Requirements for a blockchain-based proof of origin for green hydrogen

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Hydrogen produced from renewable energy, so called green hydrogen, is seen as a key element of the energy transition in Germany. So far, however, a green hydrogen economy is barely developed, industrial applications require restructuring, are cost intensive and lag, while the pursued ecological benefit of transitioning to hydrogen technology is difficult to prove. Blockchain is a promising technology here. It offers the potential to trace the origin of hydrogen and thus contributes to document sustainable business practices. This paper examines requirements for a blockchain-based proof of origin for green hydrogen by carrying out a literature review and deriving requirements from the data found. In total, 11 requirements are found to be crucial to establish a working solution. While future research on how to overcome these challenges is needed, the benefits of a blockchain-based solution outweigh traditional approaches, which are lacking both standardization and transparency.

1. Introduction

The energy landscape is transforming significantly as the global search for sustainable energy solutions intensifies. This shift is driven by technological innovations and an increasing commitment to environmental protection [1]. A central element of Germany's strategy to combat climate change is the energy transition, which aims to meet the electricity demand entirely from renewable sources by 2045 [3]. Hydrogen, as a green energy carrier, plays a central role in this transformation [4].

Hydrogen, known for its high energy content and environmentally friendly combustion, is emerging as a promising alternative to conventional fossil fuels. Since its oxidation produces only water, hydrogen significantly reduces carbon emissions and promotes the development of energy storage technologies [5]. The European Union has also adopted this approach for the European market, introducing the EU Hydrogen Strategy in 2020 [6].

Currently, hydrogen is used as a process gas in various industrial sectors. Different methods for hydrogen production exist, such as electrolysis or steam methane reforming [7]. Depending on the production method, hydrogen is assigned a color, indicating the associated greenhouse gas emissions. Green hydrogen, in particular, plays a crucial role in the energy transition, as it is produced through electrolysis using renewable energy sources like wind and solar power, making it potentially emission-free [8, 9].

Current forecasts predict that by 2050, up to 23% of the total energy consumption in the EU will be supplied by hydrogen [10]. In Germany alone, this will require electrolysis capacities in the double-digit gigawatt range [11]. However, a significant portion of Germany's hydrogen demand will need to be met through imports in the medium to long term. The German government anticipates a national demand for hydrogen and its derivatives of 95 to 130 TWh by 2030, with approximately 50 to 70% (45 to 90 TWh) expected to be imported [12].

Substantial challenges in production, storage, and logistics along the hydrogen supply chain must be overcome to fully exploit the potential of hydrogen [5]. Production capacities and supply chains need to be newly established in many areas. The decentralized production of hydrogen and increasing international imports also heighten the need for transparency regarding the origin of hydrogen and its derivatives [13, 1].

Parallel to these developments in the hydrogen sector, complementary technologies that promote establishing a sustainable hydrogen economy are gaining increasing focus. Notably, blockchain technology offers extensive potential for digitizing the supply chain [14]. Due to its inherent properties, its application in the hydrogen market, especially for the seamless traceability of green hydrogen and its derivatives, is being discussed [15].

This paper examines the use of blockchain technology for the traceability of green hydrogen based on the following research questions:

RQ1: What role can blockchain technology play in the hydrogen supply chain?

RQ2: What are the requirements for a proof of origin for hydrogen, and how can a blockchain-based implementation succeed?

2. Background

2.1 Hydrogen Supply Chain

Efforts of the European Union and the Federal Government of Germany to successfully manage the energy transition require the rapid and widespread adaption of existing infrastructure and machinery. The extent of how existing supply chains are affected, can be seen in the example of North Rhine Westphalia, Germanys state with the highest industrial density of steel, chemical and power sites [16]. Only 6.2% of the primary energy consumption of the state has been achieved by sustainable energy sources in 2021 [17]. With an estimated hydrogen demand of 127-177 TWh by 2045, of which 90% is estimated to be satisfied by imports, challenges in transport, distribution, and storage become apparent [16].

In ambient atmospheric conditions, hydrogen is an ultralight gas with a density of just 0.082 kg/m³ and a high flammability range with air. This results in expensive and complex handling processes to safely move sufficient amounts needed in industrial applications [18]. According to Iulianelli *et al.* [19], 40-75% of the total expenses of the hydrogen supply chain are caused by distributing hydrogen from producer to consumer.

