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Application of Blockchain Technologies for Traceability, Certification and Sustainable Governance in the Renewable Energy Sector

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Master's in Digital Technologies for Business

Supervisors:
Doctor João Carlos Ferreira, Assistant Professor with aggregation, ISCTE, University Institute of Lisbon

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Abstract

The ongoing global transition toward renewable energy demands robust systems for verifying the sustainability and traceability of energy production. However, existing mechanisms often suffer from limited transparency, vulnerability to manipulation, and administrative inefficiencies. These challenges compromise the credibility of environmental claims and hinder regulatory compliance and stakeholder trust.

Blockchain technology, with its inherent characteristics of decentralization, immutability, and transparency, offers a promising foundation for enhancing certification, traceability and governance systems in the energy sector.

This thesis investigates the application of this distributed ledger technology to support traceability, digital certification, and sustainable governance in renewable energy environments. It combines a comprehensive literature review with empirical insights gathered from industry professionals, including contributors from Greenvolt, a leading European renewable energy company.

Keywords: Blockchain, Renewable Energy, Governance, Guarantees of Origin, Traceability, Immutability, Tokenization

Resumo

A atual transição global para as energias renováveis exige sistemas robustos para verificar a sustentabilidade e a rastreabilidade da produção de energia. No entanto, os mecanismos existentes sofrem frequentemente de transparência limitada, vulnerabilidade à manipulação e ineficiências administrativas. Estes desafios comprometem a credibilidade das alegações ambientais e dificultam a conformidade regulamentar e a confiança das partes interessadas.

A tecnologia Blockchain, com as suas caraterísticas inerentes de descentralização, imutabilidade e transparência, oferece uma base promissora para melhorar os sistemas de certificação, rastreamento e governança no sector da energia.

Esta dissertação de mestrado investiga a aplicação desta tecnologia de registo distribuído para apoiar a rastreabilidade, a certificação digital e a governança sustentável em ambientes de energias renováveis. A dissertação combina uma revisão literatura estruturada com conhecimentos empíricos recolhidos junto de profissionais do sector, incluindo colaboradores da Greenvolt, uma empresa europeia líder no sector das energias renováveis.

Palavras-chave: Blockchain, Energia Renovável, Governação, Garantias de Origem, Rastreabilidade, Imutabilidade, Tokenização

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List of Abbreviations

AIB	Association of Issuing Bodies
API	Application Programming Interface
DSRM	Design Science Research Methodology
DvP	Delivery-versus-Payment
EECS	European Energy Certificate System
EEGO	*Entidade Emissora de Garantias de Origem*
ERSE	Energy Services Regulatory Authority
ESG	Environmental, Social, and Governance
EU	European Union
FBA	Federated Byzantine Agreement
GoO	Guarantee of Origin
GoOs	Guarantees of Origin
IEEE	Institute of Electrical and Electronics Engineers
ISC	Issuance Smart Contract
MWh	Megawatt hour
NFT	Non-Fungible Token
PoS	Proof of Stake
RECs	Renewable Energy Certificates
RED III	Renewable Energy Directive
REN	*Rede Elétrica Nacional*
RN	Renewable Energies
SCP	Stellar Consensus Protocol
WoSCC	Web of Science Core Collection

Chapter 1. Introduction

1.1. Background and Motivation

Over the past decade, global efforts to make energy production and supply sustainable have accelerated the transition toward renewable energy sources such as solar, wind, and biomass [1].

As countries and corporations face mounting pressure to meet sustainability targets and reduce carbon emissions, the integrity and transparency of environmental data have become essential for both compliance and stakeholder trust. Mechanisms such as Renewable Energy Certificates (RECs), Guarantees of Origin (GoOs), and sustainability disclosures play a central role in demonstrating that energy is produced from renewable sources and that environmental commitments are being fulfilled [2].

At the same time, emerging digital technologies are being explored to strengthen the infrastructure supporting the energy transition.

One of the most promising technologies in this regard is blockchain [3]. The distributed ledger technology has evolved into a broader paradigm for managing decentralized, secure, and tamper-resistant records. Its characteristics, immutability, transparency, and decentralization, make it especially suitable for environments that require trust among multiple parties and high integrity of shared data [4].

