the consortium blockchain, the identity management of the participating network subjects needs to be considered next to access rights. In contrast, in public blockchains such as Bitcoin, all identities are mutually anonymous, keeping the highest level of privacy (Tasca & Tessone, 2017). The hydrogen producers insert hydrogen production data and associated emissions automatically via

Table 5.1: Access rights per blockchain type based on Christidis and Devetsikiotis (2016) and 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

digital connection of the smart meters, manual identity checks need to be executed as a prerequisite (Knirsch et al., 2020) and in line with RQ2.1. There is a mutual willingness to prove the identity during the digital hydrogen certification. Hydrogen producers provide their identity to the authority and hydrogen consumers to prove the integrity of the data; authorities require the identity for attributing the certificates to the correct entity. Thus, the design choice is physical identity management and additional proof of identity with the public-private key pair whenever transactions are pushed into the system.

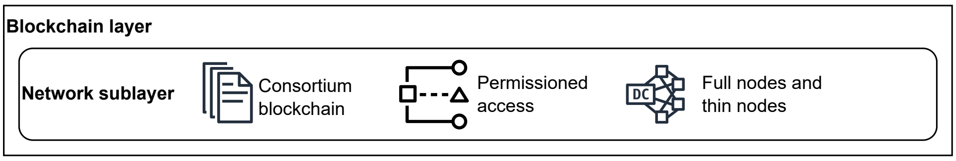

Figure 5.6: Network layer.

Consensus sublayer

The consensus sublayer defines how the rules of interaction are enforced and gives the blockchain an institutional structure. That means the consensus is the translation of existing rules of hydrogen certification in blockchain-based digital rules. There are different types of reaching a consensus in the literature, with the major ones listed in Table 5.2. Each type has its benefits and drawbacks, depending on the use case. Generally, the chosen type of blockchain in the network layer creates path dependencies for the decision room of the type of consensus mechanism. For example, selecting a restricted blockchain type, such as private or consortium blockchain, determines that the consensus mechanism must be permissioned, too.

Table 5.2: Consensus mechanisms adapted from Ahmadjee et al. (2022) and Zheng et al. (2017)

	Proof of Work (e.g., Bitcoin)	Proof of Stake (e.g., Solana)	Proof of Byzantine Fault Tolerance (eg. Hyperledger)	Proof of Authority
Blockchain type	All	All	Consortium/ Private	Private permissioned
Energy consumption	High	Middle	Middle	Low
Scalability	High/Middle	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

In that sense, the preselected authorities of the network determine that the blockchain cannot be controlled by a distributed consensus mechanism such as Proof-of-Work and Proof-of-Stake. 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, 11.3). As seen in Table 5.2, other parameters also play a role in choosing a suitable consensus mechanism. Energy consumption should be low, as the blockchain architecture aims at facilitating a process to stimulate green hydrogen production. The system's scalability is important considering an expanding future hydrogen market (RQ13). This observation excludes the Proof-of-Byzantine-Fault-Tolerance (PBFT) mechanism. Voting-based PBFT systems are dependent on the majority voting for transactions' validity, which means it is timely dependent. If transactions can only be validated with the activity of many nodes it can be inefficient when many transactions need to be processed. Generally, the system should not be subject 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). According to I2 (A.4) the transaction speed is not vital for validating hydrogen transactions, however, the number of transactions entering the system is relevant for the artifact[1]. Their validation requires a certain level of facilitation, else manual reports or other information systems would suffice. Based on these decision factors, the most suitable solution to create a blockchain-based hydrogen certification system is the Proof-of-Authority (PoA) consensus mechanism. In Figure 5.7 the design decision PoA is visualised. The design components ZKP and single chain are related to security and privacy and extensibility, respectively, and will be discussed subsequently.

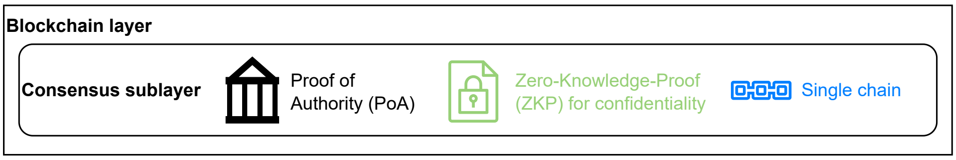

Figure 5.7: Consensus layer.

Incentive sublayer

The incentive sublayer describes handling digital rewards provided when the transactions are validated and the consensus reached (Kumar et al., 2022). It is usually deployed in public blockchains to prevent miners from malicious behavior like Sybil attacks - fake nodes help to mine their own blocks and prevent other miners from block creation (Christidis & Devetsikiotis, 2016). Similarly, transaction fees, such as gas fees on the Ethereum blockchain, can prevent fraudulent sybil nodes from causing Denial-of-Service attacks (Buterin, 2014). Sybil nodes can only flood the blockchain network with transactions if the transaction costs are low, high costs would multiply the costs to conduct a Denial-of-Service attack. In contrast, in private/consortium blockchains, rewards or fees are not needed because identity management and the verification of transactions via authorities secure the consensus process. Only operating transactions in a smart contract can induce costs. Creating an individual blockchain can prevent the variable costs of applying and issuing certificates, as smart contracts will automate these processes. Furthermore, rewards will be provided by issuing certificates and verifying the sustainability of the hydrogen. In that sense, the consortium PoA-based blockchain does not require a fee system as a potential option mentioned by Tasca and Tessone (2017).

Another design choice on the incentive layer is the **tokenization** of assets related to the transactions on a blockchain. Tokens can embed ownership of digital assets within the blockchain (Tasca & Tessone, 2017). The ownership can then be transferred or traded through transaction metadata. Blockchain was introduced initially to digitize paper currency in a decentralized manner (Lemieux, 2017). Introducing tokens is the next level of distributed information systems. A digital record can now represent physical goods such as hydrogen. Such digital tokens can facilitate verification, prove the (fractional) ownership, and distinguish digital property (Johannes et al., 2022). Furthermore, scientific research attributes tokenization also the potential to make supply chains more sustainable and reduce transaction costs between value chain participants (Sunyaev et al., 2021). G. Wang and Nixon (2021) distinguish different types of tokens:

1. **Fungible tokens**: Tokens have similar attributes and are mutually interchangeable, for example, payment tokens should be interchangeable to facilitate trade.
2. **Non-fungible tokens**: NFTs are unique, indistinguishable tokens that unambiguously keep track of digital ownership. They cannot be divided, which provides the inherent attributes. They can only be transferred by providing the necessary transaction metadata.

[1]The number of transactions covers the projected green hydrogen market of the EU, according to Odenweller et al. (2022) that is 127TWh in 2030

3. **Semi-fungible tokens**: SFTs combine features of fungible and non-fungible tokens. Through that, ownership can be tracked while tokens can be bundled and do not have to be traded individually with singular transactions.

Generally, the artifact 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. Tokenization is an appropriate function of blockchain technology to accomplish this requirement. Each digital hydrogen certificate has to be linked indistinguishable from the belonging hydrogen batch to fulfill the mass balancing requirement (RQ3.2, RQ10.4). Non-fungible tokens can create such links as only one owner can be attributed to the token at a time. That helps to enforce the continuous link between the digital certificate and the physical good. Deploying NFTs also complies with other requirements, such as gradually monitoring emission metadata along the hydrogen value chain (RQ1.6). Smart contracts can facilitate the transfer of the digital certificate once the hydrogen value chain step is finished and pass the ownership on to the next supply chain step. While closed hydrogen production and distribution systems can benefit from this architectural setup, they can keep the digital certificate throughout the entire process until the hydrogen is sold to customers with the belonging digital certificate.

However, hydrogen can be sold in smaller amounts than 1MWh. To address this issue, Babel et al. (2022) further introduces the fractional ownership of NFTs based on the implementation of electricity GOs. They use the transactional model of unspent transactions, representing the available number of GOs in the wallet. Based on that, the system operator requests 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 according to the amount of hydrogen used. In this way, the injection and the withdrawal points can be monitored, and the trade can be facilitated. Furthermore, the concept of composition tokens can be utilized. Johannes et al. (2022) suggest that tokens are created while producing a good and passed on throughout the supply chain, where participants add data on each value chain step. This Partchain concept can help to add emission information along the hydrogen value chain while the physical and digital assets are continuously linked. The final design decision sees NFTs with fractional ownership as the optimal solution for the requirements.

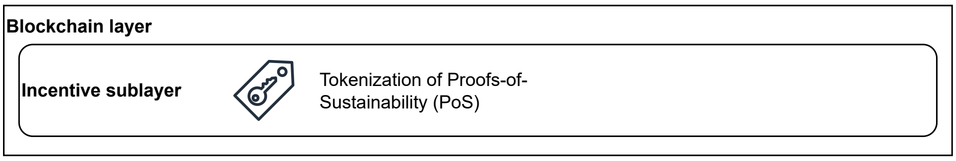

Figure 5.8: Incentive layer.

Security and privacy

Security and privacy pervade all architectural layers of the artifact; in the overview of the design choices Figure 5.9, they are indicated in green color. Although blockchain uses encryption methods such as Secure Hash Algorithms (SHA-256 or SHA-512) to encrypt the transactions and link the blocks, different types of security and privacy leakages were identified by literature (cf. Ahmadjee et al. (2022). The article mentions, for example, reconnaissance attacks that aim to collect sensitive data through man-in-the-middle attacks to launch privacy-infringing attacks. 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, one requirement for the artifact is to guarantee the confidentiality of the sensitive hydrogen production data and to secure the data-sharing process (RQ5 and RQ9). Sedlmeir, Völter, et al. (2021) address this problem by implementing Zero-Knowledge-Proofs (ZKP). This technology enables proving a statement without revealing additional information or intermediate steps leading to that mathematical state (Schellinger et al., 2022). The concept was already developed long before the decentralized data-sharing properties of blockchain (Fiege et al., 1987). Combined with blockchain's security properties, it can serve as a powerful privacy mechanism. Considering the case of revealing the emission intensity of hydrogen production, the ZKP protocol would allow to solely prove compliance with the green/low-carbon qualification without revealing sensitive business information such as the amount of hydrogen produced, the electricity input, and the receiver of the hydrogen. 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 to preserve the confidentiality of the data. In the design, ZKPs are chosen to comply with the confidentiality requirements of the artifact.

The validating node receives the verified emission data of the hydrogen producer by sending the emissions with the public key of the local data repository as validation. The data includes a balance of the energy consumption and the signed consumption data of the previous step (e.g., the electricity data). The system operator can update the Merkle tree ZK-rollup based on the verified data through the smart contract. The Zk-rollup is the on-chain stored operator of the user accounts, their transactions, and historical data (Sedlmeir, Völter, et al., 2021). In this way, the authorized account holders (hydrogen producers) can nudge a transaction (change of state of the user's Merkle tree account) with a privacy-preserving ZKP operator, which the smart contracts process in the system.

Extensibility

First, considerations regarding the **chain structure** are important for the extensibility. These have a major influence on the scalability and efficiency of the network. Generally, there are two types of chain structures: *single chain and multiple chains* (Ahmadjee et al., 2022). The former is one singular chain that stores all the transactions. They are easier to oversee and assure a high level of security. However, the larger the blockchain network becomes, the more limited the transaction throughput may be. Multiple chains are a nascent solution to incorporate multiple blockchain protocols and allow inter-blockchain asset exchange through special communication protocols. As inter-chain communication increases the surface of the network and the newly connected complexity, multi-chain structures require specific management techniques (Belchior et al., 2022). If the communication among different chains is not aligned, they can also induce a lower security level. Tasca and Tessone (2017) introduce further the design elements **intra- and interoperability**. These are vital considerations regarding the modularity design principle of the artifact. Intraoperability concerns the compatibility of the blockchain with other blockchains and the transferability of assets to another blockchain and is thus closely related to the chain structure decision.

Digital hydrogen certificates must be linked persistently to the physical hydrogen batch and should not be transferred separately (RQ3.3 and RQ10.4). That means the artifact should be capable of intra-operating other blockchains' information. Especially, cases of hydrogen import require the blockchain to incorporate certificates of other blockchains to allow the certificate to travel with the belonging hydrogen batch. Opposing, confidentiality (RQ5), and security (RQ9) are important requirements for the artifact. Upon this, Ahmadjee et al. (2022) mention that the cross-blockchain transmission can induce significant drawbacks for the privacy, security, and tracing of assets and amplifies the complexity of system governance and usage. Users might need to switch wallets and accounts depending on which chain needs to be used. For example, the Ethereum Virtual Machine is a multi-chain operating blockchain network with side chains like Polygon and Avalanche, but cannot communicate directly with them. Inter-chain communication services are required to solve this intraoperability issue which is usually operated by third parties. These cross-blockchain exchanges are prone to potential fraudulent activities that undermine the security and trusted data-sharing infrastructure (Back et al., 2014; Belchior et al., 2022). Besides, supported by the PoA consortium set-up, new participants shall be onboarded to the system easily and integrated with the help of oracles. Consequently, a single-chain design without intraoperability properties is adequate to operate as a hydrogen certification tool in Europe.

A more decisive factor for the system's success poses **interoperability**: it is a new system's property to connect to existing legacy systems and generally external information systems (Tasca & Tessone, 2017). 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 artifact should account for emissions for all types of hydrogen. Therefore, smart contracts can be individually programmed to qualify the hydrogen based on the input information. The smart contract entails the qualification parameters, and as emissions exceed the level for green hydrogen, the hydrogen no longer qualifies for low-carbon.

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). For example, the smart contract can verify the identity of the local facility and calculate the emission reduction by requesting the off-chain data of the local repository. The oracles allow each user to move data between on-chain and off-chain storage.

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, RQ15.3). Most of the time, hydrogen production, compression, and preparation for transport happen in a closed system. The transporting entity has access to the certificate but must not receive ownership, so the transport does not need to be addressed in the hydrogen value chain emission reporting. The ownership of the certificate proceeds directly to the buyer of the hydrogen, who now has the data control over the content of the certificate and can resell it or use it and thus cancel it.

Interoperability is complementary to the flexibility requirement of the artifact. 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, as accessing the system is standardized with oracles and pre-audits (RQ7.1). Figure 5.9 provides an overview of the blockchain architecture taxonomy with the associated design choices.

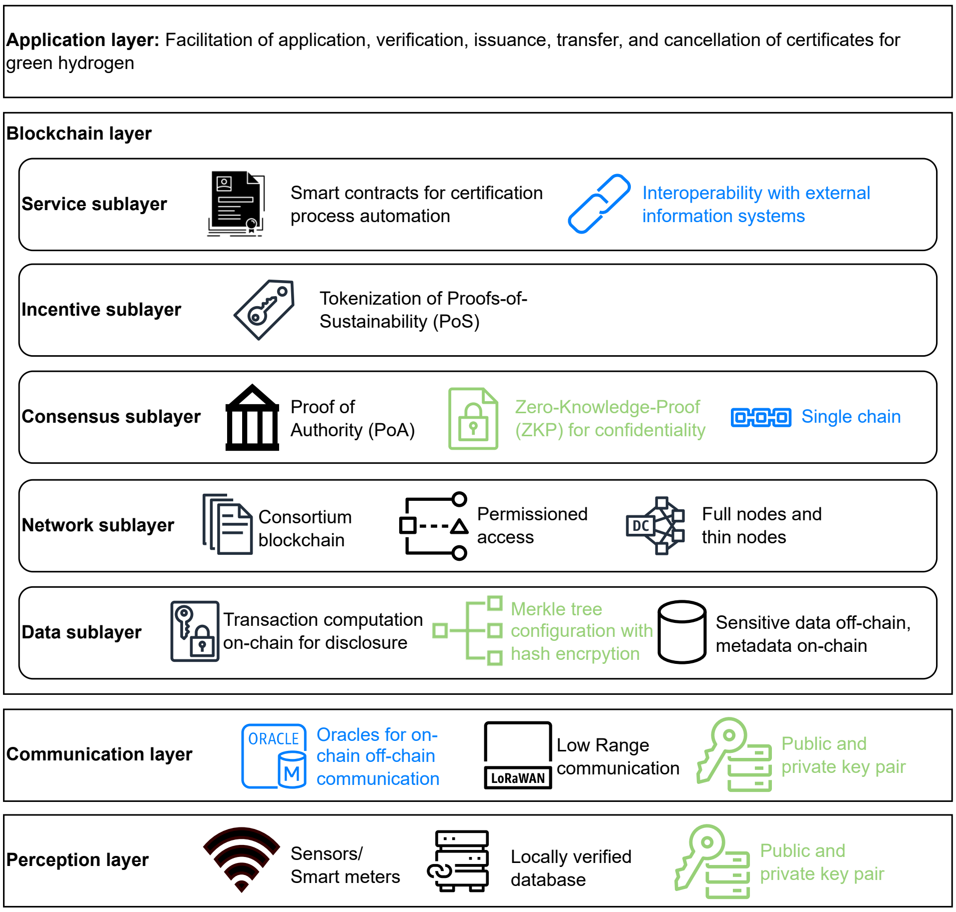

Figure 5.9: Overview of design choices.

5.3. Conclusion

In this Chapter, the third step of the design science approach *artifact design* was addressed (Peffers et al., 2007). A tailor-made framework for IoT-Blockchain systems has been developed that can serve the creation of a blockchain-based hydrogen certification system. The framework was utilized to address research question 3: *What are the technical design components for a blockchain-based IT architecture for hydrogen certification?*. In the design process, three system design layers are the foundation for the application in the hydrogen certification field. The perception layer entails the design choices for a robust and reliable data collection method that can serve as data input for the blockchain while preserving the confidentiality of sensitive business data and preventing the infusion of erroneous data that can lead to the garbage in - garbage out vulnerability. The communication layer connecting the physical IoT layer with the digital blockchain infrastructure must be secure and connectable with business information systems and reporting registries. Oracles were chosen as means to fulfill the requirements. The blockchain layer is divided into five sublayers. The raw data for emissions is stored off-chain to ensure the confidentiality of the data layer, and ZKPs serve as means to prove compliance with green hydrogen qualification standards. The general decentral infrastructure is a consortium where local authorities can commit new blocks while economic operators nudge the transactions. Verification bodies serve as intermediate and ensure compliance with the decentral nature of the blockchain. Smart contracts automate the compliance verification and issuance of digital PoS tokens, token trading, and cancellation.

The chosen design decisions fulfill the requirements to the best of the author's knowledge and according to design thinking in systems engineering. Design decisions always come with trade-offs regarding the design principles and the requirements for an optimal solution. The most important trade-offs are discussed in the artifact's evaluation (cf. Chapter 7), for example, privacy and system interoperability as mentioned in Chapter 5.2.3. Subsequently, the implementation process of the technical artifact in the socio-technical context is addressed.

6

Implementation of blockchain-based hydrogen certification

The sixth chapter addresses the third research subquestion: *How can a blockchain-based IT architecture design be implemented in the socio-technical hydrogen certification industry?* The Chapter aims to cover the third part of the DSR approach introduced by Peffers et al. (2007), the implementation and demonstration of the designed artifact in the socio-technical context of hydrogen certification. Therefore, the technical artifact of Chapter 5 is demonstrated in the first part of the sixth chapter. To complete the socio-technical alignment of the artifact, the second part of the chapter covers the allocation of roles and responsibilities or the system's governance. Thirdly, this chapter clarifies the alignment with the institutional environment of the hydrogen certification field. The last sub-chapter addresses the integration of the hydrogen certification process with the technical artifact design by illustrating the onboarding of the hydrogen production facilities, the data collection and issuance of the tokens, and the transfer and cancellation of tokens.

6.1. Holistic blockchain IoT architecture model

In Chapter 5 the design decisions for the blockchain-based hydrogen certification system were analyzed and chosen. Subsequently, Figure 6.1 demonstrates the design in a high-level system architecture. The architecture entails the connections of the application, blockchain, communication, and perception layer with the design choices of Chapter 5. The technical architecture model is from the perspective of one hydrogen producer represented by the local manager responsible for the trusted data repository at the hydrogen production site. The Figure describes its interaction with the certification process and associated stakeholders. This architecture can be multiplied for other hydrogen producers and thus serves as the basis architecture to connect to the blockchain system.

On the perception layer, the covered emission scopes are illustrated as outlined by the RED II regulation. The regulation covers mainly the upstream emissions for hydrogen production. The emission data is gathered in a local data repository and verified during the onboarding process of the hydrogen production facility. A local manager manages the interaction with the hydrogen certification process, triggers the hydrogen transactions, and maintains the local repository. The oracle ensures secure communication between off-chain data repositories and on-chain smart contracts. The private-public key pair identifies the facility and encrypts sensitive data transferred to the blockchain. The smart contracts can then act as business logic on the blockchain to execute the verification of the hydrogen batches registered through the sensors. After verification through the Issuing Bodies, the smart contract automatically issues the right amount of PoS tokens to the hydrogen producer. The tokens are transferred to the personal wallet of the hydrogen buyer. When the sensors measure the withdrawal of the hydrogen by the user, the PoS tokens are burnt gradually with the usage. The use phase is indicated as part of the certification process from cradle to gate; however, the proposed artifact does not report the end-user emission. The process flow is explained in Chapter 6.4 below.