Niermann *et al.* [2] describe an exemplary supply chain for the import of green hydrogen by the following steps, which are visualized in figure 1. First, renewable energy sources, like wind turbines or photovoltaic systems, are utilized to generate electricity. Subsequently, the generated power is transformed into hydrogen using electrolysis. Produced hydrogen is conditioned before export to enable safe and efficient transportation. Rasul *et al.* [18] describe various conditioning approaches, including liquifying and pressurizing hydrogen, or converting hydrogen into derivatives such as ammonium. Conditioning approaches differ by maturity, investment, efficiency, capacity and lifetime, and therefore, must be selected depending on the requirements and nature of the use case. For example, the state of North Rhine Westphalia supports projects like "GET H2", which drive the buildout of hydrogen pipelines to distribute green hydrogen from the Netherlands to local industrial parks. While of substantial investment compared to other conditioning approaches, transportation via pipeline can be worthwhile for lower distances between production and consumption and provides a high maturity level [18]. Other means of transportation than pipelines include ships or trucks. The conditioned hydrogen is stored in reserves such as tanks or caverns within the importing country before it is distributed to the target sites. There, the conditioning process is reversed to reconvert into hydrogen or to achieve the desired physical conditions.

While additional research is needed to discover novel approaches and to further optimize the existing ones, the challenges of the hydrogen supply chain go beyond the safe and efficient transport and storage of hydrogen. According to Ratnakar *et al.* [20], the high cost and lack of existing infrastructure, which is only slowly developed and deployed, hinders the global energy transition. As most hydrogen is currently being produced using fossil fuels, the desired sustainability impact of adopting hydrogen is missed. The authors argue that the high cost and low availability of renewable electricity hinder the widespread adoption of green hydrogen. While additional research is needed to discover novel approaches and to further optimize the existing ones, the challenges of the hydrogen supply chain go beyond the safe and efficient transport and storage of hydrogen. Additionally, efforts of the European Parliament point towards a strong regulation of the production process of green hydrogen [21]. In 2023, the European Union passed the Renewable Energy Directive III, which pushes the disclosure of used energy mixes for the production of hydrogen in an effort to provide standardized guarantees of origin [22].

2.2 Blockchain in hydrogen supply chain

The hydrogen supply chain is characterized by its complexity and multifaceted nature. Blockchain technology is a central enabler for digitizing logistics, trade, and transaction processes in the hydrogen market [15]. Blockchain technology is a decentralized, distributed, tamper-proof, and cooperatively utilized data storage system [23, 24]. In these infrastructures, accounts are not centrally managed by a single entity but maintained