Among the many use cases being studied and piloted, the renewable energy sector has emerged as a potentially relevant area for blockchain application. In recent years, initiatives around the world have begun to explore blockchain as a tool for tracking energy production [5], certifying green energy origins [2], facilitating peer-to-peer energy trading [6], and managing carbon credit markets [7]. These implementations reflect growing interest in using distributed ledger technology to simplify, secure, and scale sustainability-related processes.

Despite the enthusiasm, blockchain adoption in the energy sector remains fragmented and exploratory. While pilot projects exist, when it comes to RN certification, many organizations face challenges in identifying clear requirements, aligning blockchain architectures with regulatory frameworks, and ensuring real-world usability. This creates an opportunity for applied academic research, particularly through investigation and design of prototype systems that demonstrate how blockchain could support transparency, traceability, and governance in renewable energy environments [8].

This thesis is motivated by the opportunity to investigate how blockchain technologies can contribute to the improvement of traceability and certification processes in this sector. The aim is to contribute not only to academic understanding but also to the practical development of conceptual frameworks that can support more transparent and sustainable energy systems.

1.2. Problem Identification

Despite the increasing adoption of renewable energy worldwide, the mechanisms used to certify and trace the origin of renewable electricity, such as GoOs and RECs, remain limited by several critical challenges [9]. Existing systems often rely on centralized registries or third-party intermediaries, which can result in fragmented record-keeping, limited interoperability, and a lack of real-time transparency. This increases the risk of data manipulation, double counting of certificates, and administrative inefficiencies, ultimately undermining stakeholder trust in sustainability claims [5].

Moreover, as regulatory pressure on companies to demonstrate genuine environmental impact intensifies, there is a growing need for certification and reporting frameworks that are not only robust but also easily auditable and resistant to tampering. Traditional digital solutions and manual processes struggle to deliver the level of integrity, automation, and transparency demanded by both regulators and energy market participants [10].

The emergence of blockchain technology offers the potential to address these shortcomings by providing decentralized, tamper-proof, and transparent ledgers for managing the issuance, transfer, and validation of renewable energy certificates [2]. However, the application of blockchain in this domain is still in its early stages, and significant gaps remain in terms of practical design, business requirements alignment, and industry adoption [8]. Particularly for companies operating at the intersection of renewable energy production and sustainability governance.

This thesis addresses these gaps by investigating how blockchain technologies can be systematically designed and evaluated to enhance traceability, certification, and governance in the renewable energy sector, thereby supporting more credible and efficient sustainability practices.

1.3. Objectives

The primary aim of this thesis is to contribute to both academic and practical advancement in the fields of traceability, certification, and blockchain application within the renewable energy sector. The research is designed to deepen theoretical understanding while delivering a conceptual framework tailored to real-world challenges, with a particular emphasis on the traceability and certification of GoOs.

The specific objectives of this thesis are:

- To advance academic understanding of traceability, certification, and blockchain integration in renewable energy systems.
- To design a conceptual framework for blockchain-based traceability, specifically applied to GoOs, addressing both technical and organisational requirements for secure, transparent, and auditable certification of renewable electricity.
- To collect and integrate stakeholder input from industry professionals, ensuring that the framework addresses practical business needs, regulatory considerations, and real-world operational challenges.
- To evaluate the proposed framework using expert feedback and alignment with industry best practices, assessing its potential impact on the credibility, efficiency, and governance of renewable energy certification processes.

1.4. Methodology

This thesis employs the Design Science Research Methodology (DSRM) as its primary research framework. DSRM is particularly suitable for studies aiming to bridge the gap between theoretical knowledge and practical application by developing and evaluating innovative digital solutions to real-world problems [11]. Within the context of this research, this methodology provides a structured approach to address the core challenges of traceability, certification, and governance in the renewable energy sector, specifically those associated with Guarantees of Origin.

The research process begins with the identification and analysis of current limitations in existing traceability and certification systems for renewable energy [8]. This step is informed by both a systematic literature review and exploratory discussions with industry professionals. Based on this analysis, the thesis defines the main objectives and functional requirements for a

blockchain-based framework tailored to the needs of renewable energy certification, with an emphasis on traceability and auditability.