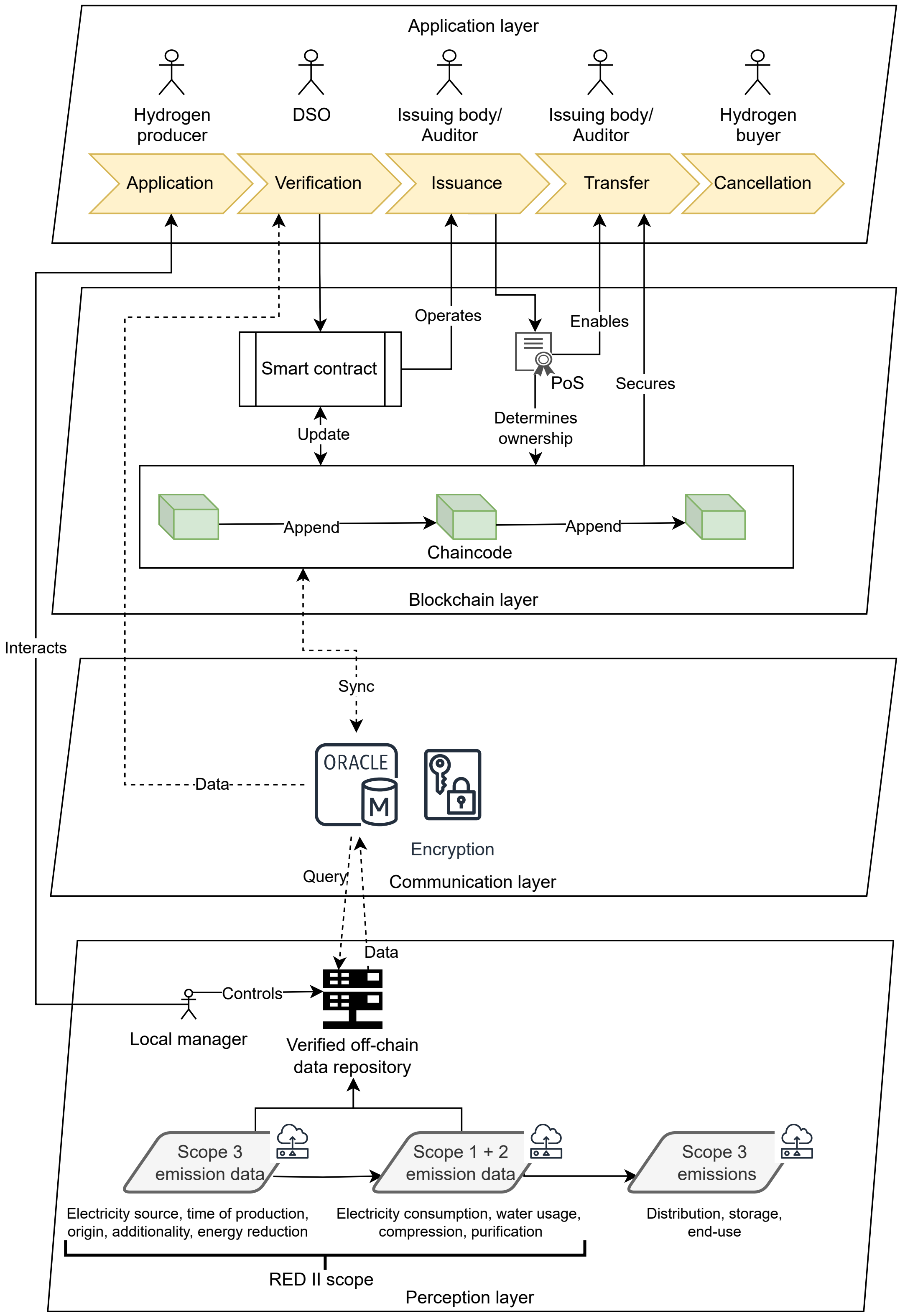

Figure 6.1: Technical architecture model.

6.2. Stakeholder roles and responsibilities

The requirements analysis with the hydrogen certification experts also resulted in requirements that are related to the governance of the artifact when being implemented in the market. In the requirements structure of Table 4.1, they are categorized as RQ8: Allocation of roles and responsibilities as can be seen in Table 6.1.

Table 6.1: Requirements structure

Type	ID	Higher level	ID	Lower level	Source	Tracing
F	8	Allocation of roles and responsibilities	8.1	The artifact should enable benefits and active roles for all parties involved in a transaction of hydrogen (Incentives)	I2	DP5
			8.2	The artifact 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	
			8.5	The artifact should be clarifying the validation party of the data	I3, I4	
			8.6	The system should determine a system maintenance party	I3, I4	

The first lower-level requirement points out that the blockchain only functions if participants have active roles (RQ8.1), or else they would start not using the blockchain and finding other means of transacting the hydrogen and associated certificates (I2, A.4). For the artifact, it is essential to gain user numbers to reach sufficient transactions for scaling the system. Also, the artifact is required to facilitate mass balancing. It implies a close attachment of the digital certificate and the physical hydrogen batch, which supports incentivizing active roles and responsibilities in the blockchain prototype. Thus, for each participant, active roles are proposed. To start (Step 1 in Figure 6.2), the EOs nudge the process by agreeing on a PPA with the hydrogen buyer. The automatic collection of the data and smart contracts trigger the insertion of hydrogen transactions into the system. The complete process of nudging a transaction until reaching consensus and adding a new block to the chain is illustrated in Figure 6.2.

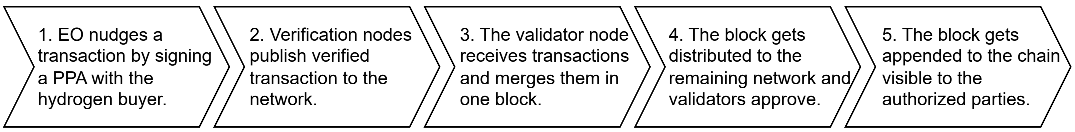

Figure 6.2: Proof-of-Authority consensus mechanism.

The artifact should clarify rules for the data collection control (RQ8.2) to ensure that the artifact can mitigate the garbage in data collection vulnerability. Sensors must be standardized and verified regularly by independent third parties that the European Union accredits. This observation goes hand in hand with the prerequisite of Knirsch et al. (2020) to allow for secure data collection. Furthermore, to redundantly control the data integrity, at the withdrawal points from the grid, another set of sensors controls the coherence with the input of green hydrogen. This allows the authorities to double-check if the green hydrogen entering the grid matches the green hydrogen exiting the grid and being sold to clients.

Deploying distinct storage of on-chain and off-chain data addresses the data ownership requirement (RQ8.3). All sensitive business data related to the competitive hydrogen production market is stored off-chain. Only the emission data relevant to emission reporting and transparent disclosure to hydrogen buyers is revealed on the platform. That means sensitive data stays with the hydrogen producer, and data concerning the PoS is shared publicly with the authorized parties on the blockchain.

In the case of hydrogen grid distribution (cf. Figure 1.2, the TSO companies should be utilized as the monitoring entity of the hydrogen movements (RQ8.4). It is necessary to ensure a tighter link of hydrogen with the certificate. The TSOs can verify the injection and withdrawal points of the hydrogen grid as additional instances next to the digital verification (Step 2 in Figure 6.2). The continuous monitoring allows for mass balance-compliant monitoring of the hydrogen grid. In this way, TSOs can sign the hydrogen transactions before being forwarded to the validation parties. The verification party is an important governance entity in the blockchain. They act as an intermediate between validating, full nodes and thin nodes (EOs).

The validation parties are the only committing party of the network; they create new blocks by merging hydrogen transactions and validate blocks of other consortia actors (RQ8.5). The validation parties are the accredited third parties by the European MS, namely the issuing bodies/ auditors that collect and validate the transactions before forwarding them to the system (Step 3 in Figure 6.2). Other validators can approve them and, in this way, create a cross-border alignment of hydrogen transactions which ensures the information comprehensiveness of the European hydrogen market (Step 4 in Figure 6.2).

Lastly, the maintenance of the system needs to be addressed (RQ8.6). Maintenance in the artifact is equivalent to system governance in the sense of maintaining a long-term system functioning, maintaining stakeholder roles and interactions, and updating the software. Each MS elects a national system administration responsible for the national consortium maintenance. Collectively, the national administrations represent the maintenance council of the system that oversees the entire blockchain-IoT infrastructure[1]. The main tasks of the system maintenance entail the negotiation of the smart contract functionalities across consortia, the legal considerations of the smart contract enforcement, the regular updating of the system, the acceptance of new VS and hydrogen production facilities, and the potential extension to international certification schemes as mentioned by dena - German Energy Agency (2023). The maintenance council, thus, aims at sustaining fair system access and operating rules, the potential disclosure of system vulnerabilities, and mitigation actions for security risks. The maintenance 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 & Fraga-Lamas, 2018). The system maintenance council cannot sign and commit transactions, as that would concentrate the system's power and oppose the blockchain's decentral trust setup.

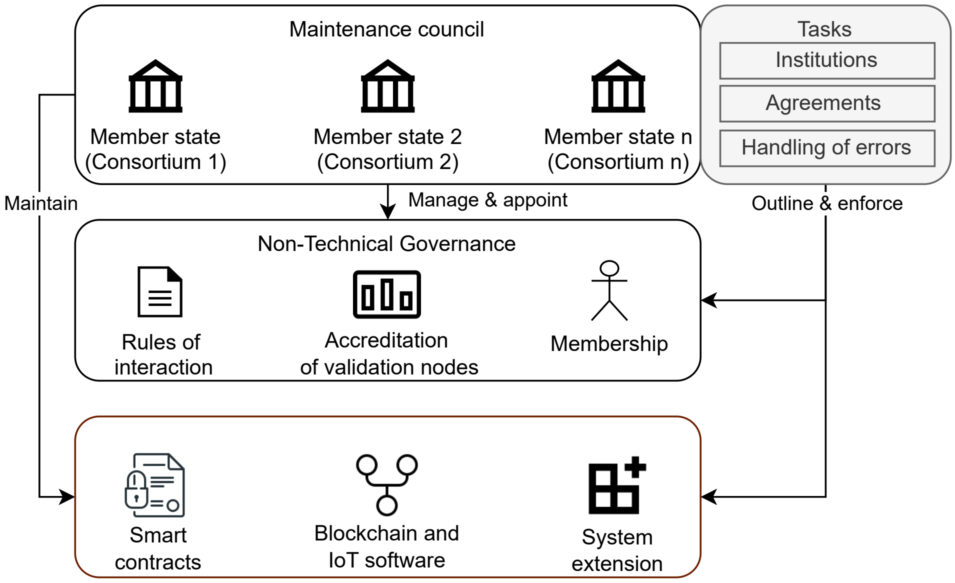

Figure 6.3: System maintenance council.

Henceforth, the institutional alignment of the technical architecture is addressed, focusing on integrating legacy systems of the national and European authorities.

[1]Each MS forms one consortium in the blockchain representing a closed system that interacts with other consortia to ensure the cross-border validity of the artifact, cf. the MS consortium setup in Figure 5.5

6.3. Institutional alignment

The technical system architecture can only help certify hydrogen, issue PoS certificates, and cancel them if aligned with the institutional framework of the EU hydrogen certification (RQ10). In this sense, Figure 6.4 illustrates the implementation of the technical artifact with the existing and planned institutional hydrogen certification system. The Figure shows objects related to international entities in orange, objects related to national regulation in green, third-party certification facilitating parties in blue, hydrogen market participants in white, and the central blockchain-based certification system in violet. For the European market, the regulations of the EU and National Authorities play a significant role. International regulations are less critical for the system as all hydrogen producers that want to sell hydrogen in the European market need to comply with the EU regulation. The information systems of non-European hydrogen producers must be connected to facilitate hydrogen import as one business scenario to comply with the projected European hydrogen demand (Clean Hydrogen Joint Undertaking, 2023). The system needs to connect to the information systems of the European Union as they need a central collection of all hydrogen-related movements in the market. Hence, the blockchain synchronizes with the Union Database and the National registries. The certification bodies and the issuing bodies[2] are the facilitating parties of the certification and need read-and-write access to the system. Integration of their legacy systems is vital for the success of the holistic blockchain-based information system in the European Union. Market participants also have access: hydrogen producers enter emission data, and hydrogen producers access the information related to the hydrogen qualification and the cancellation of the used PoS.

Another potentially important extension is the linkage to the information system of the Emission Authorities; they issue emission reduction allowances for transport companies. Every transport company will have to report on the number of renewable energy units (HBEs: Hernieuwbare brandstofeenheden)[3] they use and how much carbon emissions they emit (Nederlandse Emissieautoriteit, 2022). As stated on the website, it is only applicable to the transport sector for now[4] and not necessarily important for the certification of the hydrogen facility itself. However, it is relevant for trading hydrogen certificates and issuing potential emission allowances to hydrogen end users. Figure 6.4 entails also the emission trading system for the comprehensiveness of the current emission market.

Another important consideration for the institutional alignment is the concordance with the electricity GO system, as hydrogen producers will have to prove the provenance of the electricity to produce green hydrogen. Electricity GOs do not entail information about the time and location of the production, but hydrogen certificates require it. The timestamp function of the blockchain transactions can add this extra parameter to the certificate whenever electricity is consumed to produce green hydrogen in the electrolysis process. The unique public key helps identify the electricity's provenance and locate the hydrogen production location. As the RED II regulation also thrives towards the additionality principle of linking green electricity production directly with hydrogen production, the consideration of linking the electricity GOs with the PoS for hydrogen might get obsolete if accomplished.

[2]they are the same entity
[3]1 HBE is equivalent to 1 Gigajoule (GJ) of renewable energy (in this case hydrogen)
[4]status April 2023 for testing purposes, cf. Nederlandse Emissieautoriteit (2022)

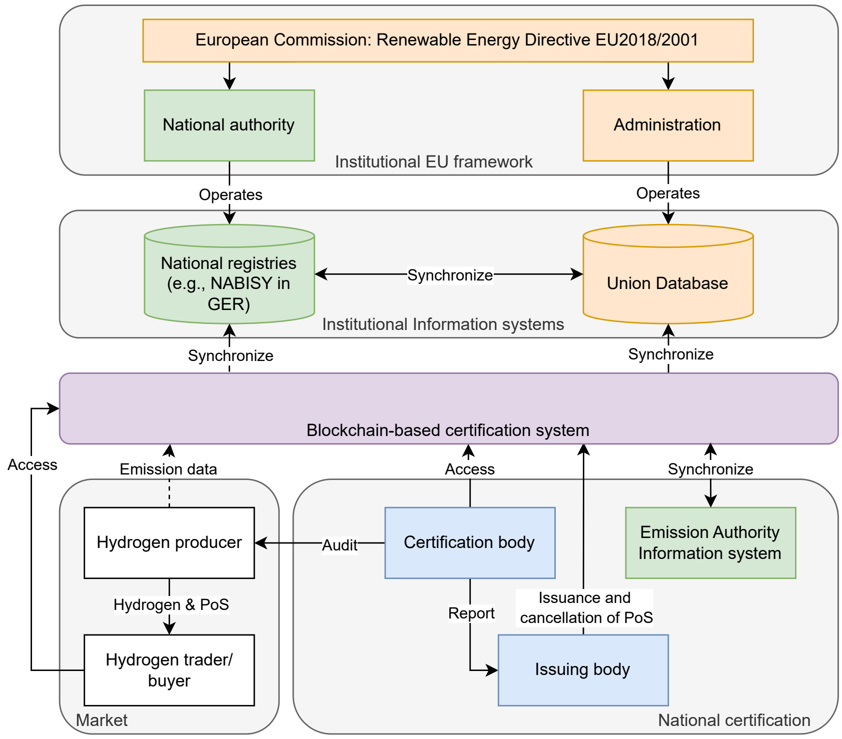

Figure 6.4: Alignment with the institutional certification system.

6.4. Certification process alignment

Even though the current certification process of green hydrogen and the transparent trajectory of the PoS with the hydrogen certificate still need to be established, processes of the gas and electricity certification mechanisms can be used. Subsequently, a conceptual overview of the system's main functions is given, entailing the onboarding of the hydrogen production facilities, the continuous data verification and issuance of PoSs, and the trajectory of the physical hydrogen and digital PoS until reaching the hydrogen end user in the European Union.

6.4.1. Onboarding of hydrogen production facilities

The underlying layer for the blockchain architecture is the IoT sensor/smart meters layer. The requirements of the European regulation enforce gathering specific data points that allow for qualification as green hydrogen. However, the data is subject to the tools used for physical perception. In line with Knirsch et al. (2020), the proposed architecture uses an independent third party registered with an EU government to verify the smart meters for energy consumption measurement and thus ensure data integrity. The same goes for smart meters used during hydrogen production to measure water usage, conversion rate, and all parameters mentioned in Figure 3.3. The audit to install and verify the official sensors happens once during the initial registration of the hydrogen production facility. It can be repeated in longer cycles within one year or similar. After being verified as an eligible hydrogen producer, each local data repository receives a private account with a public-private key pair. The pair of keys allows anonymous identification with the network as a trusted green hydrogen supplier. As mentioned in Knirsch et al. (2020), only pseudo-anonymity can be achieved as the personal Voluntary Scheme provider, and the auditor must know the identity for the initial verification. However, these entities are assumed to be trusted and independent from the market competition. The data collection of the smart meters triggers the subsequent verification of the produced hydrogen volumes. It is operated continuously through automated smart contracts. Subsequently, the exact processes are described.

6.4.2. Data verification and issuance of the PoS

The verification of the hydrogen emission data and the subsequent qualification is visualized in Figure 6.5. 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. It is the central data collection point for the emission data obtained through smart meters. Smart contracts can be programmed to obtain only relevant information from the off-chain data repository synchronized with the blockchain. Before transferring the data on the blockchain, the local hydrogen producer creates a ZKP, which allows transferring only relevant metadata on the emission 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 rules coded in the smart contract. These rules check the emission reduction of the hydrogen production process 3.11, the temporal correlation, the geographical correlation, and the additionality of the hydrogen production facility according to the RED II requirements. Once verified, the hydrogen producer gets notified about the qualification of the produced hydrogen[5]. 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 UDB, and the token issuance is secured redundantly.

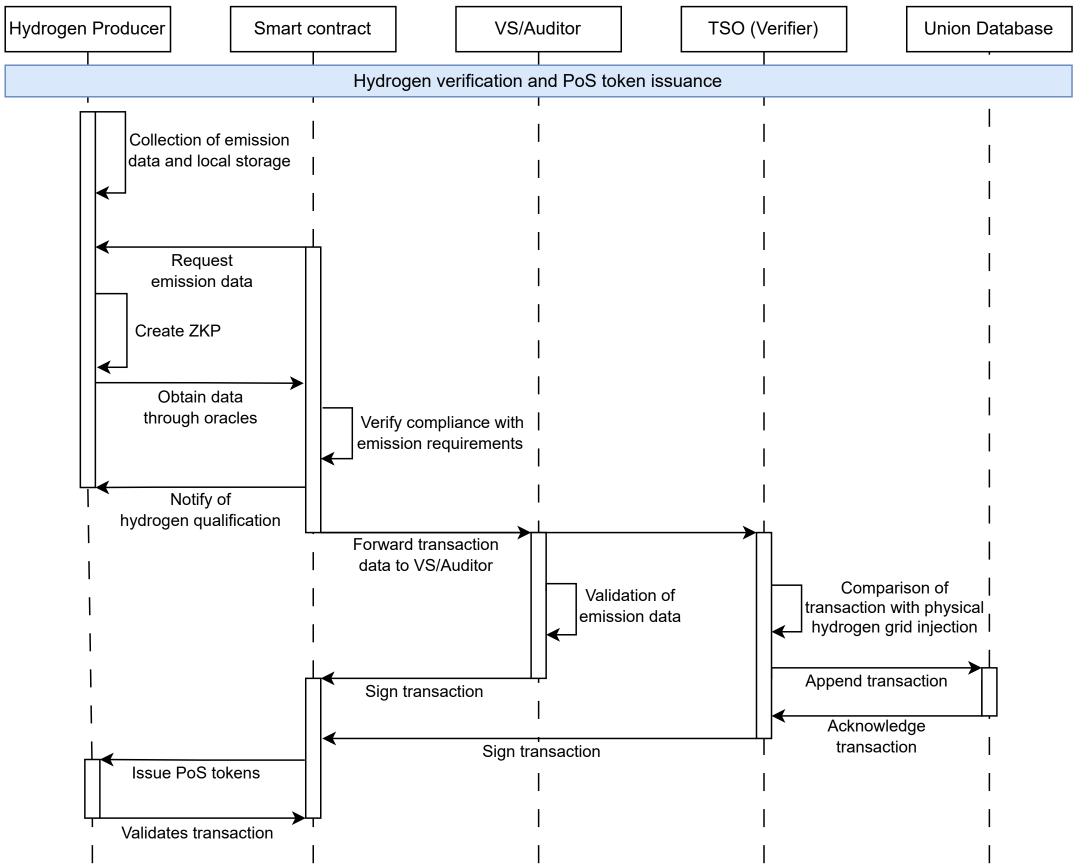

Figure 6.5: Hydrogen verification and PoS token issuance.