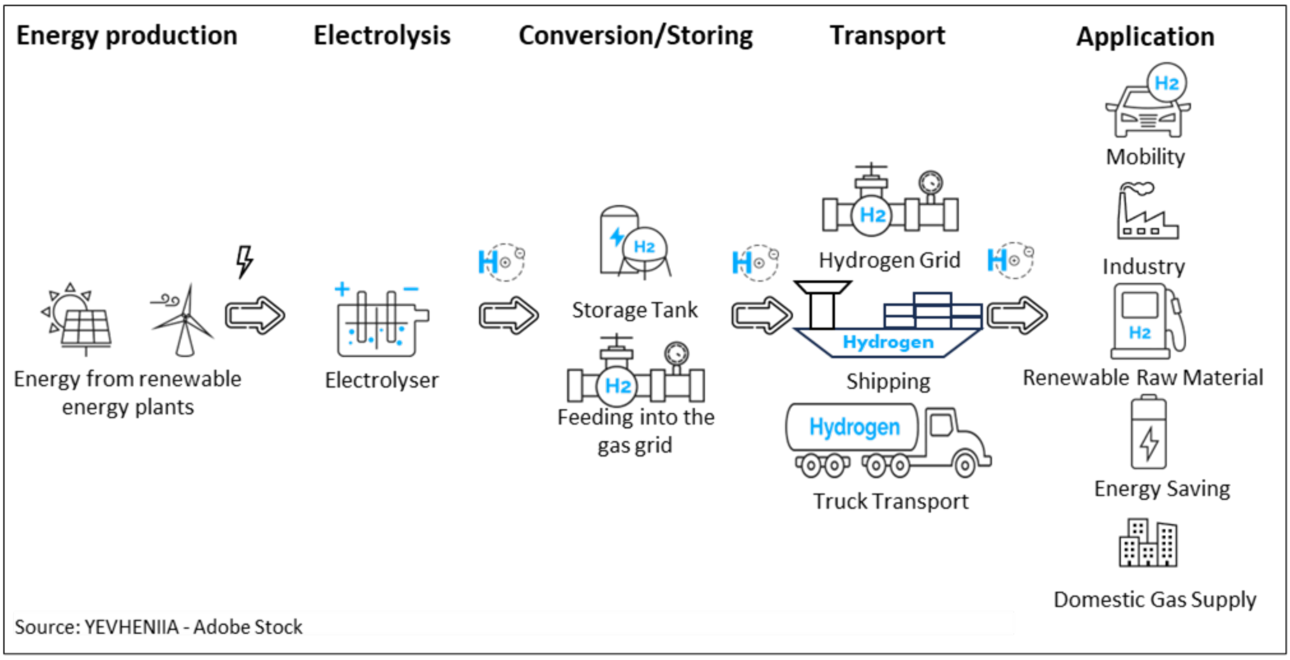

Figure 1: Hydrogen supply chain from energy production to application domain with hydrogen produced by Electrolyser [2]

within a peer-to-peer (P2P) network without a central authority [25]. Blockchain technology employs cryptographic mechanisms to encrypt data sent to the network and stores transactions in "blocks".

Data is distributed among network participants, represented by nodes, which all possess the entire transaction history of a blockchain [23]. A consensus mechanism allows for the validation of transaction contents and decides which node is allowed to form recent transactions into a new block of the blockchain. Once consensus is reached, the new block is added to the existing chain, and the change is broadcast within the network. Each block is linked to the preceding blocks by using hashing algorithms, making it difficult to remove or alter information on the blockchain [26]. Thus, the blockchain is attributed to being tamper-proof and creating a single truth point [27].

Blockchain technology can potentially revolutionize supply chains, especially logistics and inter-company exchange relationships [14]. It connects companies that may not know or trust each other, ensuring transparency, security, and efficiency. Blockchain technology allows companies to manage and synchronize their material, information, and financial flows in a traceable and seamless manner [14, 28, 29], making blockchain particularly suitable for supporting digital value creation in the green hydrogen supply chain.

One promising application of blockchain in the hydrogen economy is certification. The regulatory requirements in Europe stipulate that to produce green hydrogen, either the electricity used must be generated mainly from renewable energy sources or the electricity available in the power grid must be obtained from predominantly renewable energy production [22]. How this process is verified has not yet been conclusively defined. Thanks to its inherent properties, the blockchain promises to automate the necessary certification processes seamlessly from electricity generation to hydrogen production, prove its origin, and bring transparency to the supply chain.

3. Methodology

First, to answer the underlying research questions specified in section 1, a systematic literature review was conducted to examine the present status of hydrogen certification in research. This was added by desk research analysis to further complete the findings with already existing regulatory frameworks regarding the certification of hydrogen in Germany and the European Union. Based on the collected data, a requirements engineering approach was used to derive requirements for a digital solution for certifying renewable hydrogen.

The systematic literature review followed the established guidelines by vom Brocke *et al.* [30] and Webster & Watson [31]. First, the scientific literature database *Scopus* was selected, which was searched in the summer of 2024 using the search term *("proof of origin" OR "Certification" OR "certificate" OR "guarantee of origin") AND "hydrogen."* The literature search was limited to English-language articles published in peer-reviewed journals or conference proceedings. Based on the European hydrogen strategy for a climate-neutral Europe, published in 2020, the period considered for publication was set from 2020 to 2024 [6]. Further, only literature in which the search terms appear in the title, keywords, or abstract was included. This resulted in a selection of 163 articles. Second, the title, keywords and abstract were screened for relevance of content, which led to the selection being reduced to 27 articles. Finally, through a manual full-text screening, which was completed by a forward and backward search, 12 relevant articles were identified.