In the early stages of this research, several potential areas for applying blockchain in the energy sector were considered, such as peer-to-peer energy trading, financial power purchase agreements, and ESG reporting tools [12]. However, preliminary stakeholder engagement with the energy management director at Greenvolt indicated that GoOs represent the most practical and pressing domain for innovation. GoOs are a regulated and widely adopted mechanism in Europe, yet current processes remain highly centralized, manual, and vulnerable to inefficiencies, as evidenced by the reliance on REN's digital platform and the lack of automation in certificate transfers. These limitations highlight a clear design opportunity where blockchain can enhance transparency, traceability, and trust. For this reason, the conceptual artifact designed in this thesis is explicitly focused on addressing the challenges associated with GoOs, rather than alternative energy market mechanisms.

Following the establishment of objectives, the design and development phase focuses on creating a conceptual framework for blockchain-enabled traceability. This framework is informed by academic literature, existing technical standards, and empirical insights from stakeholders in the energy sector. The practical relevance of the framework is demonstrated through illustrative use-case scenarios and, where possible, simulated prototype logic.

The evaluation phase involves critical assessment of the proposed framework through expert feedback, benchmarking it against industry standards and best practices for energy certification and governance. This iterative process ensures that the framework is not only theoretically sound but also aligned with the real-world needs of energy market participants and regulatory authorities.

Finally, the methodology encompasses the communication of findings and recommendations to both academic and professional audiences, thereby contributing to the broader discourse on digital innovation and sustainability in the energy sector. The literature review underpinning this research adheres to the PRISMA methodology, ensuring a transparent and systematic approach to the identification and analysis of relevant studies [13].

1.5. Research Questions

Building on the contextual background, the problem definition, the objectives, and the methodological foundations established in the previous subsections, this thesis is guided by the following research questions. Together, they frame the design, justification, and evaluation of the blockchain-based conceptual framework developed throughout this work.

- RQ1: *How can a blockchain-based architecture be designed to enhance end-to-end traceability, integrity, and auditability of Guarantees of Origin (GoOs), when compared with the current EEGO-based certification process in Portugal?* This question directs the technical and architectural dimension of the research, focusing on how blockchain can address traceability gaps identified in the literature and in practical GoO operations.
- RQ2: *Which functional and non-functional requirements must a blockchain-enabled GoO framework fulfil to ensure interoperability with existing European infrastructures, such as REN/EEGO and the AIB EECS Hub, while remaining compliant with evolving regulatory frameworks, including RED III?* This question structures the requirements analysis and system design, ensuring that the proposed solution remains institutionally realistic and aligned with European policy.
- RQ3: *How do domain experts involved in renewable energy certification and trading (e.g., energy managers, asset managers, risk managers, and IT/security specialists) perceive the usefulness, feasibility, and risks associated with the proposed blockchain-based framework?* This question frames the evaluation stage of the Design Science Research Methodology and ensures that the artifact is assessed from the standpoint of practitioners directly involved in GoO issuance, validation, and commercialization.
- RQ4: *To what extent can the proposed conceptual framework contribute to strengthening sustainable governance by improving transparency, reducing counterparty and greenwashing risks, and enhancing ESG reporting in the renewable energy sector?* This question links the technical architecture to broader governance and sustainability implications, ensuring that the framework contributes meaningfully to policy and organizational debates.

Together, these research questions connect the literature review, the Portuguese GoO context, the design requirements, the proposed blockchain architecture, and the expert-based evaluation, providing a coherent analytical lens for the thesis.

1.6. Contributions

This thesis contributes to academic research, methodological practice, and the energy certification domain by bridging blockchain concepts with the operational and regulatory characteristics of the Portuguese Guarantees of Origin system and also cross-border trading to the EU and European

regulation for this type of renewable energy certification process. The contributions fall into four complementary dimensions:

- Theoretical Contribution: This work consolidates and critically synthesizes academic literature on blockchain applications in renewable energy, with specific emphasis on certification mechanisms such as GoOs and Renewable Energy Certificates (RECs). The State of the Art and PRISMA-based review identify major themes, including tokenization of energy units, decentralized market structures, traceability architectures, privacy-preserving mechanisms, and carbon-market integrity. The review also highlights a gap in audit-grade, GoO-specific blockchain models tailored to national regulatory infrastructures such as REN/EEGO. By clarifying these gaps, the thesis positions certification as a technologically feasible and scientifically relevant domain for blockchain integration.
- Methodological Contribution: The thesis applies a combined methodological approach involving a PRISMA systematic review and the Design Science Research Methodology (DSRM). The PRISMA review establishes a structured and transparent evidence base, while the DSRM framework guides the iterative development of requirements, conceptual architecture, information flows, and stakeholder-facing mockups. The evaluation stage, based on targeted expert interviews, demonstrates how design science can be operationalized in highly regulated domains, providing a replicable methodology for similar energy-sector digitalization studies.
- Practical and Industrial Contribution: The thesis proposes a blockchain-based conceptual framework grounded in the operational reality of the Portuguese GoO issuance process, informed by insights from Greenvolt, a major renewable producer operating across multiple markets. The artifact integrates architecture layers, consensus mechanisms (FBA/SCP), functional and non-functional requirements, oracle-based metering validation, and stakeholder dashboards simulating producer, regulator, and registry perspectives. These outputs offer a structured blueprint for future prototypes, pilot tests, or internal digitalization initiatives within energy companies.
- Governance and Policy Contribution: By explicitly incorporating RED III, the AIB EECS standard, and national GoO regulatory constraints, the framework demonstrates how permissioned blockchain models can coexist with institutional roles already established in the European energy certification ecosystem (REN/EEGO, ERSE, AIB). The design illustrates how blockchain can strengthen governance objectives such as auditability, market trust, counterparty risk reduction, and mitigation of greenwashing practices. This

produces actionable insights for regulators, auditors, and corporate sustainability actors exploring more transparent certification infrastructures.

Overall, this thesis project contributes a structured, requirements-driven conceptual architecture for blockchain-enabled GoO traceability and certification, empirically grounded in expert feedback and aligned with the operational and regulatory context of the Portuguese renewable energy sector. These contributions aim not only to advance academic understanding but also to support future digitalization strategies, governance reforms, and prototype development in energy certification.

Chapter 2. State of the Art

2.1. Blockchain Applications in the RN Sector

2.1.1. Current Blockchain Applications in the Renewable Energy Sector

The integration of blockchain technology into the renewable energy sector has accelerated markedly in recent years, driven by the growing demand for decentralized, transparent, and efficient energy systems [3]. Blockchain's decentralized ledger capabilities offer solutions for a variety of longstanding challenges in energy management [14] including the verification of renewable energy production, facilitation of peer-to-peer (P2P) energy trading, automation of billing, and the streamlining of administrative processes [15], [16].

One prominent area of application is the issuance and management of RECs and GoOs. Blockchain platforms enable the digitalization of these certificates, ensuring that each unit of renewable energy generated is uniquely and immutably recorded. This approach addresses the risks of double counting and fraud by providing a transparent and auditable record of energy production and transfer [2].

Beyond certificate management, blockchain has been employed to foster peer-to-peer energy trading. In such systems, individual energy producers often prosumers with rooftop solar installations can sell excess electricity directly to local consumers via smart contracts. Platforms like PowerLedger in Australia and the Energy Web Foundation have demonstrated how blockchain can facilitate secure, real-time transactions without the need for central intermediaries [12]. These solutions not only empower consumers but also promote the integration of distributed renewable energy resources into the grid.

Additionally, blockchain is increasingly utilized to support microgrid management, decentralized demand response, and carbon credit trading [7]. In microgrids, blockchain coordinates energy flows, settlements, and load balancing among multiple participants [17]. For carbon markets, blockchain enhances the credibility of emission reduction claims by recording all transactions and retirements of carbon credits on an immutable ledger [18].

Despite these advancements, most implementations remain at the pilot or demonstration stage, facing hurdles such as regulatory uncertainty, scalability concerns, and the integration of legacy energy infrastructure. Nevertheless, the cumulative evidence from worldwide pilot projects suggests that blockchain holds significant promise for enhancing transparency, security, and efficiency in the renewable energy sector [19], [20].

2.1.2. Certification and Traceability

Certification and traceability are central to ensuring the credibility and integrity of renewable energy markets. Traditionally, certification schemes such as RECs and GoOs serve as the backbone for verifying the origin and environmental attributes of electricity supplied to the grid. Even though they serve similar purposes these two examples represent some of the current frameworks that are used for renewable energy certification of production, and they mainly differ by the countries or regions they are used for trading and issuing.