6.4.3. Transfer and cancellation of the PoS

The second and third function of the blockchain-based hydrogen certification system is the transfer and cancellation of PoS tokens. The two mentioned processes are visualized in the sequence diagram 6.6. The PPA initiates the former function between the hydrogen producer and buyer. Once they agree upon a hydrogen delivery contract, the hydrogen producer requests the transfer of the PoS tokens according to the amount of energy the hydrogen entails. The smart contract automatically requests to

[5]According to the hydrogen colors

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 PoS tokens based on the amount of hydrogen agreed in the PPA. Referring to requirement granular emission monitoring (RQ1, Table 4.1), 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 be in real-time, but whenever the reporting due date approaches. Also, the TSO appends the hydrogen grid injection information to the UDB to update the overview of green hydrogen in the market. The smart contract finally operates the transfer of the tokens to the personal wallet of the hydrogen buyer.

The third function is concerned with the cancellation of the PoS tokens. Based on the PPA, the hydrogen buyer withdraws hydrogen from the distribution grid. The sensors of the TSO trigger the smart contract to automatically burn the tokens as the buyer consumes/withdraws the hydrogen. The predetermined rules in the smart 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.

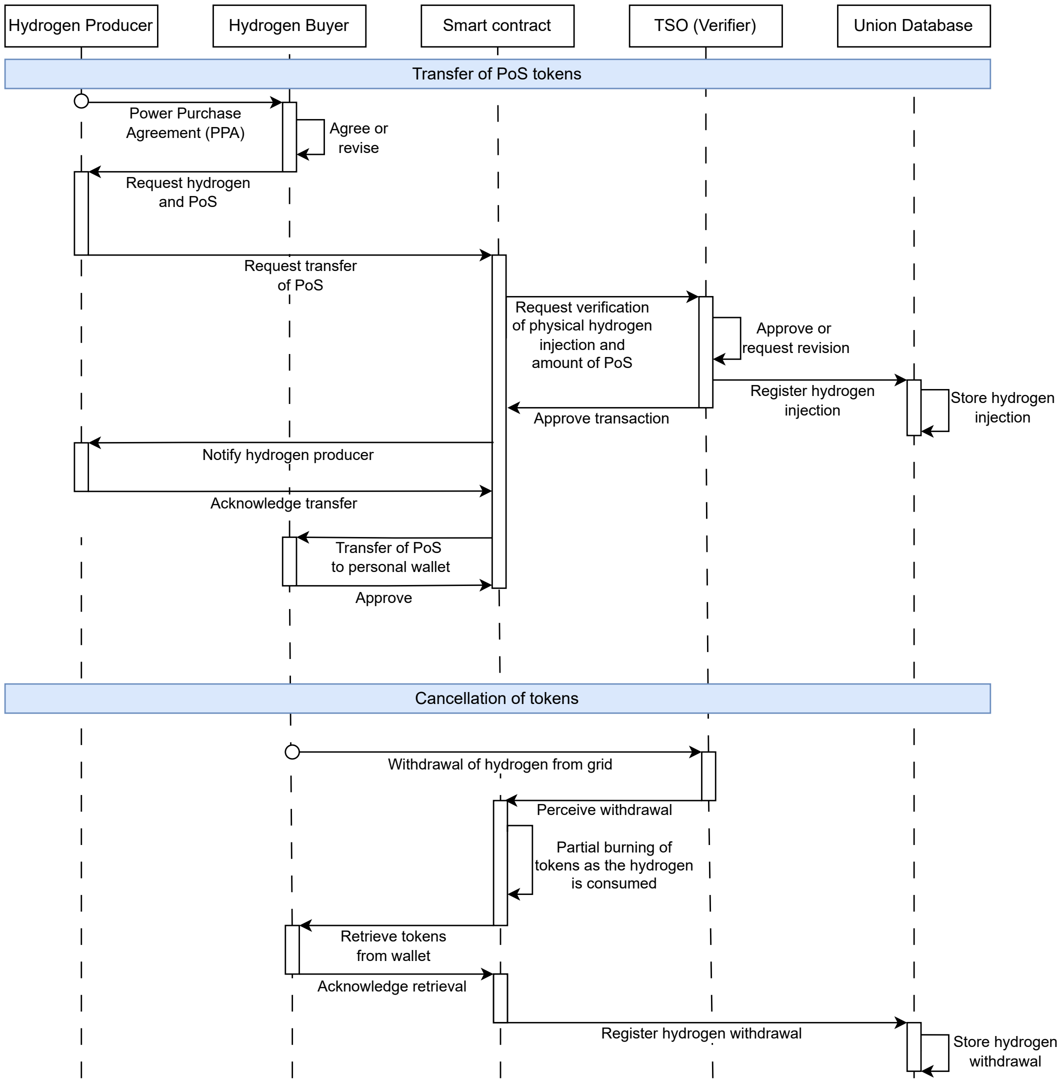

Figure 6.6: Transfer and cancellation of the PoS tokens.

6.5. Conclusion

This Chapter addressed the fourth subquestion of the research project: *How can a blockchain-based IT architecture design be implemented in the socio-technical hydrogen certification industry?*. To do so, according to the design cycle of Peffers et al. (2007), the blockchain-based hydrogen certification architecture is demonstrated in the first sub-chapter. It shows the connections between the perception, communication, data, and application layer. The second sub-chapter addresses allocating roles and responsibilities as an essential success factor for the system implementation according to the requirements. The roles entail the allocation of read, write, and commit responsibilities in the PoA consortium blockchain, the process of reaching consensus, and the maintenance of the system. The third sub-chapter entails the institutional alignment of the artifact with the socio-technical certification system of the European Union, the extensibility to the emission authority, and interoperability with electricity certificates. The last sub-chapter illustrates the processes of the system's key functions: the onboarding of hydrogen facilities, the data verification and PoS token issuance, and the transfer and cancellation of PoS tokens. The Chapter output visualizes how actors and existing legacy information systems interact with the blockchain artifact. However, implementing the artifact includes variable parameters that can change over time. Continuous updating of the artifact implementation strategy helps to implement the design in the socio-technical context successfully. The Chapter output concludes the thesis's design and implementation artifact and serves as the final product for the subsequent evaluation.

7

Evaluation

This Chapter addresses the fourth step of the design cycle of Peffers et al. (2007): the evaluation. In the course of the Chapter, the demonstrated artifact of Chapter 6 is discussed on its fulfillment of requirements and the feasibility for the hydrogen market. This approach addresses the fifth research question: *How feasible is a blockchain-based hydrogen certification system for the hydrogen production market?* To address this subquestion, we adhere to the evaluation strategy of Venable et al. (2016) to provide a summative evaluation of the artifact. Following their research approach, first, an evaluation of fulfilling the requirements is conducted. The artifact is evaluated based on the extent to which it can accomplish the requirements identified in Chapter 4, and the potential trade-offs and drawbacks of design choices are discussed. In the second part of the evaluation, experts are consulted to validate the technical artifact, the role and responsibility distribution, the institutional alignment, and the blockchain-based certification process demonstration. The expert reflection aims to consider critical views on the feasibility of the designed artifact.

7.1. Discussion of the requirements

According to the DSR approach of Peffers et al. (2007), an initial set of system requirements was collected during Chapter 4. Based on these requirements, a blockchain-IoT architecture design taxonomy was developed in Chapter 5; it addressed each functional requirement through design elements. Subsequently, each functional requirement and the associated design choices are presented, and an indication of the fulfillment is visible in Table 7.1. The requirements evaluation is done by comparing the architectural elements with the design choices and assessing the logical compliance with the requirements. Likewise, the non-functional requirements can assess the artifact's utility/performance in the hydrogen certification market illustrated in Table 7.2. In this way, it can be evaluated to what extent the artifact fulfills the initial requirements to serve as a reliable and automated certification system tracing granularly the emissions of hydrogen production.

Fulfilment of functional requirements

The evaluation of the artifact's fulfillment is the last step of the analysis in this thesis. However, the artifact only serves as an initial design to set a foundation for working toward a standardized green hydrogen certification system in Europe. Multiple subsequent iterations are needed to develop a first Proof-of-Concept. As seen in Figure 7.1, the artifact can fulfill most requirements. The artifact can facilitate hydrogen certification compliant with the RED II regulation, provide a modular architecture for businesses and public authorities, automate the PoS certification process, and ensure the traceability of the hydrogen molecules back to their origin. Additionally, blockchain can establish structured system governance in a decentralized untrusted market, where different players have different roles and responsibilities (cf. Chapter 4). Only two lower-level functional requirements need more attention in a future design step: *RQ6.6, The system should allow the readability of certificates across national borderlines* and *RQ7.2, The system should be unbiased adaptively for domestic as for international hydrogen producers*. These are related to the lack of international alignment of the artifact. Due to the

Table 7.1: Fulfillment functional requirements.

Type	ID	Requirement	Design decision	Fulfilment
F	1.1	The injection interface point should to be documented closely	Smart meter (5.2.1)	✓
	1.2	The hydrogen withdrawal interface point has to be documented continuously	Smart meter (5.2.1)	✓
	1.3	The liquid transport should be documented	Smart meter (5.2.1)	
	1.4	The artifact should be monitoring the hydrogen storage	Smart meter (5.2.1)	✓
	1.5	The artifact should be able to measure the hydrogen quality/pureness	Smart meter (5.2.1)	✓
	1.6	Metadata on the hydrogen batch should be shared gradually along the value chain adding up emission on each value chain step	Smart meter (5.2.1)	✓
	1.7	The artifact should be monitoring the electricity input	Smart meter (5.2.1), Interoperability, Timestamp (5.2.3)	✓
F	2.1	Sensors should be verified by an external third-party	External sensor provider (5.2.1), (6.2)	✓
	2.2	The artifact should store the emission data reliably	Verified local repository (5.2.1) (5.2.2)	✓
	2.3	The data collection should directly be linked to the secure blockchain system	Automated data acquisition through smart contracts via oracles (6.4)	✓
F	3.1	The system should be able to lock proofs of sustainability	Tokenization (5.2.3)	✓
	3.2	The system should link the virtual hydrogen certificate to the belonging hydrogen batch	Non-fungible tokens (5.2.3)	✓
F	4.1	Automated verification of the injected hydrogen based on historical data	Smart contracts (6.4), full nodes and thin nodes (5.2.3)	✓
	4.2	The emission data should be verifiable by an independent third party	Full nodes, permissioned blockchain (5.2.3), Transaction signing through issuing body/authorized auditor (6.4)	✓
	4.3	The system should ensure the data quality of hydrogen emissions	On-chain data storage and immutability (5.2.3)	✓
F	5.1	The artifact should only transparently show metadata about hydrogen emissions, but no identity and intellectual property related sensitive data	Off-chain on-chain data storage (5.2.2)	✓
	5.2	The emission information has to be stored accessibly to authorized parties	Transparent on-chain data storage (5.2.2)	✓
F	6.1	The system should be compatible with the EU GO process	Interoperability through oracles 5.2.3	✓
	6.2	The artifact should be compatible with the renewable electricity certificates/GOs for green electricity	Interoperability through oracles 5.2.3	✓
	6.3	The artifact should be able to synchronize with the different certification schemes/systems accredited by the EU	Consortium blockchain (5.2.3), Interoperability through oracles 5.2.3, Smart contracts for qualification (6.4), Onboarding with Voluntary Scheme (6.4)	✓
	6.4	The artifact should be able to connect to all hydrogen producers' information systems	Interoperability through oracles 5.2.3	✓
	6.5	The artifact should be compatible to account for emissions for all types of hydrogen	Interoperability through oracles 5.2.3, Smart contracts for qualification (6.4), Onboarding with Voluntary Scheme	✓
	6.6	The system should allow the tradability of certificates across national borderlines	Consortium blockchain (5.2.3), Acceptance of different VS	✗
F	7.1	The system should support fair and open standards for all users	Interoperability (5.2.3), System maintenance council (6.2)	✓
	7.2	The system should be unbiased adaptively for domestic as for international hydrogen producers	Consortium blockchain (5.2.3)	✗
F	8.1	The artifact should enable benefits and active roles for all parties involved in a transaction of hydrogen (Incentives)	Clear roles and responsibilities in PoA consensus and smart contract signing (6.2), (6.4)	✓
	8.2	The artifact should clarify the controlling party for the data collection	Third-party standardized sensor provider (6.2)	✓
	8.3	The system should establish rules for data ownership	Off-chain data storage (6.2)	✓
	8.4	TSOs should be utilized as the regulators for the hydrogen injection and withdrawal of the grid	TSO as verification instance to sign the transactions (6.2)	✓
	8.5	The artifact should be clarifying the validation party of the data	Issuing bodies/ authorized auditors (6.2)	✓
	8.6	The system should determine a system maintenance party	MS administrations as system maintenance council members (6.2)	✓
F	9.1	The system should ensure tamper-proof data collection (garbage in prevention)	Onboarding audits, third-party sensor providers (6.4), (5.2.1)	✓
	9.2	The system should prevent fraudulent activities due to many varying certification systems	Interoperability with all accredited VS in the EU (5.2.3)	✓
	9.3	The artifact should be able to prevent double counting	Cross-border interoperability (Union Database) and synchronization (5.2.3), (6.3)	✓
F	10.1	The system should comply with the additionality requirement	Secure communication, external sensors, automated data collection, PoA validation (5.2.1), (6.2), (6.4)	✓
	10.2	The system should be able to prove the geographical correlation	Secure communication, external sensors, automated data collection, PoA validation (5.2.1), (6.2), (6.4)	✓
	10.3	The system should be able to prove the temporal correlation	Timestamp, secure communication, external sensors, automated data collection, PoA validation (5.2.1), (5.2.3), (6.2), (6.4)	✓
	10.4	The system should be able to comply with mass balancing	Tokenization, Interoperability (5.2.3)	✓
F	11.1	The system should clarify the emission influence factors and their calculation for producers and consumers	Standardized data collection points 6.3, Automated qualification through smart contracts (6.4)	✓
	11.2	The artifact should set clear data sufficiency criteria for the hydrogen qualification	Automatized qualification of the hydrogen through smart contracts (6.4)	✓
	11.3	The artifact should allow registration with the national responsible emission authority/ registry	Onboarding (6.4), Consortium blockchain (5.2.3)	✓

complexity of the hydrogen certification field, the thesis focuses on the European market and excludes certification schemes outside of Europe from the design. It implies a potential drawback for international hydrogen producers registered with international certification schemes as they have to comply with European regulations to sell hydrogen in the European market. In the artifact's design, a single chain with multiple channels represented by the consortia was chosen. Single chains only entail one major drawback; they lack the capability of inter-blockchain communication between different single chains (Ahmadjee et al., 2022; Yu et al., 2018). For example, transferring assets from the Ethereum blockchain to Bitcoin requires intermediary business logic, such as cryptocurrency exchanges. However, in the chosen consortium blockchain design, the lack of interoperability induced by the single-chain design decision can be mitigated. If agreed upon in the maintenance council, smart contracts can be adapted to international hydrogen standards and allow international producers to register with VS of other nations. These off-chain agreements would allow a hydrogen producer in Australia to connect to the European hydrogen certification blockchain while complying with the Australian standard. New channels can be created for each national framework and linked to the consortium blockchain. In this way, the artifact can flexibly mirror the volatile hydrogen certification market whether the political direction leans towards multiple national hydrogen standards or one international standard (dena - German Energy Agency, 2023).

Furthermore, (see Chapter 5), the technical blockchain artifact offers greater ease of extension to other information systems than aligning multiple heterogeneous information systems of actors in conventional supply chains. Oracles can be adjusted to meet hydrogen users' and institutional entities' legacy systems and data structures. In this sense, the next design iteration could entail a deeper focus on the adaptability of international schemes to facilitate the process for international producers and increase the fairness of the hydrogen certification. The current volatile hydrogen certification market and institutional setting must be monitored closely to adapt the system design accordingly. Further considerations of the adaptability of international producers are for future research when the institutional setting is determined.

For the functionality of the artifact in facilitating green hydrogen certification with trusted information exchange, the unfulfilled requirements (6.6 and 7.2) are not vital. The hydrogen market will evolve globally considering the EU's plans of importing 10 million tonnes of green hydrogen by 2030. However, for domestic users, the artifact can fulfill its functionalities, extensions to other systems, and third-country hydrogen producers must be tested in future research.

Fulfilment of non-functional requirements

Subsequently, the system's performance is evaluated based on the non-functional requirements. Four non-functional requirements were identified throughout the requirements engineering in Chapter 4: Flexibility, Scalability, Reliability, and Efficiency. Each of the performance measures is discussed in the following.

Table 7.2: Fulfillment non-functional requirements.

Type	ID	Requirement	Design decision	Fulfillment
NF	12.1	The system should be adaptive to volatile institutional reporting obligations and regulation	Decentral governance and system maintenance (6.2), Institutional alignment (6.3)	✓
	12.2	The system should be adaptive to changing roles and responsibilities in the volatile hydrogen certification market	Decentral governance and system maintenance (6.2)	✓
	12.3	The artifact should take local national/municipal varying emission-influencing difficulties into account	Consortium blockchain (5.2.3), Institutional alignment (6.3)	✓
NF	13	The artifact should be scalable to many supplying hydrogen producers (as the hydrogen backbone evolves)	Merging of transactions in off-chain edge computer (5.2.1)	✓
NF	14	The artifact should be robust according to the long-term electrolyzer use-phase (appr. 13 years)	Decentral system maintenance (6.2), Oracles (5.2.1)	✓
NF	15.1	The documentation, reporting, and verification process should be automized	Smart contracts, PoA consensus (6.2), consortium blockchain (5.2.3), single chain (5.2.3)	✓
	15.2	The system should be easy-to-use	Interoperability (5.2.3)	✓
	15.3	The system should facilitate the issuance, transfer, and cancellation of PoS	Smart contracts (6.4), PoA consensus (6.2), consortium blockchain (5.2.3)	✓

The system complies with the required **flexibility** (RQ12) through a decentral system maintenance council which can adapt to changing standards and institutions. If agreed upon, the smart contracts can be adapted whenever changes in the RED II regulations appear. Further, the consortium blockchain allows for the deployment of private channels that can be adapted to the specifics of the associated consortium [1] (Hyperledger, 2020).

The second non-functional requirement is **scalability** (RQ13). Sedlmeir, Völter, et al. (2021) note that the expected user numbers have to be estimated during the initialization of the blockchain as the Merkle tree is dependent on it. The size of the Merle tree should then exceed the number of expected users in the system to comply with the scalability requirement. It is difficult to predict the future size of the hydrogen market as it depends on variables such as the effectivity of hydrogen as an alternative energy source, market acceptance of green hydrogen, and volatile institutional frameworks. Table 7.3 shows the current and projected European hydrogen market. Under the assumption that one hydrogen batch[2] is equivalent to one PoS token on the blockchain, 127.000 transactions would be required per year in 2030. That is without consideration of blue and grey hydrogen transactions. Due to the prerequisite that only certified producers can be onboarded to the system, these transactions can be neglected for now. However, producers cannot produce solely green hydrogen as the renewable electricity input is variable and needs to be compensated with other electricity sources. The smart contracts functions are compatible with qualifying hydrogen colors other than green, but also, in calculating the system's scalability, these extra transactions need to be considered. Regarding the internationally intertwined hydrogen market, the IEA points out that global hydrogen production[3] can reach levels of up to 700 TWh per year by 2030 (Bermudez et al., 2022). Considering this significant market increase, scalability is an important aspect to consider in terms of prospected user numbers and transaction capabilities for the next design cycle of the artifact. Scalability generally suits permissioned consortium blockchains, as permissioned authorities can sign transactions in batches and thus increase the transaction throughput of the system (Zheng et al., 2017). When the system scales, more authorized parties can be installed for transaction validation/signing to comply with the rising transaction numbers. When considering the transaction throughput of the blockchain certification system, the consortium setup helps to avoid transaction costs. However, transaction capabilities of the blockchain system are largely correlated to the consensus mechanism, the latency between network nodes, the number of network nodes, and the data storage (cf. Hyperledger Fabric (2023)). As nodes' geographical locations are settled within the EU and the number of authorities is predetermined through the participating countries, the transaction throughput does not restrict the artifact's success.