Additionally, government regulations from the European Union and especially from Germany that are described in the identified literature were added. In this way the regulatory perspective was also included.

The data collection formed the basis for deriving requirements for a digital certification solution for hydrogen. Therefore, according to Pohl and Rupp [32], the requirements engineering approach was used. The method consists of a five-step process model that allows specification and management of requirements. The process is shown in figure 2.

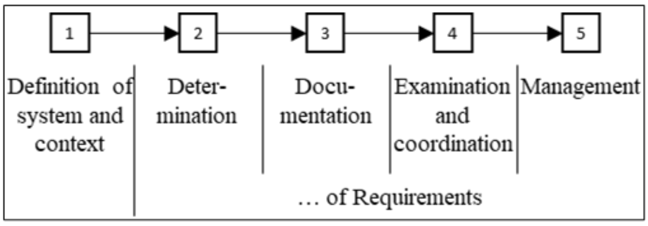

Figure 1: Requirements engineering process according to [32]

First, the system and context were delimited. This paper focuses on the certification of sustainability of hydrogen produced in Germany or transported to Germany through an international or national supply chain. Then, the data from the systematic literature research and the regulatory frameworks were used to determine the requirements. According to Kano *et al.* [33] the derived requirements were divided into basic, performance, and excitement factors. The documentation of the requirements is carried out in section 4. Future scientific work will aim to challenge the identified requirements from the literature and regulatory databases with hydrogen experts. This will also allow the authors to add further requirements derived from expert interviews and workshops. Lastly, the requirements will be translated into design principles, which is the basis for the design process of a blockchain-based solution for the certification of hydrogen.

4. Results

4.1 Requirements for a blockchain-based proof of origin for green hydrogen

In total, 11 requirements were identified from scientific literature and regulatory frameworks. The results were categorized by basis, performance, and excitement factors and are presented in table 1.

Table 1: Derived requirements for green hydrogen certification

Requirement	Source
Basic factors	
Regulatory compliance	[34], [1]
Integrity and accuracy of data	[1], [35]
No double counting	[36], [37], [35]
Consideration of different production pathways	[34], [1], [37]
Transparency	[37], [1], [36]
Performance factors	
Adaptability	[38]
Emission accounting	[34], [39], [40], [41], [38], [13], [37], [42], [37], [43], [35], [44]
International interoperability	[39], [45], [46], [43], [35]
Holistic supply chain integration	[37], [1], [40], [13], [46], [38], [36], [35]
Excitement factors	
Holistic sustainability assessment	[34], [39], [45], [37]
Tradability	[39]

A survey of international energy experts carried out by Goodwin *et al.* [34] revealed that *regulatory compliance* is the criterion most frequently rated as "essential" for a certification solution. This is also confirmed by Abdin [1], who considers this requirement as a basis for technology-based certification solutions. Examples for important regulatory requirements that must be met by German hydrogen players are the European Renewable Energy Directive II (REDII) [43], the European Renewable Energy Directive III (REDIII) [35], and the German Federal Immission Control Act (37. BImSchV) [44].

In the complex networks of hydrogen supply chains, data is exchanged at numerous intersection points. The integrity and accuracy of data must be ensured to operate efficiently and to be able to prove compliance with legal requirements [1]. According to REDIII [35], this also applies to data included in a certification solution. The directive requires that the issued proofs of origin are accurate, reliable and fraud-proof.

Another requirement for the certification solution is to guarantee that emission reductions and the certificate itself are not *double-counted* along the supply chain [36, 37]. This is particularly important for the intersection point between renewable energy and hydrogen certificates [37]. This requirement can also be found according to REDIII [35]. The directive requires that for one unit of sustainable energy only one proof of origin can be created and that every unit of sustainable energy can only be considered once.

In order to allow everyone to assess the sustainability of the hydrogen available to them, *all production pathways* should be certified [37, 34]. This includes the corresponding production inputs and various hydrogen products [34]. As a result, sustainable hydrogen can be clearly distinguished from less sustainable variants [1].