However, these mechanisms have been criticized for their reliance on centralized authorities, susceptibility to administrative errors, and lack of real-time auditability [8].

Blockchain technology offers a paradigm shift by providing a decentralized, tamper-resistant infrastructure for recording the issuance, transfer, and retirement of energy certificates. Each transaction on a blockchain is time-stamped, immutable, and transparent to all network participants, which mitigates the risk of double counting and fraud. For example, recent research has introduced consortium blockchain protocols to issue non-transferable green certificates, ensuring that certificates cannot be resold or reused, thereby enhancing trust and compliance in green power trading schemes [21].

The traceability enabled by blockchain extends beyond energy certificates. It allows for detailed tracking of every kilowatt-hour generated, transferred, and consumed linking production data from renewable facilities to the final consumer or corporate buyer. This end-to-end traceability is crucial for meeting regulatory requirements and for substantiating sustainability claims made by companies. In some advanced implementations, smart contracts automate the certification process: when renewable energy is produced and measured (e.g., via a smart meter), a certificate is automatically generated, registered, and can be instantaneously transferred to a buyer [21].

In addition to RECs and GoOs, *carbon credits* play an increasingly important role in renewable energy traceability and sustainability governance. Carbon credits are tradable certificates representing the reduction or removal of one metric ton of carbon dioxide (or equivalent greenhouse gas) from the atmosphere. These credits are vital in voluntary and compliance carbon markets, enabling companies and governments to meet climate targets or offset emissions. The process of generating, verifying, and trading carbon credits is complex and historically has faced challenges of double counting, lack of transparency, and market manipulation [7].

Blockchain-based solutions are now being developed to bring greater integrity and traceability to carbon credit systems [22]. By recording each stage of a carbon credit's lifecycle, issuance, transfer, retirement on an immutable ledger, blockchain can prevent credits from being double-sold or claimed multiple times. Furthermore, smart contracts can automate the validation of offset

projects and enforce the retirement of credits upon use, thus improving trust in the environmental impact of offset activities. Enhanced transparency also allows for the integration of co-benefit data (e.g., biodiversity, social impact), enabling a new generation of digital carbon assets with verifiable sustainability credentials [7].

Moreover, blockchain-based systems can integrate additional layers of information into certificates, such as metadata about the generation source, carbon intensity, and compliance with ethical or social standards. This enables new models for sustainable governance and supports ESG (Environmental, Social, and Governance) reporting obligations.

Nonetheless, challenges persist, particularly regarding standardization, interoperability with existing market platforms, and the alignment of blockchain protocols with evolving regulatory frameworks [14]. Recent literature emphasizes the need for continued research and pilot projects to validate blockchain's scalability and real-world impact on traceability and certification in renewable energy and carbon markets.

2.2. Literature Review

2.2.1. Search Method

To analyze the state of the art on the application of blockchain technologies in renewable energy traceability, certification and governance, a systematic literature review was conducted following the PRISMA methodology (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) [13]. PRISMA is a widely accepted and recommended approach for systematic reviews, providing a structured and transparent protocol for planning, executing, and reporting literature research. The adoption of this framework ensures clarity, replicability, and academic rigor of the literature review process, particularly suitable for research involving emerging technologies such as blockchain.

The search strategy was conducted in accordance with the PRISMA guidelines, resulting in a methodical and structured step-by-step process. Searches were carried out on the Scopus, IEEE Xplore and Web of Science Core Collection (WoSCC) databases. These databases were selected due to their extensive coverage of high-quality scientific and technical publications relevant to the fields that are being investigated for the fulfilment of this dissertation project.

The search terms were developed around three core dimensions: the technological perspective, including keywords such as "blockchain" and "smart contracts"; the sectoral application, covering terms like "renewable energy", "energy certification", and "guarantees of origin"; and the governance layer, which included concepts such as "traceability", "transparency", and

"sustainability". This multi-dimensional approach aimed to capture a comprehensive set of studies relevant to the application of blockchain in energy traceability and certification contexts.