Table 7.3: Hydrogen market projection based on Odenweller et al. (2022)

	Green hydrogen in the EU		Projected green hydrogen transactions	
Year	2023	2030	2023	2030
Amount	2.000.000 kWh	127.000.000 kWh	2.000	127.000

Thirdly, **reliability** is mentioned as a performance indicator by the experts for the requirements (RQ14). The financial commitment for an electrolyzer is high and long-term, as mentioned by the expert, around 13 years (I5, A.6). 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) state 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, around 1,60$ per kg, whereas green hydrogen prices fluctuate between 1,86$ and 3,64 $ per kg (Longden et al., 2022). Considering this unstable fluctuating price, a cost- and effort-reducing certification system to keep the long-term administrative costs down is required. Abad and Dodds (2020) state that fees for GOs for green energy range between 0.15 and 0.30 MWh in the UK. Comparing the fees to the potential of the PoA-powered consortium blockchain design, the administra-

[1] reminder: each MS is set up as one consortium
[2] equivalent to 1MWh of energy
[3] in the net zero by 2050 scenario

tive costs could be cut completely. For the hydrogen producer, it only remains the initial investment costs and audit. In the designed artifact, the decentral system maintenance council can adapt the system's software so that the hardware can rely on long-term virtual support. Thus, the system is robust to changes.

The last non-functional requirement is **efficiency** (RQ15). The single-chain design decision facilitates the effectiveness of the maintenance council of the system and the clarity over the entire system. If transactions do not need to be transmitted between multiple chains, the efficiency of the artifact can be preserved. Multi-chains would require synchronization efforts, increasing the artifact's complexity and energy consumption (Ahmadjee et al., 2022). The deployed smart contracts also ensure that emission reporting is conducted automatically (RQ15.1 and 15.3), so the resource commitment for hydrogen production companies decreases, requiring only the management of the sensors and the locally verified data repository. The interoperable character of the system further allows adapting the application interfaces for users to their personal needs. It makes the system easy to use (RQ15.2), while the background data collection and sharing can serve the complex entanglement of green hydrogen standards, mass balancing, and secure information sharing.

Due to the inductive methods of requirements engineering and the requirements-induced design, the evaluation of requirement fulfillment is limited to the findings of the requirements elicitation. Thus, in the next chapter, a naturalistic evaluation method is conducted with expert interviews to include an objective perspective in the evaluation according to Johannesson and Perjons (2021).

7.2. Expert validation

The evaluation of the artifact is continued by consulting six industry experts. Experts can contribute to validating the artifact by applying field knowledge about the hydrogen market and blockchain technology applications. They were chosen to include different evaluation perspectives based on their experience and knowledge in the hydrogen and blockchain economy. Table B.1 provides a detailed description of the chosen experts. The experts include mostly industry experts and potential users of the blockchain system, but also governmental and research institution experts. An interview protocol guides the experts through the artifact design and obtains feedback on each design element (cf. Appendix B). First, the experts answered questions about the technical design choices to receive feedback on how the design decisions can fulfill the requirements. Secondly, the experts reflected on the chosen roles and responsibility allocation. Thirdly, the artifact's institutional alignment was evaluated, and lastly, the proposed process flows were discussed. For each interview, Appendix B entails an anonymized summary of the interview's essential aspects. These summaries serve as input for evaluating and discussing the artifact's feasibility in the sections below. The Chapter is structured followed by the four types of questions asked in the interview: technical, governance, institutional, and societal integration evaluation. The last aspect was not explicitly asked in the interviews but indicated as a critical success criterion for the artifact and is thus included as an additional evaluation factor.

7.2.1. Technical artifact evaluation

The first part of the evaluation interview examined the technical blockchain architecture and its design decisions. The architecture was created to serve the hydrogen certification's main functions, which entails the qualification for one of the hydrogen colors. Secondly, the issuance of PoS tokens should be facilitated, and thirdly, the transfer of the tokens and the cancellation. To evaluate the fulfillment of the main functions of the artifact, the interviewees were asked to reflect on each technical design choice and evaluate to what extent it can fulfill the artifact's main functions. To do so, each design choice is explained to the interviewee and brought in coherence with the artifact's functions. The interviewee reflects on this particular design choice and provides feedback on its feasibility. The comments of the interviewees are used subsequently to nudge a discussion on the technical feasibility and extensibility of the artifact. The results for the particular design choice are highlighted in boxes at the end of the associated section. The evaluation's outcomes can have four dimensions: *Future research, Extension of the artifact, adaption of the artifact, and recommendations*.

Overall impressions of the artifact

In sum, the interviews' outcomes resulted in intense and animated discussions on the technical feasibility of the artifact. The interviewees reflected on the selected design choices concerning their capability of fulfilling the desired functions from a practical perspective. Interviewee I8 (B.2) approved the potential of blockchain to facilitate hydrogen import and track the mix of hydrogen in the grid. Especially considering the unsafe market of importing green hydrogen trustworthy. According to Interviewee I9 (B.3) and I13 (B.7), the technical design choices can indeed facilitate the procedures necessary for effective green hydrogen certification and entail a comprehensive translation of requirements into technical design aspects. Interviewee I12 (B.6) further engaged on the capabilities of blockchain and mentions that it could replace current and legacy systems that save data energy intensive and central.

However, the interviewees I12 (B.6) and I13 (B.7) also expressed general criticism regarding the technical design choices. The nascent top-notch blockchain software on oracles and tokens can induce higher complexity and costs causing rebound effects on the alleged efficiency through implementing the technology. Also, some technologies are not mature enough yet to allow a feasible implementation in the market. Generally, the artifact's technical composition was reflected as highly comprehensive. However, due to the low maturity of the hydrogen market and associated existing blockchain concepts, it was difficult to judge if the artifact was practically sufficient. The discussions about the existing design options and potential extensions are elaborated below and resulted in fruitful advice for the technical artifact and potential extensions.

Decentralized oracles

Oracles were the first technical design option that was highly discussed among the interviewees. According to Interviewee I12 (B.6), oracles are an effective way of connecting the real world with the blockchain world, as the blockchain environment is inherently decoupled from the real world. There needs to be some middleware in place to transport the information from sensors to the blockchain securely, "but then the widespread criticism is when we are working on a decentralized technology like Blockchain and when you are using smart contracts […] to verify and validate the transactions. They [the system creators] also need to make sure that the data that you are receiving is also from a decentralized source […] because if you receive from a centralized source, it could be corrupted." (I12, B.6). To put it differently, if there is only one oracle for communication between on-chain and off-chain, one single point of failure can poison the entire system. The prevention of a single point of failure of the central data repository connected with the oracle can be surrounded by connecting every sensor individually with the blockchain system. However, the direct coupling of sensors with the system is also difficult as sensors are resource-constraint and 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 addressed widely. As mentioned by Al-Breiki et al. (2020) and Mastando (2023), there are different types of oracles for different purposes and security levels. Oracles can be distinguished based on the type of data they process: financial software data, RFID chip/emission data from hardware, or human data. Furthermore, oracles are reciprocal and can function inbound or outbound; for the case of this thesis, the data is collected and fed into the blockchain system. Lastly, oracles can have a centralized or decentralized architecture. A centralized architecture is vulnerable to single-point-of-failure security problems, as mentioned by Interviewee (I12) and by Al-Breiki et al. (2020). However, new developments work towards decentralized oracle infrastructures to ensure the integrity of real-world data and mitigate the single-point-of-failure vulnerability of centralized oracles.

"It's [decentralization] very philosophical in nature as well because decentralization cannot happen in just one layer. It needs to happen in almost all layers of your application, right?" The interviewee implies that the decentralized structure must drag through all layers of the architecture. That means, before implementing the blockchain system, the integrity of the real-world data needs to be addressed by an extensive analysis of different oracle infrastructures; further, the design decision should consider external oracle operators as their service responsibility binds them. Different oracle operation companies are established in the market and can be evaluated to play a role in the blockchain-based hydrogen certification (Schout, 2021). The choice of the Oracle infrastructure determines the confidentiality of the data provided to the public blockchain, the security of the data that enters the system, the availability and real-time properties of the off-chain on-chain communication, the reliability of the data, and the reputation of the stakeholders that provide the data (Al-Breiki et al., 2020). Thus, the stakeholders should be involved in the development.

Future research: Oracles feed real-world data in the blockchain system, but at that point, centralized data collection can be induced opposing the decentralization properties of blockchain technology. Further research into the feasibility of decentralized oracles can enhance the value of the artifact by preventing single-point-of-failure vulnerabilities.

Necessity of ZKP

The second design component that animated strong discussions is ZKP. Generally, in any blockchain design, all the published transactions are visible to all participants in the blockchain (Schellinger et al., 2022). That always induces the question of confidentiality or data ownership towards other parties in the system. According to the technical architecture, ZKP addresses the confidentiality requirement. Through ZKP, parties can prove a specific state of the information without revealing the data itself. It is most commonly used in privacy-constrained environments, whenever one's identity shall stay hidden (Fiege et al., 1987).

After the technical introduction of ZKP, Interviewee I12 (B.6) responded, "If you want to hide some confidential information data, there are multiple ways you can accomplish this." 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 (one more transaction). As seen in the sequence diagram 6.5, the ZKP induces one more computational loop before the hydrogen producer can share the data with the on-chain system. According to the interview, there are easier ways of creating confidentiality for the participants. For example, the consortium blockchain development platform Hyperledger facilitates the creation of private channels with a selected number of users with the private key to enter the system (Hyperledger, 2020). In such channels, hydrogen producers and validators can share data and exclude unwanted participants such as competitors and national authorities. Thus, they can preserve sensitive business data about green hydrogen balances or quantities. Another possibility of anonymization is the so-called hashing of information in Merkle trees (Merkle, 1988). Hashing is a method of reducing data size into an encrypted one-way function. That means only the creator can retrace the origin of the function; other parties cannot reverse engineer the function to identify the creator (Schellinger et al., 2022). This technology allows for confidentiality-conform data sharing without linkage to the identifiable credentials of a hydrogen production facility. The only constraint is that it requires careful management of encryption keys, as disclosure could allow the traceability of identities and reveal confidential data. That means users need to install sufficient control mechanisms in their accounts. Hashes already found application in various scientific blockchain concepts, for example, sustainable asset logging in the energy sector (Djamali et al., 2021). As mentioned in the architecture of this thesis, no raw data is shared because hashes encrypt the data before sharing it (cf. Chapter 5); ZKP would only add an extra level of confidentiality to prove compliance without revealing confidential data.

The interviewee (I12, B.6) adds, "Zero Knowledge Proofs can be extremely expensive. A very, very hot topic when it comes to handling blockchain scalability." To put it differently, ZKP balances at the edge between providing more scalable blockchain solutions but increasing computational complexity and, thus, costs. As mentioned by Sedlmeir, Völter, et al. (2021), the verification through ZK-SNARKS[4] costs around 50$. The deployment of this technology would increase the transaction costs considering that every hydrogen batch equivalent to 1MWh corresponds to one transaction. The actual goal of the blockchain system is to reduce administrative efforts and certification costs. However, the authors also point out that currently fast developments of the ZKP technology would soon be able to compete with regular hardware prices to allow computational processing (Sedlmeir, Völter, et al., 2021). ZKP can increase the scalability as they move computational operations to off-chain computers; however, the individual costs for users rise in terms of variable costs per transaction and fixed investment costs in

[4]SNARKS are a form of ZKP on the Ethereum platform

computational hardware and software. The development of ZKP should be closely monitored to identify the right time for adoption; however, other technologies, such as hashing and private channels, might outscore the benefits of ZKP.

Adaption of the artifact: ZKP can establish complete anonymous and trustworthy proof of information between untrusted parties. However, additional costs and complexities are added, while the anonymity and trustworthiness of data can be ensured through simpler technologies like Merkle trees and Hash encryption. For a minimum viable product, the latter technologies might be sufficient, and ZKP can be considered for further security once the minimum viable product functions.

Tokenization of certificates

The tokenization of digital assets induces another technical challenge. According to the interviews, Hyperledger is one of the most prominent consortium blockchains (I12, B.6). These blockchain types often do not have inherent tokenization. Platforms that use tokens are often coupled with a digital currency, and it is difficult to program such currency. Cryptocurrencies establish over time to receive their intended value, specific smart contracts have to be developed for that, and the minting process, the minting policy, and the burning process must be defined. These procedures induce several additional complexities.

Interviewee I12 reacts, "[…] if you just want to represent a certificate as an asset, for which you can transfer the ownership at a later stage, right?" […] "You can just represent it as an asset that belongs to a particular owner with a particular certificate and a private key." (I12, B.6). Tokenization in the system of this thesis enables the unambiguous identification of ownership. Blockchain inherently entails the identification of transactions based on hashes to identify a transaction with a certain address. The tokenization can add useful properties to the design, such as the fractional ownership of PoS tokens to allow smaller transactions 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 stays an interesting parameter in a future design cycle.

Future research: Tokens can unambiguously assign property of digital assets, in this case, the certificates, and also split ownership of such. Further research could shed light on the benefits of tokens versus traditional identification of ownership through hashes. The additional costs of tokens could increase the monetary adoption barriers for hydrogen producers.

The technical design choices must be considered thoroughly when implementing the artifact, as each 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, ZKP, and tokens can be established when the system evolves.

7.2.2. Institutions and governance

In this section the second part of the design is addressed, the implementation of the blockchain architecture in the ecosystem of hydrogen certification considering the governance of such decentralized architecture and the institutional setting. Throughout the interviews, it appeared that governance plays an essential role because blockchain introduces a paradigm-changing decentralized system structure (I10, B.4; I12, B.6; I13, B.7). The artifact should be aligned with the institutions that set the artifact's boundaries. Subsequently, an evaluation of the artifact's governance mechanisms and institutions' influence is executed.

Roles and responsibilities

Implementing a paradigm-shifting blockchain system in the hydrogen space causes a fundamental change in roles and responsibilities. Throughout the interviews, the proposed task disposition between existing actors is discussed to see how practically feasible the design can be in the current hydrogen field. According to interview I10 (cf. Appendix B.4) and I12 (cf. Appendix B.6 governance is the most critical challenge in developing a decentral hydrogen certification system: “So, governance is a very, very crucial aspect in any blockchain system.” (I10). Either one central party is responsible for pushing it into the market and getting everyone on board, or a collaborative approach is taken, but no one will feel responsible. As commented, “[…] the Dutch Emission Authority says, well, if the market wants this, they need to come with it, and the markets parties say, yeah, we can participate, but the government needs to make it possible. So, they’re all looking at each other for developing and maintaining the system.” (B.4). However, the problem of no central entity feeling responsible for setting up this hydrogen certification system is also an opportunity. Blockchain is a suitable solution for distributed problems where different entities have different roles, stakes, and responsibilities (I10, B.4). Scientific literature examines, for example, blockchain’s impact on cooperation and coordination of organizations (Lumineau et al., 2021). According to the authors, blockchain governance differs from conventional contractual governance because contracts are self-contained and not enforceable promises, the principles are code-based rules and not regulatory law, and the enforcement is automatic and not through third parties. 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 resolved/notified by installing smart contracts.

Other scientific research found that blockchain can reinvent the governance of systems by changing the paradigm from centralization to decentralization. Several scientific articles examined the topic of governance in distributed systems; for example, Beck et al. (2018) and van Pelt et al. (2021) identified six governance dimensions: formation, roles, membership, decision rights, accountability, and incentives. van Engelenburg et al. (2020) bring blockchain governance rights in the context of business and government information sharing and analyze it under blockchain design aspects. Upon this, the interactions of stakeholders mentioned in Chapter 6.4 can be structurally aligned with the technical design choices and reconciliated with governance dimensions described by Beck et al. (2018) and van Pelt et al. (2021).

Extension of the artifact: Considerations about governance dimensions help to determine how the system and cooperation in the system are coordinated. Extending the current maintenance council as a governance mechanism according to the mentioned dimensions can help to complete the artifact’s system governance.

One dimension of blockchain governance is role distribution. In the artifact, the TSOs shall monitor the distribution grids as a second instance to verify the injection and withdrawal of green hydrogen mass-balancing conform. Interviewee I8 reflects that TSOs have solely the duty to guarantee the constant supply of gas/ hydrogen and to ensure the quality of the hydrogen in the market, but “[...] regarding the monitoring of the grid, TSOs are completely colorblind because they do not discriminate, everyone should have access to it.” (I8, B.2). TSOs do not have to or cannot monitor the distribution grids on the hydrogen mix yet, which induces an additional investment to equip the sensors for the distribution grid with the functionality of time-conform measurements. Additionally, TSOs do not have any emission reduction potential to offset carbons yet, so different incentive mechanisms have to be explored to stimulate more granular monitoring of distribution grids and provide beneficial roles for TSOs compliant with requirement RQ8.1 (cf. Table 6.1).

Extension of the artifact: The role and responsibility distribution have to be compliant with the current capabilities of actors for hydrogen certification and must stimulate actors to participate.

Another dimension of blockchain governance is the accountability of errors. Interviewee I13 states, “if there are certain actors that have an incentive to sort of write false information on there [the blockchain]. How do you deal with that?” (I13, B.7). The question is how to deal with deliberate or non-deliberate mistakes in the system; how is it being backtracked and changed? The interviewee continues, “[…] maybe the process must be immutable, right? So, the way in which the smart contract is changed must be subject to an immutable process. [...] the code is mutable, but the governance procedure determines how to change certain things so that there is a fallback option in case of errors in the smart contract." (I13, B.7). Concerning the system's governance, the architecture included two redundant process steps for error-checking on-chain before a transaction is signed and committed to the network. Figure 7.1 illustrates the iterations of data retrieval if the smart contract results do not comply with the physical hydrogen injection in a process diagram. It involves verification through Auditors and TSOs.

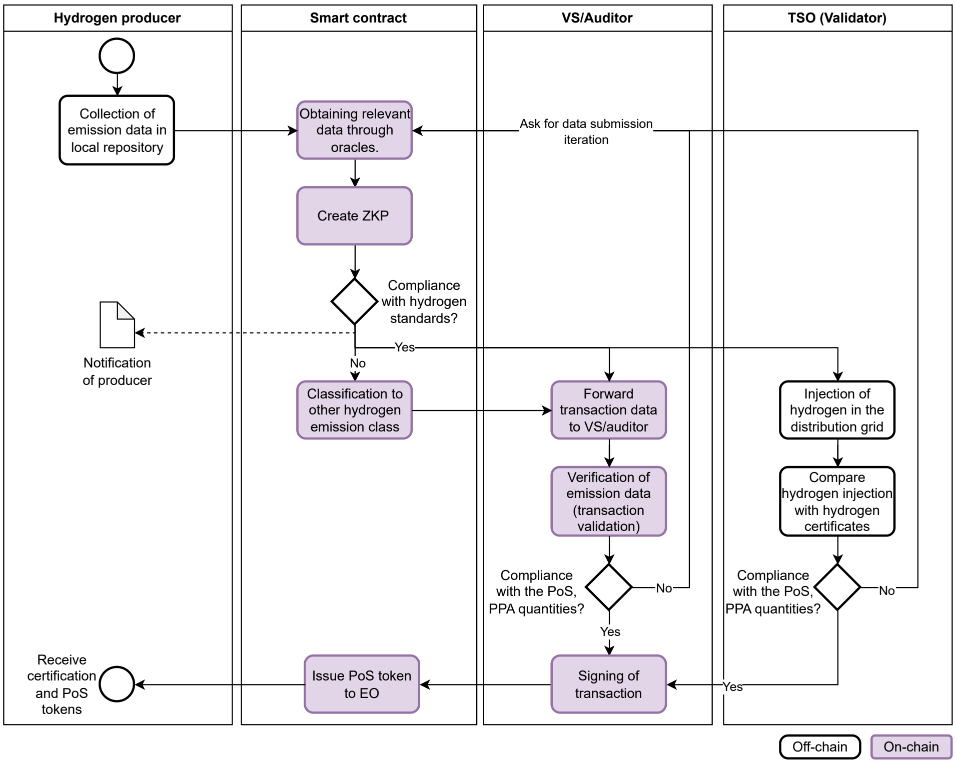

Figure 7.1: Dealing with smart contract errors.

> **Adaption of the artifact: Dealing with errors is an essential component of the governance of information systems. The process flow of how it can be handled illustrates the addition to the artifact.**

As identified by Interviewee I12 B.6, governance is important in contractual agreements on-chain and off-chain. van Pelt et al. (2021) states three governance layers are essential when designing the artifact: off-chain community, off-chain development, and on-chain protocol. The off-chain governance is related to the establishment of a real-life governance council that engages in the development of fundamental system rules and functional agreements for smart contracts. This off-chain council can also continuously adjust changes to the operating system if externalities affect the codified rules on-chain, such as changing institutions.