Existing solutions for the certification of hydrogen do not enable end-to-end tracking due to their centralized structures. This results in a lack of *transparency*, which in turn indicates a certain susceptibility to manipulation [1]. Due to the increasing decentralization in the energy market, there is a need for a consistent traceability [36].

To date, there is no standardized classification system that defines when hydrogen is considered sustainable. In particular, the definition by color is not meaningful and implies sustainability, especially via the green color, without providing verified arguments for this [41]. It is therefore necessary to create transparency and comparability by linking the definition to the carbon content of hydrogen [37]. Beyond that, as new hydrogen production processes may be developed in the future certification solutions must be *adaptable* to new conditions [38]. Accordingly, a certification solution should include *emission accounting*. From a regulatory perspective, according to RED II [43] and RED III [35], hydrogen is defined renewable if it is produced by electrolysis based on renewable energy sources. In addition, various constellations and specific requirements like additionality, geographical correlation and temporal correlation are mentioned. However, a specified threshold for carbon content of green hydrogen is still missing. RED II [43] only contains the requirement that hydrogen may be considered renewable if its use leads to a 70 percent reduction in CO_2 emissions. This has already been translated into German law with the 37. BImSchV [44]. An exception is the recently published import strategy of the German Federal Government, which sets the GHG limit at a maximum of 3.4 kg CO_2 eq/kg H_2 [12]. It is not known at the time of publication of this article whether this threshold will be incorporated into a legal provision.

The incompatibility of certificate solutions between import and export countries complicates international trade and hinders the establishment of a global hydrogen market. Therefore, it is necessary to ensure the *international interoperability* of certificates [46]. In addition, different countries have different views on which criteria should be used for the classification and certification of renewable hydrogen. Exporting countries such as Chile or Australia are therefore facing the challenge of having to decide which certification solutions and standards they want to comply with [41]. On the other hand, countries relying on hydrogen imports, such as Germany, will need to decide which approaches they accept [39]. For both cases, an international harmonization would greatly reduce friction of hydrogen trade. From a regulatory perspective RED II and RED III can be seen as attempts to harmonize the European hydrogen market [43, 35].

The example of blue hydrogen shows that emission accounting is applied very differently from case to case [37]. Accordingly, for a standardized certification, it is necessary to integrate the whole supply chain (*holistic supply chain integration*) from electricity generation to end-user consumption [1, 13]. This also means that hydrogen-based products like green steel must be included in the certification solution [38]. Furthermore, the intersection points has to be defined, so that the transfer of information is regulated between the different supply chain participants [37]. However, the RED III announces a database for tracking of liquid and gaseous renewable fuels and recycled carbon-containing fuels. Here, among others, information about the lifecycle carbon emissions of hydrogen that occur from the place of production to the moment the hydrogen is used or traded in the European Union will be saved [43].

In addition to the carbon emissions that occur along the hydrogen supply chain, further environmental and social aspects have to be considered [37]. For example, the electrolysis process has a high demand for water, which can negatively impact water resources, especially in water-stressed regions [34]. Therefore, a *holistic sustainability assessment* is necessary for certification.

According to Steinbach & Bunk [39], who investigated a suitable hydrogen market design by conducting interviews in five expert groups, most experts prefer a system that allows for the *tradability* of the certificates.

4.2 Blockchain for hydrogen certification

The use of blockchain and certificates is still relatively new in the energy industry and their synergies are not investigated sufficiently to date [36, 47]. Research in the field of blockchain focuses primarily on its use in financial and general supply chain management applications, while the fields of application in hydrogen networks are hardly considered [48]. To help close this research gap, this section explains how blockchain-based solutions can contribute to fulfill the identified requirements for certifying the sustainability of hydrogen. The explanations are based on the previously shown example of a supply chain for hydrogen produced by an electrolysis process (figure 1).

Starting with energy generation, it can be observed that the electricity grid is becoming increasingly digitized. This is accompanied by the challenge of guaranteeing data security [36]. By capitalizing on increasing digitization, blockchain offers a solution for data security challenges, as data manipulations become known to the network through the cryptographic processes and hash functions of blockchain [49]. Additionally, the energy market is becoming increasingly decentralized due to the spread of renewable energy plants [50]. In such an environment, the technology can provide traceability of data on renewable energies by distributing transparent information between the different actors in the energy market [50, 36]. The collection, network-wide distribution and tamper-proof storage of data are rendering blockchain to be a suitable approach for proof of origin or certification cases. A general framework for a blockchain-based certification process is described by Wannack [15]. The author suggests that energy trading between an electricity producer and the electrolysis operator can take place by tokenizing the amount of electricity produced, storing the tokens on a blockchain and transfer them as proof of origins.