To ensure the inclusion of recent and relevant literature aligned with the rapid development of blockchain-based energy solutions, the review was limited to studies published between 2020 and 2025. Furthermore, only articles published in English were considered, due to the dominance of English-language publications in international scientific literature and the standard indexing practices of the selected databases.

2.2.2 Results using the PRISMA Methodology

The systematic filtering process yielded a focused set of articles that provide insights into blockchain applications in the renewable energy sector. The final group of studies was categorized into five main themes: certificate issuance and *tokenization*, peer-to-peer trading, privacy and security, carbon and ESG alignment, and traceability models.

Figure 1, shown below shows the filtering process and results while applying PRISMA to the investigation topic in question.

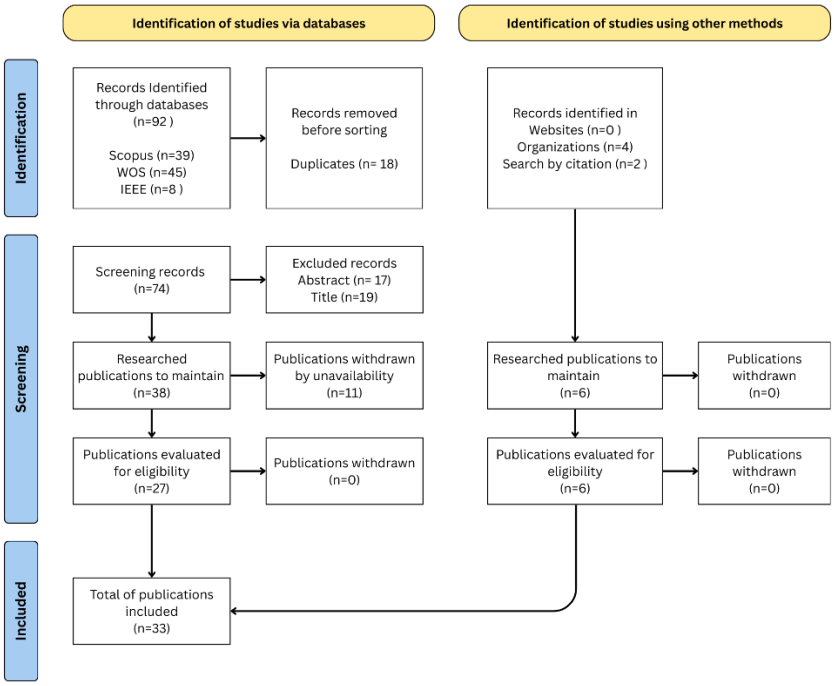


Figure 1 - PRISMA diagram, search process [13]

First, certificate issuance and *tokenization* studies demonstrated how blockchain can eliminate double counting and improve transparency in the lifecycle of GoOs and RECs. These works

emphasize automated issuance based on verified energy production data and the advantages of representing certificates as unique digital tokens [9].

Second, research on peer-to-peer trading and microgrids highlights blockchain's capacity to enable decentralized energy markets. Prosumers can directly trade surplus electricity, with smart contracts ensuring secure and transparent settlement. These findings confirm the feasibility of marketplace mechanisms in the proposed framework [23].

Third, privacy and security emerge as critical design factors. Studies stress the importance of permissioned blockchains, consensus mechanisms with low energy consumption and hybrid approaches that combine on-chain proofs with off-chain data. This aligns with the need to ensure GDPR compliance and protect sensitive information while maintaining transparency.

Fourth, the integration of carbon markets and ESG reporting is increasingly visible. Selected studies show that blockchain can link renewable energy certificates with carbon credits. improving accountability in voluntary and compliance markets.

Finally, the traceability models confirm that blockchain is well suited for end-to-end tracking of renewable energy production, certification, and consumption. These models demonstrate how verifiable audit trails can be created, enabling regulators and auditors to access tamper-proof records in real time.

Also in Table 1, all the articles used for the necessary research and reference for this project are clearly stated by title, author and date.