> **Future research: Governance is vital for the success of complex information systems. The off-chain and on-chain system governance has to be determined to clarify beneficial roles for all participating parties, the rules of interaction, and incentives for participation. Only if these governance dimensions are clarified the success of the artifact can be ensured.**

Institutional integration

The institutional hydrogen market is in a volatile state, as the market's maturity is still in the beginning. It is important to set the institutional direction right upfront so that market participants have a clear room for establishing their business according to the interviews. For example, interviewee I7 (A.8) mentioned in the requirements analysis and system analysis validation that institutions affecting the hydrogen economy are still subject to change. According to the interviewee, an example is the unclear distinction between PoS and GO. Whereas the former relates only to hydrogen production and the actual sustainability of hydrogen by linking it to mass balancing and the specifications of 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, 2022b). The regulation targets a gradual transition from the less specific GO system towards the PoS system: Through that, they want to ensure the true sustainability of the hydrogen and substantially prove the sustainability of each hydrogen batch. By 2030 all hydrogen producers will be obliged to match the green hydrogen production with the electricity supply (EU Commission, 2023b). Interviewee I8 (B.2) supports that the volatile regulations strongly affect the future development of the hydrogen market. The hydrogen market is highly competitive, and producers can choose where to sell their hydrogen. Thus, the artifact's success is dependent on the regulations steering the European Hydrogen market. If the public authorities set high market barriers, hydrogen producers would choose to sell their hydrogen in different countries even though the information system would ease the compliance checking process. However, an extensive analysis of the artifact efficiency and cost reduction would give more insights into how it can influence the adoption willingness of hydrogen producers and to what extent it can stimulate a flourishing green hydrogen market.

Regarding the institutional change in Europe, Interviewee I8 (B.2) continues that it is easy to audit and verify the European hydrogen facilities, but "I also do not know how fraudulent that could be in the end. I mean, for example, within the EU, it is probably easier to do that [verify the production facility], but once you go to get the hydrogen from other countries. [...] there are certain countries that are known to be more corrupt, but those are also the same countries that are likely to be able to produce hydrogen at very low cost." (I8, B.2). The institutional developments of changing from purely claim-based carbon offsetting to actual sustainability measurements might reduce the imbalances of hydrogen production costs (cf. CBAM regulation (EU Commission, 2021)). Recent EU regulation developments aim to make carbon offsetting more substantial and traceable (Segal, 2023). Cheap hydrogen from companies in low-cost countries that are allegedly more corrupt than European companies would have the same price as RED II-compliant hydrogen. As mentioned in the paragraph above, the trade-off between enforcing compliance with green hydrogen standards without expelling international suppliers to sell hydrogen in Europe is important when these regulations are settled. Blockchain technology can help to facilitate transparent and trustworthy information sharing combined with automated compliance verification but cannot mitigate the written rules for selling hydrogen in Europe.

Recommendation: Institutions set the playing room for the actors in the hydrogen market. Setting low barriers for market entrance but effective rules to stimulate the green hydrogen market can standardize the certification procedure and facilitate a flourishing market.

Also, the institutional information systems are questions; for example, Interviewee I11 challenges the connection to the UDB: "They [regulators and the Union Database] want to have everything [emissions, volumes, balances] and basically the big companies, we are working together with Shell, Cargill, and Coca-Cola, you know, big, big companies. They are basically saying, sorry, we are not going to do that. This is not ok. This is competitive information." (I11, B.5). Blockchain can serve as a tool to feed encrypted emission data in the UDB while keeping companies' sensitive data confidential. Blockchain can serve as a mediating party to address the trade-off between compliance and transparency. Another interview adds that an integration of the current certification system with blockchain technology could make the UDB obsolete because "Why would they [EU authorities] want to put that same data in [as a backup]?" (I12, B.6). Blockchain can secure the data tamper-proof and infinitely, so no external backup system is needed, only in case of continuous synchronization with, for example, front-end applications. Considering the development of decentralized systems for certifying green hydrogen, regulators should reconsider the cost- and time-intensive setup of a central server overseeing all hydrogen transactions in the EU. Among others, the UDB is one of the aspects contributing to the current institutional volatility in the hydrogen certification market.

Recommendation: Institutional endeavors of monitoring the hydrogen market need to be aligned with business needs so that a level-playing field is created benefiting reporting effectiveness and the hydrogen market feasibility.

7.2.3. Societal integration

The hydrogen market develops as part of a complex energy sector that is at the forefront of political and public interest. Steady, secure, and sustainable energy supply are among the most important topics in the current political agenda. Accordingly, hydrogen plays an important role in accomplishing this worldwide target. In this sense, the discussions with interviewees resulted in considerations on how such an information system can support the green hydrogen developments in connection with society nowadays. Interviewee I11 (B.5) mentioned that for implementing such disruptive innovation in society, a more socio-technical context analysis could help to predict how users interact with the system so that unknown trade partners can trust each other. Furthermore, considering societal integration helps align the new system with conventional legacy systems in place. The hydrogen market is evolving globally, and hydrogen producers could benefit from platform integration with external systems of other countries and maybe other blockchain systems. Connecting large hydrogen markets with an information system can be the underlying trust system between many parties in an untrusted environment. The interviewee suggests making a more in-depth analysis of the interactions of actors in the hydrogen market and classifying between types of interactions.

The study largely relies on existing literature and how blockchain is applied in similar cases, providing a future development basis. However, Interviewee I11 (B.5) suggests that adding a scenario analysis would enhance the knowledge about the applicability of the artifact and how suitable design choices are for different types of applications of the artifact. For example, Interviewee I11 illustrates the usefulness of scenarios to evaluate tokenization: if there is a transaction between a business and the EU government to track all the emissions in the EU “[…] and you attribute that as purpose to this platform, then you can say if this is the purpose of the platform, the EU needs a trusted data source as a central bank, if you will, to issue, manage, account, and police all those different actors, then that drives maybe the functional requirement to say tokenization is best to do that because it allows the EU to do XYZ.” Integrating the possible interactions between stakeholders in the artifact design is a valid approach to drawing a line to the real world. At the moment, the artifact focuses on the functionality of the hydrogen producer, the needs of the perspectives of hydrogen buyers and traders, the regulatory bodies, and other societies can be considered in a subsequent research project to receive more insights into how the artifact would satisfy their needs.

Future research: Potential stakeholder interactions with the artifact can enhance the tests toward real-world applicability and should be considered in further research.

Furthermore, Interviewee I11 (B.5) introduced different trade scenarios imaginable in a future hydrogen market. Applying these scenarios with the artifact would give substantial insights into the artifact’s feasibility in serving the holistic hydrogen market. According to evaluation methods of design science research introduced by Peffers et al. (2012), illustrative scenarios can support the applicability of the artifact in the societal context. An illustrative scenario is an ”Application of an artifact to a synthetic or real-world situation aimed at illustrating the suitability or utility of the artifact.” (Peffers et al., 2012). Different scenarios can be imagined for the hydrogen market trade movements, and for each of the scenarios, the utility and viability of the artifact can be evaluated. Figure 7.2 an overview of four imaginable trade scenarios in the hydrogen economy is provided, and each of the scenarios would have different effects on the artifact’s evaluation.

Case one represents the research design of the thesis. Following the European Union’s planned developments, the hydrogen backbone’s successive creation, hydrogen would be distributed in gas pipelines which can be measured at injection points and withdrawal points to verify data on the hydrogen mass balance in the EU. The second case covers the domestic trade and usage of hydrogen, which can be monitored by domestic means; in this case, blockchain technology can prevent double counting when hydrogen moves across borders. The third case comprises two subcases: an onsite closed system and a closed system with separated owners. The former could be a Dutch steel plant installing a local electrolyzer to feed the steel-making process with green hydrogen instead of fossil gas, according to Interviewee I11 (B.5). The latter could be so-called hydrogen valleys such as NorthH2 (NortH2, 2023) and form consortia of different actors along the hydrogen value chain such as electricity producers, hydrogen producers, processors, distributors, and users. In these consortia, the hydrogen value chain is to be fully integrated with the local smart grid so that grid balancing can be more effective. In the fourth case, hydrogen could be imported from countries outside the EU. Import will play a significant role in the hydrogen strategy of the European Union, making up approximately ten million tonnes of hydrogen by 2030 (EU Commission, 2023a). Considering the institutional difficulties when it comes to monitoring the provenance of imported goods, the scenario plays an essential role in the artifact of this thesis. The implications of each scenario for the artifact are summarized in Table 7.4.

Figure 7.2: Hydrogen trade scenario analysis.

Future research: Scenario analysis has a significant impact on scientific research. Considering the introduced scenarios, future research can investigate the feasibility of blockchain-based hydrogen certification for different hydrogen trade scenarios covering the paths of the hydrogen market development.

Table 7.4: Implications of the scenarios for the artifact.

Trade scenario	Implications
Case 1: Intra-Europe trade and transport	Case one represents the initial case chosen for the design of the artifact 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 artifact at hand.
Case 3: Closed system onsite	Green hydrogen certificates play a role in proving emission intensities to European authorities. Thus, the certificates are needed by the user of green hydrogen. If the producer is the same entity as the user, the blockchain system still needs to be used even though the closed loop cycle would do not require certificates as trustworthy proof for the hydrogen user.
Case 3: Closed system separated	Separated closed systems function through contractual arrangements among trusted consortium partners, for instance, NortH2. They usually maintain distinct information systems, ensuring their autonomy from the EU hydrogen grid. Despite this autonomy, it remains crucial to include their needs in developing the underlying artifact, given that such closed systems contribute significantly to green hydrogen production within the EU. The hydrogen valleys within the third case hold particular importance in efficiently shaping the hydrogen market. These clusters, featuring harmonized production and demand, facilitate the rapid establishment of isolated hydrogen distribution networks. In the future, these independent clusters could eventually be connected through corridors, paving the way for the eventual creation of a comprehensive 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 to ensure trust across EU borders. It is to be considered in future research.

7.3. Conclusion

In this Chapter, the fourth step of the design cycle of Peffers et al. (2007) was conducted: Evaluation of the artifact. The following research question addressed the design step: *How feasible is a blockchain-based hydrogen certification system for the hydrogen production market?* Upon this subquestion, the evaluation strategy of Venable et al. (2016) was followed to provide a summative evaluation of the artifact. In the first step, the fulfillment of the system requirements was analyzed, resulting in fulfillment of 95,8%. Modularity/Interoperability and openness were not fulfilled, however, their importance for the system's main functions was deemed nonessential. Additionally, the non-functional requirements were examined to give insights into the utility of the artifact regarding flexibility, scalability, stability, and efficiency.

In the second step, the evaluation was enhanced by expert interviews. The experts were asked to reflect on the technical architecture, the institutions and governance, and the societal integration. For each of the aspects of the artifact, the experts gave insights based on their background knowledge. The insights were clustered in four dimensions of implications for the underlying artifact: *Future research, Extension of the artifact, adaption of the artifact, and recommendations*. It could be found that the complexities and costs of some technical design choices play a significant role in setting up the system. Moreover, the institutional environment is still fragile and needs to be monitored closely. The system's governance is the fundamental criterion for success and needs to be examined in-depth before implementing the artifact. Lastly, different trade scenarios exist in the current hydrogen economy; these need to be considered before proceeding with the artifact implementation. The evaluation resulted in helpful additions to the initial design, which can enhance the feasibility of a future artifact. The resulting implications for the design can be found in Table 7.5.

Table 7.5: Implications of the scenarios for the artifact.

Design aspect	Dimension	Implications
Technical artifact (Oracles)	Future research	Oracles feed real-world data in the blockchain system, but at that point, centralized data collection can be induced opposing the decentralization properties of blockchain technology. Further research into the feasibility of decentralized oracles can enhance the value of the artifact by preventing single-point-of-failure vulnerabilities.
Technical artifact (ZKP)	Adaption of the artifact	ZKP can establish complete anonymous and trustworthy proof of information between untrusted parties. However, additional costs and complexities are added, while the anonymity and trustworthiness of data can be ensured through simpler technologies like Merkle trees and Hash encryption. For a minimum viable product, the latter technologies might be sufficient, and ZKP can be considered for further security once the minimum viable product functions
Technical artifact (Tokenization)	Future research	Tokens can unambiguously assign property of digital assets, in this case, the certificates, and also split ownership of such. Further research could shed light on the benefits of tokens versus traditional identification of ownership through hashes. The additional costs of tokens could increase the monetary adoption barriers for hydrogen producers
Institutions and governance (Governance dimensions)	Extension of the artifact	Considerations about governance dimensions help to determine how the system and cooperation in the system are coordinated. Extending the current maintenance council as a governance mechanism according to the mentioned dimensions can help to complete the artifact's system governance.
Institutions and governance (Roles and responsibilities)	Extension of the artifact	The role and responsibility distribution have to be compliant with the current capabilities of actors for hydrogen certification and must stimulate actors to participate.
Institutions and governance (Dealing with errors)	Adaption of the artifact	Dealing with errors is an essential component of the governance of information systems. The process flow of how it can be handled illustrates the addition to the artifact.
Institutions and governance (On-chain and off-chain alignment)	Future research	Governance is vital for the success of complex information systems. The off-chain and on-chain system governance has to be determined to clarify beneficial roles for all participating parties, the rules of interaction, and incentives for participation. Only if these governance dimensions are clarified the success of the artifact can be ensured.
Institutions and governance (Institutional market barriers)	Recommendations	Institutions set the playing room for the actors in the hydrogen market. Setting low barriers for market entrance but effective rules to stimulate the green hydrogen market can standardize the certification procedure and facilitate a flourishing market.
Institutions and governance (Business-government alignment)	Recommendations	Institutional endeavors of monitoring the hydrogen market need to be aligned with business needs so that a level-playing field is created benefiting reporting effectiveness and the hydrogen market feasibility.
Societal integration (Stakeholder interactions)	Future Research	Potential stakeholder interactions with the artifact can enhance the tests toward real-world applicability and should be considered in further research.
Societal integration (Hydrogen trade scenarios)	Future Research	Scenario analysis has a significant impact on scientific research. Considering the introduced scenarios, future research can investigate the feasibility of blockchain-based hydrogen certification for different hydrogen trade scenarios covering the paths of the hydrogen market development.

The interviews mirrored the expectations from the hydrogen market, embossed by the unclarity of technical specifications of hydrogen production, volatile regulatory developments, and lack of experience in hydrogen certification. However, the interviews animated interesting discussions about potential developments and how these developments influence the hydrogen market. Merging the results of the interviews provided a comprehensive picture of the unclarities and open questions to be answered by authorities and blockchain practitioners. Subsequently, the thesis's overall conclusions are recapitulated.

8 Conclusion

The last Chapter of the thesis answers the main research question and summarizes all results found throughout the research project. First, an overview of the outputs of each research design step is given according to the research flow diagram 2.3. Second, practical implications for hydrogen producers, specifically, and society, in general, are provided. The third step includes the contribution to science, which is twofold: contribution to the identified knowledge gap and the DSR approach. Finally, a future research outlook, the limitations of the thesis research, and the connection to the complex socio-technical research field are provided.

8.1. Conclusions

The thesis introduced a design aimed at addressing the trust issue in the hydrogen economy by focusing on the certification of green hydrogen and transparent data-sharing, thereby contributing to the growth of the hydrogen production market. Upon this issue, the study analyzed blockchain technology's potential to facilitate secure and automated certification processes. DSR is the chosen approach as guidance throughout the research to address the main research question:

MRQ: What blockchain-based IT architecture can support the requirements for reliable green hydrogen certification in the European Union?

In conclusion to the results of the research approach throughout this study, the MRQ can be answered. Out of the need for a credible hydrogen certification system, an extensive requirements analysis was conducted. On this basis, a decentralized blockchain information infrastructure was created to support the requirements of the complex stakeholder field for hydrogen certification. Blockchain has by now a vast field of software specifications that can aid trustworthy information sharing along complex supply chains with asymmetric information distribution. Each of the relevant requirements can be addressed by the blockchain-IoT architecture and thus provides a competitive alternative to traditional centralized certification of green hydrogen. As analyzed in the implementation phase of the artifact, the design can likewise facilitate the reporting, data verification, PoS token issuance, and cancellation in compliance with the RED II regulation on hydrogen. The volatile institutional setting and the far-ahead expansion of the hydrogen market (2030-2040) induce uncertainties in the design but allow expanding research on the artifact's practical feasibility to ensure the reliable greenness of hydrogen. Henceforth, hydrogen market players, regulators, and facilitating actors can rely on the functionalities of blockchain for facilitating effective green hydrogen certification in a trustful manner.

To help answer the main research question, five SQs were formulated according to the DSR design cycle of Peffers et al. (2007) (cf. 2.2. The answer to each of the SQs accumulates to the main research question. The first SQ relates to the DSR approach's first step: Problem motivation and identification.

SQ 1: What is the complex socio-technical hydrogen certification system in the European Union?

The SQ was divided into three topics addressing the stakeholder relationships, the institutional framework, and the technical composition of the hydrogen certification system in the European Union. First, the **stakeholders** were analysed: *a) Who are the stakeholders involved in the hydrogen value chain, and what are their roles?* The stakeholder analysis identified the relevant parties involved in the hydrogen certification field, analyzed their interactions, and displayed the current or planned information systems to facilitate the certification process. The business actors entail the hydrogen producers[1], the hydrogen buyer, and the hydrogen users. The main institutional influence comes from the European Commission, which sets the regulatory framework for hydrogen certification in the RED II regulation. Based on this framework, the member states' authorities enforce the rules nationally. To achieve the enforcement of institutions, multiple facilitating actors are in place: the Voluntary Scheme providers, the issuing bodies, and the auditors. The national registries and the Union Database serve as information systems to facilitate certain interactions between the parties, such as monitoring and compliance reporting.

Secondly, the **institutional framework** outlined by the RED II regulation of the European Commission is analyzed: *b) What is the institutional framework for green hydrogen certification in Europe?* In Europe, the Renewable Energy Directive and two associated Delegate Acts form the institutional framework for hydrogen certification, emission reporting, and compliance requirements. The first Delegated Act defines the rules for qualifying as green or renewable RFNBO[2], and the second Delegates Act outlines the calculation methods of GHG emission reduction we should at least be 70% compared to fossil energy source the hydrogen is replacing (EU Commission, 2023b). The Chapter gives an outline of what these institutions entail and what effect they have on the hydrogen certification. They differ from conventional GO certificates in temporal and geographical correlation, additionality, and grid or direct connection to the electricity source. Thus, extending the current certification toward more granular information can serve the institutional requirements mentioned above.

To conclude the first step of the design cycle, the **technical composition** of the hydrogen certification scheme is outlined: *(c) What is the technical certification system facilitating the European green hydrogen market?* In this Section, the processes of the current GO certification and proposed adaptions toward the new PoS certifications are analyzed - including an analysis of the planned Union Database to store all hydrogen transactions in the European Union. This Section also captures how actors are involved with the information systems and the certification process. Thus, the following design phase considered that the EU RED II regulation is still developing and subject to changes.

The actor analysis and system processes were positively approved by the expert interviews. However, often experts are still not certain about the actual functioning of these regulatory mechanisms. In general, it can be concluded that the connection of theoretical institutions on green hydrogen and the practical execution and enforcement of these rules diverge and cause unclarities for hydrogen market actors. This observation creates an opportunity for the artifact of this study to solve the discrepancy so that hydrogen market actors and regulators can be connected with an equality- and transparency-embracing information system. Hydrogen producers have a stable and trust-creating information system to prove the greenness of the hydrogen and regulators can trust the certification through the blockchain system. Based on the system analysis, the second SQ addressed the next step of the design cycle of Peffers et al. (2007):

SQ 2: What are the design principles and requirements for a blockchain-based information-sharing infrastructure for hydrogen certification?

In the second step of the research expert interviews were conducted to identify requirements for a blockchain-based hydrogen certification system. The system analysis of Chapter 3 in combination with the expert interviews results in four design principles that guided the artifact design (cf. Chapter 4):

- DP1: RED Compliance
- DP2: System Modularity

[1] the economic operators
[2] among others hydrogen

- DP3: Certification automation
- DP4: Traceability
- Governance

Throughout the interviews, it appeared that system governance plays a decisive role in the success of the artifact. Furthermore, one more category of unspecified requirements was created because some requirements could not be assigned to one of the design principles. Subsequently, in the thesis, the systems engineering approach of ISO 21840 (2019) and ISO 29148 (2018) is followed to identify and structure requirements for the artifact design. Seven experts contributed to determining relevant system requirements for the artifact. The high-level requirements and the assignment to the belonging design principles can be seen in Table 8.1; a more detailed description and the low-level requirements can be found in Table 4.1. Each high-level requirement comprises a bundle of lower-level requirements. The requirements serve as input for the artifact design.

Table 8.1: High-level requirements.