At the second stage of the hydrogen supply chain, sustainable energy is used by electrolysis operators to produce green hydrogen. According to Ferraro *et al.* [13] the blockchain offers the potential to convert the available electricity data into proof of origins for hydrogen automatically using smart contracts. Data on the plant model and the performance of the electrolyzer are taken into account for this purpose. In addition, smart contracts can be used to measure "the quantity of carbon dioxide avoided in relation to the quantity of hydrogen produced" ([13], p.5).

The proof of origin is passed on along the subsequent stages of the hydrogen supply chain, including conversion, transport, storage and consumption. In these stages the risk of data misuse is minimized by the tamper-proof architecture of the blockchain, creating trust between the supply chain actors. To tackle the oracle problem, further security mechanisms can be installed on the data-recording devices [9]. A blockchain-based solution can therefore assure the sustainability of the hydrogen.

Another challenge in supply chains which influences a certification solution is the unwillingness of actors to share data [51, 52]. According to Heeß [9], this can be solved by adding other confidence-building components such as identity management to the blockchain solution. Therefore, concerns regarding data protection can be counteracted by reducing the public disclosure of data. In addition according to Mould *et al.* [36], it is also noted that a blockchain-based solution has the potential to be accepted as an international standard due to its inherent advantages such as transparency and trust. This would solve the problems of the today's fragmented landscape of certification solutions and facilitate the cross-border trade of hydrogen.

In summary, blockchain-based solutions can replace conventional centralized certification solutions that do not offer consistent transparency. The decentralized architecture of a blockchain offers the potential to track every stage of a hydrogen supply chain and thus enable end-to-end certification for hydrogen from electricity production to the end consumer [1]. The proof of origins can be created automatically using smart contracts according to defined rules and passed on along the supply chain [13]. Moreover, the data stored on the blockchain is characterized by transparency and integrity, which makes the certification process secure and traceable [1].

5. Outlook

In this article, 11 requirements were derived from the literature and regulatory frameworks. These are shown in table 1. Despite the still rather low level of research on the certification of the sustainability of hydrogen, it is evident that there is already a broad consensus in research, particularly regarding the requirements for emissions accounting, holistic supply chain integration and a holistic sustainability assessment. However, conventional certification solutions are reaching their limits regarding the identified requirements for hydrogen certification. Innovative digital solutions are therefore needed, with blockchain proving to be particularly promising. Thanks to its inherent properties, it offers the potential for consistent end-to-end certification along the entire hydrogen supply chain. In addition, the data stored on the blockchain is characterized by transparency and tamper-proofness, which can result in a high level of trust in the solution. This brings the vision of an internationally standardized certification solution that facilitates cross-border trade within reach.

To date, the synergies between blockchain solutions and the certification of hydrogen have not been sufficiently investigated. This work represents a systematic contribution to closing this research gap. To this end, the existing literature and regulatory frameworks were first examined for requirements for hydrogen certification and then derived how the blockchain as the underlying technology of a solution can contribute to solving the requirements.

Building on this, further research work will aim to validate and supplement the identified requirements through interviews with practice partners. The requirements are then translated into design principles for a blockchain-based solution, which is the basis for the development of a practice-oriented solution. This procedure is already implemented in the research project described below.

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To explore the potential of blockchain technology in the hydrogen economy, a blockchain-based certification system for green hydrogen is being researched as part of the "DUH-IT" project. In this project, requirements for blockchain-based proof of origin are being gathered, focusing on developing and validating prototypes within a test network. The project seeks to create a reliable solution that ensures seamless traceability of green hydrogen, thereby enhancing transparency and security in the hydrogen supply chain. By utilizing blockchain technology, the system aims to prevent manipulation and ensure data integrity. The overarching goal is to develop innovative solutions that promote a sustainable hydrogen economy.

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