Type	ID	Higher-level requirement	Traceability
F	1	Granular monitoring of value chain steps	DP4
F	2	Reliable data collection	DP4
F	3	Traceability of emissions	DP4
F	4	Auditability/ Verifiability	DP3
F	5	Confidentiality preserving	Unspecified
F	6	Compatibility/ Interoperability	DP2
F	7	Openness	Governance
F	8	Allocation of roles and responsibilities	Governance
F	9	Security	Unspecified
F	10	Compliance with RED II	DP1
F	11	Standardization	DP1
NF	12	Flexibility	DP2
NF	13	Scalability	DP2
NF	14	Stability	DP2
NF	15	Efficiency	DP3
Human Factor	16	Externalities consideration	Not considered
Human Factor	17	Safety	Not considered
Usability	18	Financial incentive	Not considered

Interestingly, the interviewees' requirements input diverged largely. Experts from diverse fields had fundamentally different expectations and requirements for the certification of hydrogen. Intersections emerged at emission monitoring, data reliability, compliance, and standardization. However, many requirements are proposed by single needs and denied unambiguous assignment to the design principles. It resulted in unspecified requirements that did not appear throughout the system analysis of SQ1. The identified requirements were then structured to serve the next step of the research. The third step of the design cycle is the artifact design. To address this research step, the following research question was taken as guidance:

SQ 3: What are the technical design components for a blockchain-based IT architecture for hydrogen certification?

In this research step, a blockchain-IoT architecture framework was developed based on existing blockchain-IoT literature, serving as a level-based design framework for the artifact. Four levels were identified as relevant for the artifact design: The perception, communication, blockchain, and application layer. The framework focused on the blockchain layer, divided into four sublayers: The data, network, incentive, and service sublayers. For each layer, design decisions were discussed, bound by the requirements of the experts. Next to the layers, two more design aspects were considered: Security, privacy, and extensibility. According to the requirements identified in the interviews in the second SQ, these play a significant role in the success of the artifact. The result is a technical architecture framework with design choices that facilitate the requirements for a blockchain-based hydrogen certification, as seen in Figure 8.1.

One part of the artifact design is the demonstration of the artifact according to Peffers et al. (2007). To address this step of the design cycle, the following SQ is taken as a guide:

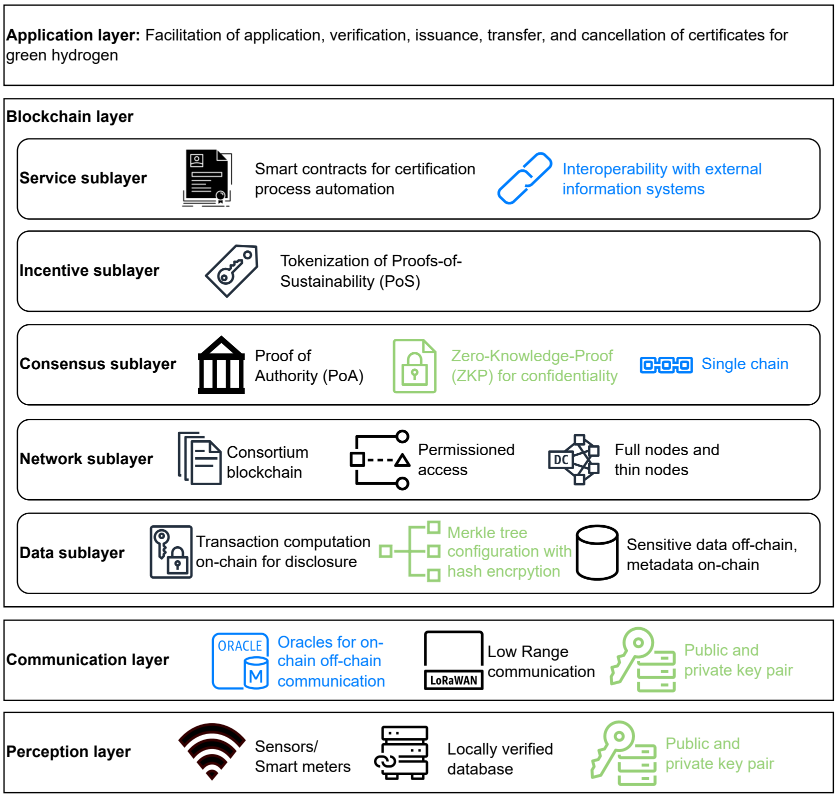

Figure 8.1: Overview of design choices.

SQ 4: How can a blockchain-based IT architecture design be implemented in the socio-technical hydrogen certification industry?

First, a holistic architecture model was presented to address this research question showing the main architecture layers and the technical design components with interactions and alignment of the application layer. Figure 6.1 shows the technical architecture model from the perspective of one hydrogen production facility. The data is collected in a local repository and managed by an external manager; the physical layer then communicates through oracles with the blockchain. On the chain, smart contracts automate the verification process; while Issuing bodies, TSOs can sign and validate transactions, and hydrogen buyers can read the information. Through NFTs with fractional ownership, the PoS certificate can be identified and traded following the physical hydrogen flow. Secondly, the system's governance was addressed by clarifying the roles and responsibilities distribution. The Section outlined the PoA consensus mechanism's workflow and the system governance's foundation. Hydrogen producers nudge transactions through the data collection of the hydrogen production process. The smart contracts capture the transaction on the chain, which is forwarded to the validator nodes that can sign or reject the transaction. All accepted transactions get merged into a block and sent to the system for peer-to-peer validation. The validated transactions are published and visible to all parties with reading rights. An off-chain maintenance council is responsible for updating the design to institutional changes, sustaining fair standards, and addressing errors in smart contracts and security issues. Third, the system was aligned with the institutional framework, particularly the Union Database and National registries that are in place to monitor the entire European hydrogen market. For each actor (governmental, business, and facilitators), the access rights and interactions with the blockchain system were displayed as shown in Figure 6.4. The fourth step of Chapter 6 entails a detailed description of the new processes induced by the integration of the artifact in the hydrogen certification environment (cf. 6.4). The processes entail onboarding hydrogen facilities, data verification, PoS token issuance, and transferring and canceling the PoS tokens. In sum, Chapter 6 gives an overview of the system implementation in the hydrogen certification market.

Notably, the system implementation was increasing the complexity of the artifact significantly. When implementing a paradigm-shifting information infrastructure in the hydrogen certification market many institutional boundaries, actors in the certification field, and societal matters must be considered. It tests the artifact's feasibility based on the case of hydrogen distribution through gas grids, leaving out other distribution paths. Also, connections to international institutions and actors were neglected. Incorporating these aspects in the design resulted in open issues of blockchain-based hydrogen certification and future research opportunities. The last step of the thesis was dedicated to evaluating the artifact, in line with the fourth step of the DSR approach of Peffers et al. (2007). The following SQ addresses the evaluation:

SQ 5: How feasible is a blockchain-based hydrogen certification system for the hydrogen production market?

In Chapter 7, according to design science evaluation strategies of Venable et al. (2016), the fulfillment of the requirements was first analyzed. It appeared that 95,8% of the lower-level requirements are fulfilled, and the artifact lacks international institutional alignment and fairness towards hydrogen producers complying with international certification schemes. The non-functional requirements enabled a performance analysis. The system is flexible to changing institutions as the off-chain governance council can act independently off-chain and make amendments to the written smart contract code. It was also found that the system size should be estimated precisely to prevent scalability issues when the hydrogen market is expanding. Moreover, the system's reliability should be ensured according to the long-living electrolyzers, so the processes of the software updates shall be standardized and amendments comply with the hardware prerequisites of hydrogen producers. Efficiency is the last performance requirement. A single-chain approach was used to facilitate fast transactions and prevent additional complexities of cross-blockchain communication issues. Smart contracts automate reporting, verification, certificate issuance, and cancellation processes and thus can improve efficiency.

In the second step, a naturalistic evaluation with expert validations was conducted. In this way, the artifact can be evaluated in the context of the hydrogen economy, focusing on the hydrogen producer. The experts were asked to reflect on the technical design, institutional alignment, system governance, and general societal integration. Regarding the **technical artifact**, it was found that oracles can induce a centralization problem, and additional analysis on decentralized oracles or other alternatives needs to be conducted. Also, ZKP is still in a very nascent stage and induces high additional costs for hydrogen producers; other alternatives might serve just as well for an initial prototype. Moreover, tokenization can be a complex and cost-intensive process involving several steps for creation, establishment, and maintenance. **Governance** was identified as the key element for the artifact's success. Different government dimensions can be applied in future research to facilitate cooperation and coordination for actors working with the artifact. The roles have to be distributed in consensus with the associated parties, and the dealing with errors has to be clarified (cf. Figure 7.1). In general, governance has to be determined on-chain, off-chain, and in interrelation to clarify beneficial roles for all participating parties, the rules of interaction, and incentives for participation. For the **institutions**, it was found that the volatile state is influencing the artifact's success. Too extensive compliance criteria could reduce the willingness to sell hydrogen in Europe compared to other markets. Even a cost-reducing artifact would have problems coping with this. Furthermore, a trade-off was found between enforcing compliance for international hydrogen producers without expelling these from the European market. The artifact can facilitate trusted information-sharing but cannot influence the written rules for compliance. Regarding institutional integration, the artifact will likely replace centralized information systems such as the Union Database or at least make them obsolete. Lastly, the **societal integration**, in general, is addressed. Different trade scenarios can be imagined when visualizing the holistic hydrogen market; the artifact feasibility should be elaborated under different application cases to ensure its wide adoption. Four different cases could be imagined as found in this thesis, while transactions and changing interests of stakeholders have not been included yet (cf. Figure 7.2). In sum, each of the evaluation points resulted in specific implications for the design that can be either *indications for future research, adaptions to the artifact, extensions to the artifact, or recommendations for policy makers*. The summary of the implications can be seen in Table 8.2 below.

Table 8.2: Implications of the scenarios for the artifact.

Design aspect	Dimension	Implications
Technical artifact (Oracles)	Future research	Oracles feed real-world data in the blockchain system, but at that point, centralized data collection can be induced opposing the decentralization properties of blockchain technology. Further research into the feasibility of decentralized oracles can enhance the value of the artifact by preventing single-point-of-failure vulnerabilities.
Technical artifact (ZKP)	Adaption of the artifact	ZKP can establish complete anonymous and trustworthy proof of information between untrusted parties. However, additional costs and complexities are added, while the anonymity and trustworthiness of data can be ensured through simpler technologies like Merkle trees and Hash encryption. For a minimum viable product, the latter technologies might be sufficient, and ZKP can be considered for further security once the minimum viable product functions
Technical artifact (Tokenization)	Future research	Tokens can unambiguously assign property of digital assets, in this case, the certificates, and also split ownership of such. Further research could shed light on the benefits of tokens versus traditional identification of ownership through hashes. The additional costs of tokens could increase the monetary adoption barriers for hydrogen producers
Institutions and governance (Governance dimensions)	Extension of the artifact	Considerations about governance dimensions help to determine how the system and cooperation in the system are coordinated. Extending the current maintenance council as a governance mechanism according to the mentioned dimensions can help to complete the artifact's system governance.
Institutions and governance (Roles and responsibilities)	Extension of the artifact	The role and responsibility distribution have to be compliant with the current capabilities of actors for hydrogen certification and must stimulate actors to participate.
Institutions and governance (Dealing with errors)	Adaption of the artifact	Dealing with errors is an essential component of the governance of information systems. The process flow of how it can be handled illustrates the addition to the artifact.
Institutions and governance (On-chain and off-chain alignment)	Future research	Governance is vital for the success of complex information systems. The off-chain and on-chain system governance has to be determined to clarify beneficial roles for all participating parties, the rules of interaction, and incentives for participation. Only if these governance dimensions are clarified the success of the artifact can be ensured.
Institutions and governance (Institutional market barriers)	Recommendations	Institutions set the playing room for the actors in the hydrogen market. Setting low barriers for market entrance but effective rules to stimulate the green hydrogen market can standardize the certification procedure and facilitate a flourishing market.
Institutions and governance (Business-government alignment)	Recommendations	Institutional endeavors of monitoring the hydrogen market need to be aligned with business needs so that a level-playing field is created benefiting reporting effectiveness and the hydrogen market feasibility.
Societal integration (Stakeholder interactions)	Future Research	Potential stakeholder interactions with the artifact can enhance the tests toward real-world applicability and should be considered in further research.
Societal integration (Hydrogen trade scenarios)	Future Research	Scenario analysis has a significant impact on scientific research. Considering the introduced scenarios, future research can investigate the feasibility of blockchain-based hydrogen certification for different hydrogen trade scenarios covering the paths of the hydrogen market development.

Nonetheless, introducing a new technology in the market cannot be proven unless practically tested according to the philosophical principle of Collingridge (1982). Testing the artifact in real-life cases with a minimum viable product and iterative addition of complexity would ground the artifact's feasibility evaluation.

8.2. Societal contribution

For complex systems research, identifying the societal effects of technology can cover the impact dimensions of technological interventions in society. According to Bornmann (2013), there are four dimensions of the societal impact of scientific research: social, cultural, environmental impact, and economic returns.

8.2.1. Social impact

Social impact refers to the research's impact on the social capital of a nation in terms of providing new approaches to social issues, policymaking, or stimulating public debate (Bornmann, 2013). The European policymakers are working towards standardized institutions for green hydrogen supply in the EU following international policies (dena - German Energy Agency, 2023). However, the current developments are uncertain and induce uncertainties for the hydrogen market. Producers have cumbersome reporting processes and unclarity about how and what to report, consumers need more transparent information about hydrogen consumption, and policymakers need help conserving reliable reporting and hydrogen qualification. This thesis argues that the blockchain-IoT artifact can serve policymakers and businesses as a tool to facilitate hydrogen certification in compliance with EU regulations, automated processes, and transparent information while introducing secure decentralized governance mechanisms.

8.2.2. Cultural impact

The cultural impact can be categorized as contributions towards society's cultural capital (Bornmann, 2013), for example, preserving a society's culture and stimulating creative community interaction (Department of Education, Science and Training, 2006). Blockchain technology can make it possible to revolutionize the interactions of actors by making them transparently visible and immutable to changes (Lemieux, 2017). Actions can be seen, documented, and allocated. In this sense, blockchain also greatly influences sustainability by accounting for emissions reliably and keeping an immutable record. In the artifact, NFTs bind emissions in the hydrogen production process to an identifiable user and pinpoint their origin. In this way, the artifact can creatively stimulate new forms of interaction between government, businesses, and consumers. The actors can allocate emissions, have an overview, and be aware of them. Thus, the artifact can contribute to a sustainable European society by making them aware of emissions in the hydrogen space and giving them a chance to decide for themselves about the approval or denial of hydrogen usage.

8.2.3. Environmental impact

Environmental impact is defined as the contribution to the natural capital of society (Bornmann, 2013); in other terms, the artifact's contribution to climate change. According to the IEA (source hydrogen review 2022), hydrogen plays a significant role as an alternative energy carrier. Integrated into the European Hydrogen Strategy (EU Commission, 2023a), it is identified that EU hydrogen is only 2% from renewable production, with the proposed plan to produce and import 20 million tonnes of green hydrogen by 2030. An informational infrastructure is needed to support the hydrogen provenance's transparency and ensure it towards consumers and regulators. In this way, the artifact can contribute to sustainable development goal seven: "Ensure access to affordable, reliable, sustainable and modern energy for all" (United Nations, 2022). Further, it contributes to fostering innovation in information systems research in tackling climate change and thus contributes to SDG 11 (United Nations, 2022).

However, blockchain technology faces negotiable criticism for having adverse effects on energy consumption. Most PoW-based blockchains consume tremendous energy, such as Bitcoin about 170 TWh annually as much as entire countries (Marr, 2023). Also, other platforms such as the Proof-of-Stake platform Solana cause approximately an annual carbon footprint of 3412 tonnes CO2 (Cheikosman & Mulligan, 2023). Considering these developments, current political and private endeavors strive for environmentally-benign blockchain-based solutions. Such can be the cause of usage, as blockchain can help to trace emissions and identify causes, as well as allocate responsibility for emissions (European Commission, 2023a; Friedman & Ormiston, 2022). But also includes technological development of sustainable blockchain concepts such as Proof-of-Authority, or Proof-of-History suggested by the World Economic Forum in Cheikosman and Mulligan (2023). The sustainability backfire effect can be prevented if technology and purpose are thoroughly chosen.

8.2.4. Economic impact

Economic impact means contributing to a society's economic capital, namely reduced costs or improved service quality, but also unquantifiable economic benefits from policy impact (Bornmann, 2013; Department of Education, Science and Training, 2006). The economic impact of this thesis is twofold: first, the conceptual blockchain architecture has the potential to create added value by automating reporting processes and creating a trustful business environment; secondly, the artifact can contribute to public policymaking by evaluating new decentralized governance models in the business to government information sharing context. The former economic impact denotes the impact of the technical artifact. The thesis found that automatizing data collection and verification can facilitate reporting. Hydrogen producers can benefit from it by sparing valuable business resources otherwise used for compliance reporting. Furthermore, through integrity-ensuring data collection, hydrogen producers can increase the trust of consumers/buyers and thus establish long-term business relations. Secondly, the policymakers benefit from the new form of decentral information sharing because it spares the maintenance of sizeable central service systems, which are prone to single-point-of-failure, and tend to turn into data dumps. The blockchain is an alternative to cope with the unbalanced standards for hydrogen certification in different nations while securing hydrogen supply in the globally competing hydrogen market. An efficient tool would lower the market entrance and administrative barriers for international hydrogen suppliers. It can benefit a stable European hydrogen supply, one of the primary objectives of the RED II regulation (EU Commission, 2023a).

Not to underestimate is the economic commitment to take within participating organizations and for setting up the infrastructure. Traditional companies have low touching points with decentralized technologies lacking human resources and technological software and hardware infrastructure. Changing to the paradigm-shifting blockchain technology requires large technology investments and structural changes within organizations and is often accompanied by doubts and fears (Saberi et al., 2019). Nonetheless, the authors emphasize that the environmental and economic long-term effects benefit a sustainable company strategy when implemented thoroughly and inclusively with all stakeholders. These effects are also driven by customers' demand for transparent sustainability. Thus, in the context of hydrogen supply, transparency is pivotal in shaping the long-term economic objectives of green hydrogen producers, ensuring their ability to meet the EU's hydrogen demand while maintaining trustworthiness.

8.3. Scientific contribution

Next to the artifact's practical impact, DSR aims to contribute to its underlying foundations and methodological approach (Hevner et al., 2004). Baskerville et al. (2018) argue that within DSR in information system research, the technical IT artifact and the design theory contribute inseparable and cohesive to research and practice.

First, in the research, we provided an overview of scientific, business, and institutional documentation for hydrogen certification and blockchain technology. To the best of the knowledge of this thesis's author, scientific research on blockchain in combination with hydrogen certification is scarce. The study found that blockchain research has not addressed the implementation of blockchain as a tool to ensure trustworthy information exchange in the hydrogen certification field (see Chapter 1.3). The articles from the fundamental literature review only problematize the trust issue in information on hydrogen provenance but do not provide specific solutions. This research combines a comprehensive analysis of the market needs for reliable green hydrogen certification with the technical capabilities of blockchain technology as a credible solution to aid the search for hydrogen certification benefiting the market and authorities. Particularly, the thesis was able to show that the hydrogen market evolves fragmented, many local hydrogen valleys in Europe, and international green hydrogen production plants appear. Aligning the complex needs of such fundamentally differing stakeholders for importing hydrogen or supporting local production needs stable and effective institutions. The connection to blockchain showed that decentralized information systems can address fragmented stakeholders in decentralizing information infrastructures to divide coordination and monitoring efforts among all participating parties.

Second, in the thesis, scientific research on blockchain architecture design, IoT system architecture, and their intersection was accumulated. On the one hand, this approach extends scientific research on blockchain architecture design, which needs to be updated and cover the use case field of blockchain in socio-technical systems (cf. the articles of (Tasca & Tessone, 2017; Xu et al., 2017)). On the other hand, the developed blockchain-IoT framework can contribute to blockchain architecture design theory: the generic framework serves as an ontology for future blockchain design applications in the energy sector. Vis-a-vis these use cases can influence the framework towards a generic blockchain-IoT architecture ontology that can serve practitioners and other use cases for future certification/ emission accounting tools. Throughout the development of the architecture, it was found that blockchain architecture modeling research appeared to be not up-to-date as respected articles go back to 2017 (Tasca & Tessone, 2017; Xu et al., 2017). The developed framework of this thesis can be enhanced to a generic up-to-date blockchain architecture ontology considering the modern developments of blockchain architecture components induced by new use cases and digital asset/ currency regulations. For example, in the evaluation, it could be found that current developments allow for easier blockchain identification than tokenization, and advancements in research can reduce costs for additional security and privacy layers such as ZKP.

Third, the theoretical blockchain-IoT framework was applied 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. Scientific research defines this dependency as the "(direct and indirect, intended and unintended) impact of these artifacts on the humans who directly (and indirectly) interact with them" (Benbasat & Zmud, 2003, Page 186). Chapter 6 discusses the implementation of the technical artifact 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 technology. In specific, the socio-technical discussions in Chapter 7 resulted in clear guidelines on how blockchain technology's maturity can be built at the moment, giving practitioner insights into the current state of ZKPs, Oracles, and token economy. Further, blockchain governance requires an end-to-end decentralized governance model including the IoT infrastructure but also software-specific decision-making on the blockchain. Moreover, the institutional setting has a decisive impact on the success of the blockchain system and in return the blockchain on institutions. The right institutions can set smooth barriers to implementing blockchain technology, but also blockchain can help to enforce institutions persistently and with less administrative effort. Lastly, the artifact provides insights into how society influences the success of complex blockchain projects. Considering all hydrogen trade scenarios will be necessary to succeed in certifying green hydrogen with blockchain technology.

8.4. Limitations and future research

In the thesis, expert interviews helped to gain insights into the needs of the stakeholders relevant to the hydrogen certification system (cf. Chapter 4). Conducting expert interviews undoubtedly yielded valuable insights and new perspectives on the underlying artifact. The interviewees were experts from companies, institutions, and universities. Since each of them brings an individual professional background, they may occasionally show preferences for certain areas of interest. A notable example of this is the ongoing developments in hydrogen legislation, where the continued engagement and thorough research of experts is essential to stay abreast of the evolving institutional landscape. However, the diversity of expertise is also a strength, leading to the emergence of a range of viewpoints. Economic experts, for example, tend to emphasize business-related criticisms such as international hydrogen trading and market entrance barriers. Institutional experts, on the other hand, provide valuable insights into the legal interpretation of hydrogen legislation. The interplay of these different perspectives not only enriches the understanding of the hydrogen certification field but also points to possible directions for future research, as illustrated below. For the technical artifact of this research, it means that the research is still ongoing; the first design cycle was introduced. Considering institutional changes, the hydrogen production technology market, and varying stakeholder constellations can iteratively enhance the initial artifact. The ongoing changes in the hydrogen certification market should be monitored closely to provide continuously up-to-date research. Also, more experts from different countries can be involved to cover a bigger picture of the international hydrogen value chain and incorporate their requirements.

Blockchain technology is a nascent field developing quickly with the continuous identification of new exaptation for new use cases. In the thesis, blockchain technology is exaptated to the field of hydrogen certification as a developing field for blockchain research and a generic blockchain taxonomy was created. For the design, the optimal technical design specifications were chosen regardless of the economic impact it might have. The top-notch technical standards in blockchain technology are less evolved and might introduce issues such as high development costs and lack of expertise. As such, the expert evaluation suggested a thorough analysis of what technical implementations are practically and economically feasible to achieve the functions desired with the underlying artifact. For example the necessity of tokens to prove ownership of certificates compared to other mechanisms like anonymized and encrypted IP addresses. Further oracles are criticized to be solving decentralized and secured real-world data collection, further research must be conducted on the feasibility of alternative solutions such as decentralized oracles.

The artifact implementation strongly focuses on hydrogen transportation in gas pipelines, namely the planned hydrogen backbone (Enagás et al., 2020). Other scenarios could be imagined based on the complex hydrogen value chain to make the artifact more realistic. Expert I11 (B.5) proposed the evaluation of the artifact in multiple hydrogen trade scenarios displayed in Figure 7.2. Adopting a use case analysis can draw a closer connection to the real world; for each case, individual needs can be identified that can influence the design choices of the artifact. Furthermore, extending the evaluation toward use cases can incorporate the feedback of the expert evaluation and extend the artifact's feasibility for the hydrogen certification market. The recommended use case analysis helps evaluate blockchain's adoptability for the use case of hydrogen certification. TAM is a method to evaluate the adoption of IT artifacts in society and thus enhance the value of this thesis (Hevner et al., 2004). Additionally, also the international alignment has to be taken into account. The artifact is scoped to the institution frame of the European Union, however, the globally entangled hydrogen market calls for an internationally standardized solution so the hydrogen market can flourish.

The technical artifact entails complex and sophisticated nascent technologies that can best represent the requirements for effective and reliable hydrogen certification (cf. Chapter 5). A more realistic analysis could entail analyzing costs and benefits per design element and secondary induced costs by adopting the technical artifact in a societal context. Such costs can be induced by introducing new governance models, purchasing the required hardware, maintaining the network, and intra-organizational transformation (Biswas & Gupta, 2019; Saberi et al., 2019; Sedlmeir, Völter, et al., 2021). After analyzing the main cost drivers for blockchain-based hydrogen certification adoption, it can be compared with its cost-saving potential to give an overview of the artifact's market readiness. As found in the requirements elicitation interviews, external factors, financial incentives, and safety were among the externalities that can affect the artifact but are not considered directly in the artifact design (cf. Figure 4.1). However, they might critically influence the artifact implementation in the market. It is recommended to analyze the validity of these requirements and, if necessary, include them in the design process to achieve a higher tangibility to the real world.

Blockchain was introduced as a single chain of trust between stakeholders participating in business-government-consumer information-sharing infrastructure. In the hydrogen economy, relevant scenarios can be imagined that would play a significant role in facilitating the adoption of the artifact. The hydrogen market is shaped by a strong trade frequency similar to the electricity market; by 2030, the EU wants to import 10 million tonnes of hydrogen and vis-a-vis domestically produce 10 million tonnes (EU Commission, 2023a). To accomplish effective green hydrogen certification and simultaneously facilitate hydrogen trade, a connection of the artifact with hydrogen trade platforms could be imagined that brings together supply and demand. For example, Hyxchange (2023) is establishing a hydrogen trade platform to facilitate a flourishing hydrogen economy in Europe. It is recommended to analyze the potential for extensibility with such information infrastructures to facilitate certification and trade and link it with financial incentives for hydrogen demand and supply. Similarly, the connection to other blockchain infrastructures can be analyzed (Schulte et al., 2019). As found in the initial analysis of this report, different market players are working on business-driven blockchain solutions for hydrogen certification (see Table 1.2, however, integration with the proposed artifact through cross-blockchain communication would provide flexibility for hydrogen producers to choose blockchain service providers but still comply with the European regulation on hydrogen. Research on the benefits of cross-blockchain connection to other existing infrastructures can bring added value to the artifact's interoperability requirement but also bears risks to be considered.

Overall, a theoretical technology artifact can only be finally evaluated for its success when implemented in the market (Collingridge, 1982). After proposing the first step of the design cycle toward a blockchain-based artifact for hydrogen certification, the artifact has to be developed further according to the recommendations above for future research. Also, the artifact has to be tested in a real-life scenario to evaluate its practical viability.

8.5. Connection to CoSEM

Complex systems engineering is embossed by thinking beyond purely technological innovations, by incorporating societal and institutional considerations about implementing technology innovations and how interventions in society can be embedded most feasible. This thesis combines systems engineering with technological artifact development intervening in the current hydrogen certification market. First, a socio-technical analysis is conducted as a key input to create the technical design. The hydrogen certification economy comprises actors from business, governmental, and facilitating origins. These actors continuously interact with each other to enable the data-sharing of hydrogen emissions, their verification, and the subsequent certificate issuance. According to Shin and Ibahrine (2020), blockchain technology affects the technical system (physical system and tasks), the social system (people and institutional structures), and the external environment. The analysis of the socio-technical certification system in Chapter 3 covers the aspects of the people and their tasks, the institutional structures, and the physical system in terms of information infrastructures and processes. Furthermore, in the thesis, an inductive method was conducted to receive requirements influenced by various actors of the hydrogen field, resulting in a socio-technical list of aspects that need to be considered in the artifact design. Technical design components can mirror the functional requirements. However, implementing the artifact in the hydrogen certification context and the potential interactions of users with the system pose uncertainties that add to the complexity of the artifact. With the technical artifact demonstration, the allocation of roles and responsibilities, and the institutional alignment, the thesis covers the main aspects of complex socio-technical blockchain systems. It aligns with the multi-stakeholder perspective when designing in complex systems. The artifact evaluation shows that the design is strongly dependent on the interactions of stakeholders with the system by criticism of future research and adoption of the artifact in society. In return, blockchain induces a paradigm shift from central to decentral governance of the hydrogen certification landscape, which implies new thinking about system governance structures that intervene in the current hydrogen certification landscape.

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A

Appendix A

A.1. List of interviewees

Table A.1: List of interviewees for the requirements elicitation

Encoding	Profession	Expertise	Organization
I1	Blockchain/IT and Energy business developer	Long-term experience in developing business models in the energy sector, first for green electricity and now for green hydrogen. Development of information systems securing critical infrastructures and pilots with emerging technologies to support new business models in the energy sector.	Consultant
I2	IT/Blockchain expert	Experience in developing IT landscapes for finance and emission/sustainability reporting. Knowledge of the application of blockchain technology in the aforementioned fields.	IT-Developer
I3	Hydrogen expert	Consultant for hydrogen business development and how information systems can facilitate the green hydrogen business.	Consultant
I4	IT/Blockchain expert	Multiple years experience in developing IT systems, among others, blockchain-based systems in the energy sector but also other fields.	IT-Developer/ Consultant
I5	Hydrogen expert	Works in one of the largest energy companies in the world and has experience in developing business models for the sustainable energy market, among others hydrogen.	Energy producer
I6	Hydrogen expert	Multiple years of advising the hydrogen field in terms of business development and how information systems can support the green hydrogen market.	Consultant
I7	Hydrogen certification expert	Independent national authority conducting gas and hydrogen certification in one of the European member states, background in chemistry and institutional expertise.	National energy authority

A.2. Interview protocol - Requirement elicitation

The goal of this interview is to gather the requirements of the perspective of the market participants in the hydrogen certification market. Specifically, the questions are framed to ask from the perspective of the hydrogen producer as the central entity in the certification process. In this way, first technical questions on the certification process are asked to gather technical requirements for the system, secondly, questions overall questions concerning all stakeholders are asked. Lastly, questions concerning institutional compliance are asked as an important actor to facilitate certifications.

Pre-interview: Ask for the signed consent form to ensure compliance with personal data usage for the research. Ask for permission to record/ transcribe the interview. All the transcripts are going to be anonymized in self-written summaries. Ask if these anonymized summaries can be used in the thesis and if applicable be quoted?

Questions: Short (2min) introduction of the interviewee:

1. What job role do you have and in which industry do you work?

2. What is your connection to the hydrogen field?
3. What is your experience in the hydrogen field?
4. What is the size of your organization?

Technical requirements elicitation:

1. How is monitoring, reporting, and verification of emission data being done in the hydrogen field?
2. How do you gather information about emissions along the hydrogen production process and upstream activities or what are your data sources?
3. On which data from predecessors in the hydrogen value chain does a hydrogen producer depend in order to guarantee the greenness of the hydrogen, and who depends on the producer's data?
4. How is information shared in the hydrogen supply chain with successors/descendants to ensure the greenness of the hydrogen?
5. Are there any problems occurring when obtaining this data, or revealing data to supply chain successors? (key terms: quality, availability, timing, errors, data processing errors, confidentiality)
6. Who checks the correct data collection and how is it verified that the data is gathered correctly, is there a potential for fraud or other issues?
7. Are there any reasons to not trust the emission data for green hydrogen certification, is it reliable, and compliant?
8. What are the biggest problems when accounting for hydrogen value chain emissions?

Stakeholders:

1. What are the key actors in the hydrogen certification field?
2. How would the introduction of blockchain technology change the situation in terms of stakeholder roles and responsibilities and data sharing?
3. From the hydrogen producer perspective, what are the data elements such a hydrogen certification needs?

Institutional requirements:

1. What data does the government need, and what are the compliance reporting obligations?
2. According to my understanding, [show Figure 3.6] this is the current process of auditing and approving the facility to be certified as a low-carbon hydrogen producer, am I right, or do I miss out on something?
3. What are the issues in the data documentation, the auditing, and the certification that allows a hydrogen producer to sell green hydrogen? and what requirements could ensure the correctness of the data and facilitate that process?
4. What are the risks with current certification in terms of reliability, trustworthiness, transparency and interoperability? (Do you know other practical problems, such as double counting?)
5. Mass balancing (proposed by EU regulation) is a potential solution for more reliable GHG emission accounting. What are the requirements needed to allow a simultaneous transfer of the digital guarantee-of-origin attached to the physical hydrogen batch?
6. Are there any more specific requirements that should be considered to make a certification with mass balancing possible?

Extra questions:

1. Considering the hydrogen backbone, what are the key challenges you see if many people feed hydrogen into one network in terms of hydrogen qualification?
2. How does certification play a role here, could there be any issues with how certification works currently (manual auditing)?

I will show some figures and diagrams that represent my system analysis. It would be great to get some feedback from you.

A.3. Contribution per interviewee

The following Tables entail the needs, and requirements contribution of the desk research of Chapter 3 and of each interviewee that was deemed as relevant for the blockchain-based artifact. The categorization of the information aims at encoding the aspects to merge them in a comprehensive but non-redundant list of requirements.

Table A.2: Requirements and stakeholder needs from literature

Categorization	Requirements and relevant needs	Source
Share information	Sharing of metadata on the hydrogen batch gradually along the value chain	(Sailer et al., 2021)
Transparency	The information has to be saved transparently in an information system (union database?)	(Sailer et al., 2021)
Monitoring	The injection interface point has to be documented reliably	(Sailer et al., 2021)
Monitoring	The extraction interface point has to be documented closely	(Sailer et al., 2021)
Monitoring	The liquid transport has to be documented (if liquified, else gas network not needed)	(World Energy Council, 2022)
Registration	Registration with the national responsible emission authority/ registry (eg. Dutch Emission Authority (DEA))	(Dutch Blockchain Coalition, 2023)
Verification	Automated verification of the hydrogen injected based on historical data	(Sedlmeir, Völter, et al., 2021)
Traceability	Proof of sustainability compliant	(World Energy Council, 2022)
Auditability	Prevention of double counting (green electricity used for green hydrogen production)	(World Energy Council, 2022)
Compatibility	Compatibility with the issuance, transfer, and cancellation of the EU GO process	(IRENA & RMI, 2023)
Openness	Fair and open standards applying to everyone in the same way	(IRENA & RMI, 2023)
Verification	Verification of data by independent third party	(IRENA & RMI, 2023)
Modularity	Modular system	(White et al., 2021)
Confidentiality	Confidentiality	(Sedlmeir, Völter, et al., 2021)
Verification	Verifiability	(Sedlmeir, Völter, et al., 2021)
Openness	Open for economic operators to join	(Sedlmeir, Völter, et al., 2021)
Scalability	Scalability	(Sedlmeir, Völter, et al., 2021)
Auditability	Additionality/ System serviceability: electricity must not be subsidized (direct connection to the grid (an installation that provides electricity max 12 months implemented), indirect connection to the grid (installation must be max. 24 months implemented prior to electrolyzer))	(EU Commission, 2022b)
Auditability	Energy must be 100% renewable and proved by PPA (power purchase agreement)	(EU Commission, 2022b)
Auditability	Geographical correlation (electricity provider and electrolyser in same bidding zone (max 1-hour correlation but same price on bidding day)	(EU Commission, 2022b)
Auditability	Temporal correlation (same calendar hour+PPA)	(EU Commission, 2022b)

Table A.3: Interviewee 1 (I1) contribution

Contribution	Categorization	Relevant information
Requirements and stakeholder needs from the hydrogen market perspective, particularly, hydrogen producers and hydrogen certification in general.	Compatibility	Interoperable with different certification schemes (Hydrogen needs to be imported (not enough in EU/ Germany), Interoperability of emission accounting systems and certification mechanisms.)
	Financing	Clarification of the return on investment of green hydrogen (Green hydrogen is not profitable yet, but it is also not clear how certification can ensure the profitability of green hydrogen (does the government give credit, and afterward companies pay back to make the market even possible?))
	Governance	Clear distribution of tasks and responsibilities (governance/collaboration) (New roles might come in place, especially DSO as the important entity overseeing the injection/ withdrawal points of the hydrogen distribution)
	Tradability	Tradeability of hydrogen certificates (To ensure flourishing markets and innovation, the certificates need to be tradable with the associated hydrogen batch (stimulates innovation, hydrogen prices))
	Modularity	Comprising multiple certification schemes in one system (synchronization in one IT system) ("an information system/ platform that is synchronizing the virtual certification and physical transport of the hydrogen will be needed" (alignment of physical and virtual flow))
	Traceability	End-to-end tracking of the hydrogen emissions (Only parts are tracked currently, but no holistic solution is yet available.)

Table A.4: Interviewee 2 (I2) contribution

Contribution	Categorization	Relevant information
Knowledge about blockchain applications in the market and their implementation process. Input of requirements from the IT perspective and the economic operator perspective of such IT systems.	Security	Tamper-proof data collection to prevent garbage in - garbage out effect, for example through external/third party sensor providers (in a data collection as a service concept).
	Confidentiality	Competitiveness in the market needs to be ensured, so the data access rights and data control need to be restricted to keep the data confidential.
	Auditability	Prevention of double counting is required, the electricity input could have been already used before for gaining subsidies.
	n.a.	24/7 availability is not needed as there is no time-related issue - there can be some delays. However, scalability and security are very important considering the computing trilemma.
	Openness	Permissioned access is needed as multiple parties will be involved within one transaction.
	Governance, Incentivizing	All involved parties in a transaction need to have active and beneficial roles to be willing to participate.
	Flexibility	Institutional reporting obligations change regularly. That means the system needs to be adaptive and flexible to function continuously.
	Documentation	Data quality plays an important role in future ESG reporting, thus, sensors and data storage need to be reliable and accurate.
	Flexibility	Changing standardization and regulation must be expected. That is why a flexible/adaptive infrastructure is needed.

Table A.6: Interviewee 5 (I5) contribution

Contribution	Categorization	Relevant information
Knowledge about the hydrogen market from the hydrogen producer perspective. Contributes requirements and needs of the hydrogen producers regarding certification. Confirmation and explanation of current certification processes.	Modularity	Hydrogen regulations still not clear (flexibility is key for a successful information system)
	Tradability	Tradability: Certificates should be linked to ETS as an opportunity to stimulate the market, once the hydrogen is in the market it should be possible to negotiate with buyers, and also with other countries tradable.
	Compatibility	Compatibility with grey and blue hydrogen. Only green won't be sufficient to satisfy the demand, distribution networks and certifications should allow multiple ways.
	Traceability	Link of hydrogen and virtual certificate: This aspect provides the value of the hydrogen to the producer.
	Compliance	Fulfillment of RED II requirements: RED II is the major institutional frame for emission accounting.
	Compliance	Prevent double counting of electricity and hydrogen. REC for electricity feeds in the GO for hydrogen (double counting is possible).
	Compatibility	Compatible with renewable electricity certificates. The GOs for electricity don't entail certain criteria but need to be convertible in PoS for hydrogen complying with time and geographical correlation and complying with the energy loss (100MWh electricity is not equivalent to 100MWh of hydrogen but is it the same certificate or degraded?)
	Auditability	Auditability of the system: The system needs to be accessible by auditors, other verification bodies, and the Issuing Body of the PoS as insurance for the greenness of the hydrogen.
	Traceability	The user of the hydrogen has to prove the usage to allow compliant cancellation of the GO.
	Financing	Financing of the certification: The process has to be funded, as green hydrogen production is expensive and not mass profitable yet (credits for the certificates that can be paid back for example).
	Verification	Independence of certification/verification body from government
	Stability	Stable system: Electrolysers are working for several years (appr. 13), information system needs to be robust for all these years.
	Automation	Current process is manual (excel spreadsheets with quantities and data sent to the certification body regularly to provide certificates)

Table A.5: Interviewees 3 and 4 (I3, I4) contribution

Contribution	Categorization	Relevant information
Knowledge about the hydrogen market. Contribution of needs and requirements from the hydrogen producer perspective, the DSO companies, and certification bodies. The second interviewee contributed knowledge about emission monitoring with blockchain technology and what can be learned from the electricity market as well as from other blockchain implementations.	Traceability	Origin of electricity needs to be proven (Location of electricity production, time of electricity production, and how is it transported)
	Security	The means of data collection has to be secure.
	Allocation of roles and responsibilities	The controlling party of the data collection (who collects data and how is it controlled, and where are the collection and control points)
	Modularity	Supporting multiple certification schemes (there are diverse ones and many are recognized)
	Monitoring	Accurate data on the emissions is needed to ensure trustworthy and reliable accounting
	Monitoring	Clear and transparent calculation and emission factors need to be in place for producers and consumers
	Monitoring	Accurate measuring through sensors/ diameters and direct linkage to information system so the
	Security	A unified certification system is needed and transparent information. Currently, there are many systems in place that allow for fraudulent activities.
	Confidentiality	Support IP and competitive advantage (Competitive advantage might obstruct the information sharing willingness of companies in a public system)
	Flexibility	Parties like grid operators, distributors, suppliers, and their interactions are still unclear and have to be formed
	Allocation of roles and responsibilities	Handling of diverse stakeholder role distributions. Also take into account that some closed systems take over multiple roles (e.g., Production, distribution, and usage)
	Automation	Minimal principle and easy to use (companies will just be willing to share as much information as needed to receive the certificate)
	Tradability	Handling of long-distance trades: How is the conversion from electron to molecule ensured over large distances? Is the promised contribution to the energy transition still given in such cases?
	Standardization	There are many fragmented and spread local production/ distribution grids and application fields plus diverse fields of certification schemes. A standardization incentive can bring them together.
	Efficiency	Generally, actors' roles and responsibilities stay the same due to regulation but it should be facilitating processes.
	Openness	Take into account international rules and regulations
	Openness	The transport companies should have access to the system. They represent the means for transporting the hydrogen to the customer (it should be accounted for how much they pollute and they should be able to see the quantities in the system)
	Governance	DSO as the regulators for the H2 injection and withdrawal from the grid
	Allocation of roles and responsibilities	Accounting and measuring parties of the sensors
	Standardization	Clear definition of green hydrogen as the major institutional requirement to facilitate certification.
	Standardization	Provide emission factors (a unified set of them) and canalize sources: Everyone should be producing and certifying hydrogen in the same way.
	Security	Clarity about data ownership (Regulations are often local)
	Governance	Clarity about maintenance of the system (governance). Governance can help to set boundaries (which roles are existing and who is doing which roles and which roles can be combined/ separated)
	Flexibility	Flexibility to changing roles. Energy systems are prone to many changes (e.g., in electricity grid operation the grid operator and electricity supplier had to be separated to ensure the market mechanisms).
	Standardization	Clarity about the data collection points. When is it collected what information is needed at which points to see the misuse of certification systems or to ensure trust and reliability.
	Scalability	Scalable when the hydrogen market is expanding, for example, the hydrogen backbone. Here the DSOs will get important to monitor the H2 extraction and injection points.
	Monitoring	Monitoring of storage and its pollution
	Modularity	Adaptable for grey and blue hydrogen, as the market will need to evolve for all sorts of hydrogen.

Table A.7: Interviewee 6 (I6) contribution

Contribution	Categorization	Relevant information
Knowledge about the hydrogen market. Contribution of needs and requirements from the hydrogen producer perspective, the DSO companies, and certification bodies. Furthermore, contribution of knowledge about extra factors that might play a role in an effective certification of the hydrogen and the associated production facility.	Compatibility	Compatible with multiple differing certification schemes that are accredited in the European market.
	Flexibility	Adaptible to changes. The certification market is continuously evolving and a lot of things are happening (innovation in production, standards, and reporting tools).
	Tradability	Tradability/ flexibility on electricity input use. What is more profitable/ makes more sense? Producing hydrogen or feeding electricity in the grid? This should be a pre-decision to ensure the profitability of the green hydrogen market.
	Monitoring	Quality and pureness measurement. The vital aspects for qualifying the hydrogen.
	Modularity	Electricity provenance linkage/ linkage with REC/GOs for green electricity. The electricity input is the most polluting factor and the main criterium for the hydrogen qualification.
	Traceability	Traceability (detailed). Consumer needs to be able to pinpoint the emissions along the value chain.
	Trustful information	Data quality and exact measurements are required to ensure this trust.
	Modularity	Linkage to energy assets of company or industry to prove their energy mix.
	Confidentiality	Confidentiality/ competitiveness guaranteeing. Companies hesitate to share their data openly.
	Verification	Sensor quality/ verification is important. Data collection strongly depends on the hardware and its installation.
	Externalities inclusion	Permits for facility construction is important to consider.
	Externalities inclusion	Value extra factors: social, environmental, construction impact of the facility. Building these huge plants has a major impact on the local environment.
	Safety	Ensure the safety of hydrogen production and transport (highly inflammable).
	Monitoring	Gradual monitoring of emissions through every hydrogen transaction step through the value chain
	Transparency	Information sharing with descendants is important to build trust and gradually take life-cycle emission into account.
	Collaboration, Allocation of roles and responsibilities, Incentives	Collaboration incentive. Sharing information and willingness to do it are important for participants.
	Standardization	Clarify data sufficiency for hydrogen qualification. What is enough accuracy for qualifying credibly?
	Verification	Verification party as an intermediary to balance between stakeholder interests
	Flexibility	Take local varying difficulties into account (modular). Per nationality, there are local peculiarities in creating an electrolyzer. These have a local effect on achieving hydrogen certification.
	Monitoring	Input output monitoring is important to credibly prove the hydrogen mix.
	Compliance	Mass balancing from a hierarchical perspective is important to have multiple sources of truth (large mass balance for the hydrogen backbone, smaller one for the transport sector, and smallest for each user).

Table A.8: Interviewee 7 (I7) contribution

Contribution	Categorization	Relevant information
In-depth knowledge about the regulatory framework of the hydrogen certification landscape. Requirements from the perspective of the legislation. Clarification about the difference between PoS and GO. Functioning and objectives of the Union Database.	Compliance	Compliance with PoS: At the moment still, GO and PoS are simultaneously available for certification, however, PoS will be the rule after the transition time.
	Compliance	Compliance with mass balancing: To prove PoS the system must be mass balance conform.
	Compliance	Compliance with RED II regulation: The RED II regulation gives an outline of which institutional requirements are given. Two important differences: first, the electricity source is directly connected and second, the electricity is taken from the grid.
	Compatibility	Compatibility with Union database: Is still in the test phase, however, it will play a major role in storing the transactions of hydrogen be it GOs or PoS. The main goal s to prevent double-spending across borders.
	Compatibility	Compatibility to multiple voluntary schemes: Multiple Voluntary schemes will be accredited and must be compatible with the system

B

Appendix B

B.1. List of interviewees

Table B.1: List of interviewees for the expert validation

Encoding	Profession	Expertise	Organization
I8	Hydrogen expert	Experience in developing business models in the energy sector, particularly, for green hydrogen import. Development of a secure supply pipeline for hydrogen in Europe and participation in developing the national/EU-wide hydrogen grid.	TSO
I9	Hydrogen and blockchain application expert	Experience in developing IT landscapes for energy and hydrogen systems. Knowledge of the application of blockchain technology and prototyping in the blockchain-based hydrogen certification field.	Large-scale energy company
I10	Blockchain expert	Freelancer consultant for blockchain development for carbon accounting and passion for spreading awareness of the benefits of blockchain technology for nongovernmental organizations and in mitigating poverty.	Blockchain consultancy
I11	IT and Energy expert	Multiple years of experience in developing IT systems, among others, blockchain-based systems for a large-scale energy company. Hydrogen strategy manager at a large-scale energy enterprise.	Large-scale energy company
I12	Senior blockchain developer	Consultant for blockchain implementation projects with experience in blockchain programming and development. Blockchain programming background knowledge in Hyperledger, Cosmos, and Tendermint. Several blockchain-based infrastructure developments and implementations.	IT consultancy
I13	Assistant Professor	Researcher in the field of institutional economics of digital infrastructures at a leading technical university in Europe. The interviewee researches how large-scale digital infrastructure projects affect society and institutions and vice versa.	University/ Research Institute

B.2. Interview protocol - Expert validation

This interview aims to gather information about the feasibility of the designed artifact. It is especially focused on the feasibility of the hydrogen producer. First, certain design aspects are explained. For each design choice and process step the interviewee is asked to criticise the artifact from a professional perspective. In this way, the feasibility of the artifact can be evaluated based on parameters that are introduced by the interviewees. Secondly, the interviewee is asked more general reflection questions to establish an open discussion about the artifact and its implementation.

Pre-interview: Ask for the signed consent form to ensure compliance with interview data usage for the research. Ask for permission to record/ transcribe the interview. All the transcripts are going to be anonymized in self-written summaries. Ask if these anonymized summaries can be used in the thesis and if applicable be quoted.

Questions: Short (2min) introduction of the interviewee:

1. What job role do you have and in which industry do you work?

2. What is your connection to/experience in the hydrogen field?
3. Do you know about blockchain technology and its application possibilities?
4. What is the size of your organization?

Evaluation of the technical artefact:

1. Emissions for green hydrogen certificates are measured through mass balancing, do you think tokenization is a feasible way of linking the certificates to the according physical hydrogen batch?
2. Do you think the on-chain off-chain data storage decision is preserving the confidentiality of the data while still transmitting the data efficiently?
3. I created the design in a consortium set up to value the national specificities in each EU country, do you think that is a feasible design choice?
4. Do you think oracles work well as APIs to connect as secure means between physical data gathering and the blockchain and to create the required interoperability?
5. Do you think the technical artefact connects the technical design components well and comprehensively with the functions and processes?

Reflection on roles and responsibilities:

1. Do you think PoA is a good way of reaching consensus? The national authorities/ issuing bodies have the power to commit new blocks, while economic operators (hydrogen producers) only submit transactions validated by DSOs. Transport companies, hydrogen traders, and buyers just have reading permission.
2. Stakeholders have different access rights as indicated in the figure 6.1, do you think this can result in issues in terms of security, confidentiality, or non-transparency (or other issues)?
3. Do you think any of these parties are obsolete, or should have different rights? Do you see general problems with this task distribution?

Reflection on the institutional alignment:

1. Do you think a possible connection to the EU Union database as a means for reporting and documentation is feasible, as well as the connection to the emission authority?
2. One problem is the double counting which shall be addressed through the Union database, do you think blockchain can serve as a service infrastructure mediating between reporting and creating confidentiality for businesses?
3. Do you see any problems operating and certifying international hydrogen producers with a blockchain-based system that complies with EU standards?

Reflection on the process artefact:

1. The data collection is a potential vulnerability of the blockchain as this process is physical, which means that the onboarding and audit of the facility are vital. Do you think problems can occur or are regular audits sufficient to ensure data integrity?
2. I found that confidentiality is a barrier for economic operators to share data on the emissions as it could trace back to the amounts of energy used/ capacities of the facility etc., do you think ZKP mechanisms can serve well to preserve confidentiality and increase their willingness to share data?
3. Do you think smart contracts are a good means to forward certificates and verify transactions automatically (based on the decision tree)? Could difficulties appear due to the many different certification schemes that can be chosen?
4. - Do you think the data verification and PoS token issuance is a comprehensive process or are vital aspects missing in the design?
5. - Do you see any more general problems with the processes displayed or find any questionable steps?

B.3. Contribution per interviewee

The following Tables entail contributions per interviewee on what was deemed as relevant for the blockchain-based artifact evaluation. The information is provided in self-written summaries. Quotes indicate direct citations from the interview.

Table B.2: Evaluation Interview I8

Interviewee	Contribution	Summary
I8	Evaluation of the artifact from a hydrogen business and TSO perspective. Contribution of challenges related to the system governance and allocation of roles and responsibilities.	The TSO is not responsible for submitting any emission-related data to the institutional authorities. They only have the duty to guarantee the constant supply of gas/ hydrogen and to ensure the quality of the hydrogen in the market, but "[...] regarding the monitoring of the grid, TSOs are completely colorblind because they don't discriminate, everyone should have access to it." The only less regulated zones are the hydrogen terminals, where preferences toward green hydrogen can be pronounced.
	Contribution of potential market-induced challenges for hydrogen producers.	It is easy to audit and verify the European hydrogen facilities, but "I also don't know how fraudulent that could be in the end. I mean, for example, within the EU, it's probably easier to do that [verify the production facility], but once you go to get the hydrogen from other countries." "[...] there are certain countries that are known to be more corrupt, but those are also the same countries that are likely to be able to produce hydrogen at very low cost." The hydrogen market is highly competitive and hydrogen producers can choose where to sell their hydrogen. If the EU sets too high market entry barriers or certification procedures, a hydrogen supplier might choose to export the hydrogen to another country with fewer regulations.

Table B.3: Evaluation Interview I9

Interviewee	Contribution	Summary
I9	Evaluation of technical design aspects of the artifact.	Important is integrity! Authentication is possible through the facility. The data collected however is not per se of integrity, it must be secured and the blockchain itself cannot ensure the security and integrity of the data injection.
	Contribution of market implementation challenges for blockchain-based hydrogen certification.	It is a highly cost-intensive commitment to install the tools for measurements of the quality, emissions, and balances. Voluntary Schemes provide standards about what needs to be measured and in which accuracies, the rest can be lump-sum based on average values. Traditionally companies purchase certificates for a certain period based on historical data about energy consumption to comply with emission targets. But in time data collection is possible today and needed to comply with the temporal correlation principle.
	General questioning of the green hydrogen certification.	Is tokenization feasible and aligned trajectory with the physical hydrogen value chain? It would be very resource intensive. Each truck would need a computer with a ledger of the blockchain. A transfer from the hydrogen producer to the buyer would be sufficient as the mass balance is the overall important goal. If a PPA is signed, it is registered in the blockchain and stored as a transaction initiating the transfer of PoS and hydrogen. Current solutions are not yet connected to public registries, they are only focused on disclosure for hydrogen buyers and to create transparency/ trust about the purchased hydrogen. However, the disclosure to authorities would give the actual value to hydrogen producers as this process currently is cumbersome and cost-intensive. PoA would be a feasible option, a lot of types could be feasible such as Proof of Share/Stake but energy-intensive mechanisms such as PoW that would contradict the nature of "green" hydrogen. It is only important to find a balance so that the market parties don't feel too restricted by regulators and regulators can enforce the reporting of emissions and correct issuance of certificates. For every piece of renewable energy source 'we' collect data, but not only the provenance is important also the proof of the hydrogen usage must be monitored, the trajectory to the end user, and means of transmission. Is the system not wrongly conceptualized? It would be easier to monitor fossil energy production and penalize it than monitor all the microtransactions in the renewable energy grid and reward them. Fossil production methods are way easier to oversee, and such companies already have the liquidity to pay for the fines.

Table B.4: Evaluation Interview I10

Interviewee	Contribution	Summary
I10	Evaluation of the artifact's market feasibility.	The PoS can be indeed tokenized very well. These tokens can also be used for automatic verification of emissions with the Dutch Emission Authority, a linkage to their system is well imaginable. However, the emission authority is at the very end of a chain, they only see the emissions of the end users and for what it is used. They do want the entire verification information of the hydrogen value chain though.
	Reflection of the system governance as the critical challenge.	TSOs are imaginable as monitoring entities, however, their sensors have to be connected to the system, too. The physical sensor infrastructure needs to be deployed "Like there needs to be some sort of measuring device to see how much goes in and out [the hydrogen backbone] because you know it's fine that the current system is not doing that yet. But in order to make this happen they should start doing that now."
	Reflection on the institutional alignment of the artifact.	Governance is the most critical challenge. Either one party is responsible for pushing it into the market and getting everyone on board (e.g., Gasunie), or a collaborative approach is taken, but no one will feel responsible. "[…] the Dutch Emission Authority says, well, if the market wants this, they need to come with it and the market parties say, yeah, we can participate, but the government needs to make it possible. So, they're all looking at each other for developing and maintaining the system." Is the connection to the Union Database thinkable? "They [regulators and the Union Database] want to have everything [volumes, balances] and basically the big companies, we are working together with Shell, Cargill, and Coca-Cola, you know, big, big companies. They are basically saying, sorry, we're not gonna do that. This is not OK. This is competitive information." Also to mention are the high-security risks of a large-scale central database like the Union Database.

Table B.5: Evaluation Interview I11

Interviewee	Contribution	Summary
I11	Evaluation of the artifact's capability to fulfill the requirements.	The research lacks research on the societal outcome, specifically how the user is interacting with the system when it is deployed. Less technologically centric and more focused on how the trust between parties can be created in the socio-technical context and how it can facilitate interaction/trade.
	Reflection on the feasibility of the architecture to accomplish the trust/ transparency problem in the hydrogen market.	Compatibility/ Interoperability of the artifact: the hydrogen market is going to establish globally. A consideration on platform integration with the non-blockchain systems outside of the EU or with the integration of other blockchains in the US or Japan for example as two major hydrogen markets in the future.
	Evaluation of the artifact's institutional alignment and governance.	Tokenization evaluation: A scenario evaluation would be helpful to get a more precise overview of what types of transactions need to be facilitated in the blockchain [now it is related to existing literature and how it is done in similar cases]. A more in-depth engagement with these would give a comprehensive overview of what the blockchain needs to do and if this concept actually facilitates the intended purpose. For example, if there is a transaction between business and government to track all the emissions in the EU "[…] and you attribute that as purpose to this platform, then you can say if this is the purpose of the platform, the EU needs a trusted data source as a central bank, if you will, to issue, manage, account, and police all those different actors, then that drives maybe the functional requirement to say tokenization is best to do that because it allows the EU to do XYZ." These kinds of considerations provide alternative views and might end up in other technology choices for the design. All in all, it is important to think of different scenarios for the evaluation of the feasibility, especially, as the market is still very nascent. Scenario imagination: In regard to the hydrogen import case, when hydrogen is shipped from Brazil/Qatar to Europe, the transportation process doesn't need live IoT data, but it is an important part of the value chain. Thus, it is vital to consider these cases in the design to simplify the processes that need less monitoring than others. Scenario imagination: A domestic steel factory using its own electrolyzer could be imagined, do they also have to use the system as they are a closed system? That would be another case of how inter-hydrogen products are covered in the design. Scenario imagination: The artifact is strong for long-distance trades. But all trade and business models should be considered. For example, contracts are also executed outside of the blockchain. Maybe Exxon Mobile and Total have a contract that Exxon can use hydrogen from the Total depot to serve customers in Europe and Total can do the same in the US based on certain pre-agreed prices. Considering this scenario, in the 'ancient' fossil oil world information on the composition of the oil is not required, but for hydrogen, we need additional information as it can be 'pimped' on paper. Trustful information exchange is needed to prove the sustainability of the trade partner and make hydrogen a competitive commodity, the process is pointing that out well.

Table B.6: Evaluation Interview I12

Interviewee	Contribution	Summary
I12	Concrete evaluation of the technical design aspects of the technical artifact.	Criticism of oracles: "But then the widespread criticism is when we are working on a decentralized technology like Blockchain and when you are using smart contracts […] to verify and validate the transactions. They [the system creators] also need to make sure that the data that you're receiving is also from a decentralized source […] because if you receive from a centralized source, it could be corrupted." So, one single point of failure can poison the entire system. However, connecting every sensor is also not feasible as they are resource-constraint, and the system would be spammed by transaction data.
	Contribution of expert knowledge on the blockchain design choices and their feasibility to be implemented.	Complexity increases through tokens. For consortia/private blockchains, it is better to use identifications: "[…] if you just want to represent a certificate as an asset, for which you can transfer the ownership at a later stage, right?" […] "You can just represent it as an asset that belongs to a particular owner with a particular certificate and a private key."
	Reflection of practical implications of the design for blockchain programming.	"So, governance is a very, very crucial aspect in any blockchain system." The benefit of the consortium setup is that parties are known and can meet in real life to settle updates and changes to the system and ensure the enforcement of smart contracts. ZKP is not necessarily important to ensure confidentiality: "So if you want to hide some confidential information data, there are multiple ways you can accomplish this." ZKP introduces another complexity through one more level of data exchange (one more transaction) and "Zero-knowledge proofs can be extremely expensive. A very, very hot topic when it comes to handling blockchain scalability." „It's [decentralization] very philosophical in nature as well because decentralization cannot happen in just one layer. It needs to happen in almost all layers of your application, right?" Implement a decentralized structure on all layers of the blockchain. Decentralization must drag through the entire system. The Union Database could get redundant "Why would they want to put that same data in [as a backup]?" Blockchain can secure the data and usually, no other system is needed besides a continuous synchronization with, for example, the front-end application.

Table B.7: Evaluation Interview I13

Interviewee	Contribution	Summary
I13	Reflection on the technical design choices and their feasibility to solve the transparency problem.	Oracles: "So, this is the typical Oracle problem. […] Think more in terms of how you incentivize good behavior and not try to greenwash. […] If there are certain actors that have an incentive to sort of write false information on there [the blockchain]. How do you deal with that?"
	Out-of-the-box input regarding blockchain governance.	Tokenization is chosen well: "You have composable NFTs and basically you have the metaphor of a bundle of rights. So you have a bundle of rights that you can individually sell, but the abstract category is the certificate of which you can sell little points and bundle it later again."
	Institutional feedback on the design.	Governance: What is being done if someone is doing deliberate or non-deliberate mistakes in the system, how it is being backtracked and changed? and the interviewee mentions the problem of immutability: "[…] maybe the process must be immutable, right? So, the way in which the smart contract is changed must be subject to an immutable process. […] the code is mutable, but the governance procedure determines how to change certain things so that there's a fallback option in case of errors in the smart contract." PoA problem: „It seems logical to choose the issuing bodies per country as being the node operators that have full node authority and then the other ones just right and read." Another level of trust could be added. "If you have wanted to have an extra layer of trust build in the system, you could say that you have to stake for certain operations, so they negotiate like what they expect from each other […]. If I'm not doing my job, or if I'm for whatever national political reasons, not being able to continue with this platform, then you're losing stake. In other words, you're committing to stay outside of your National Democratic incentives which might be good, right? […] But you could say PoA itself might be enough, but if you want to make sure this particular problem of credible political commitment over the long run, you're saying, OK, let them commit valuable steak and put it into a smart contract and lock it up in an escrow for a particular period of time." Is there an incentive that one of the parties is going to determine proof of authority consensus with a 51% majority of the system? Like assuming Netherlands, Germany, and Italy are forming a cartel. Then an additional level of security can be added.