Table 1 – Articles found

Author	Title	Year
Z Wang, C Wang, W Wu, C Sun, Z Wu	A Blockchain-Based Game Approach to Multi-Microgrid Energy Dispatch	2024
T Wang, H Hua, Z Wei, J Cao	Challenges of blockchain in new generation energy systems and future outlooks	2022
S Zhang, J Xuan, Z Lyu, Y Fu, A Emrouznejad	Application Prospect of Blockchain in Renewable Energy Certificates	2020
M Vaccargiu, G Ibba, A Pinna	Topics Analysis and Trends on Blockchain applications in the Energy Sector	2024
Q Zhang, T Xu, D Wang, Z Liu, C Cheng, S Zheng, G Wang	Study of Traceability System of Renewable Energy Power Trading Based on Blockchain Technology	2022
Y Zuo	Tokenizing Renewable Energy Certificates (RECs) - A Blockchain Approach for REC Issuance and Trading	2022
P Loreti, L Bracciale, E Raso, G Bianchi, E R Sanseverino, P Gallo	Privacy and Transparency in Blockchain-Based Smart Grid Operations	2023

J Li, X Liu, X Shao	Collaborative carbon emission reduction in power supply and demand entities based on blockchain technology	2024
A K Vishwakarma, P K Patro, A Acquaye, R Jayaraman, K Salah	Blockchain-based peer-to-peer renewable energy trading and traceability of transmission and distribution losses	2024
R.-V. Tkachuk, D Ilie, R Robert, V Kebande, K Tutschku	On the performance and scalability of consensus mechanisms in privacy-enabled decentralized renewable energy marketplace	2024
V R Kebande, J Ding, M Quwaider, F M Awaysheh, Y Jararweh	Blockchain-Enabled Renewable Energy Traceability with a Crypto-based Arbitrage Pricing Model	2023
M Gerardi, F Fallucchi, F Orecchini	Blockchain Technology for Monitoring Energy Production for Reliable and Secure Big Data	2023
S Yao, X Tian, J Chen, Y Xiong	Privacy Preserving distributed smart grid system based on Hyperledger Fabric and Wireguard	2023
A Nofuentes, J J Hernandez, L Pons	Blockchain-based Guarantees of Origin issuing platform	2022
I Haryani, I A Aditya, A H Nuraini, S Widiyanesti, A Alamsyah, E Nurhazizah, M N Hakim, T Ruwani, M Z D Arli, N D Girawan	Blockchain-based renewable energy certificate system in Indonesia	2025
D Wang, Z Wang, X Lian	Research on Distributed Energy Consensus Mechanism Based on Blockchain in Virtual Power Plant	2022
G C Okwuibe, T Brenner, P Tzscheutschler, T Hamacher	Survey and Analysis of Local Energy Markets Based on Distributed Ledger Technologies	2023
Z Zhao, J Guo, X Luo, J Xue, C S Lai, Z Xu, L L Lai	Energy Transaction for Multi-Microgrids and Internal Microgrid Based on Blockchain	2020
Shaoyuan Yu, Jing Yang, Jia Ni, Chunyi Chen, Tao Yu, Ailin Chen, Jian Geng, Hua Zhong, Weihua Weng, Tao Wei	Secure traceability mechanism of green electricity based on smart contracts and provenance model	2024
Hamed Taherdoost	Blockchain Integration and Its Impact on Renewable Energy	2024
Kufre Esenowo Jack, Ernest Ozoemela Ezugwu, Chrysogonus Chukwumere Ogomaka, Oghenekaro Kennedy Omokere, Samuel Akinwumi Adeniji, Grace Tiyeyosi Ogbenfore	The Convergence of Blockchain, Smart Microgrid, and Energy Market	2024
Ameni Boumaiza, Kenza Maher	Leveraging blockchain technology to enhance transparency and efficiency in carbon trading markets	2024
A T Mithul Raaj, B Balaji, R R Sai Arun Pravin, Rani Chinnappa Naidu, M Rajesh Kumar, Prakash Ramachandran, Sujatha Rajkumar, Vaegae Naveen Kumar, Geetika Aggarwal, Arooj Mubashara Siddiqui	Intelligent Energy Management across Smart Grids Deploying 6G IoT, AI, and Blockchain in Sustainable Smart Cities	2024

Abdullah Ayub Khan, Asif Ali Laghari, De-Sheng Liu, Aftab Ahmed Shaikh, Dan-Dan Ma, Chao-Yang Wang, Asif Ali Wagan	EPS-Ledger: Blockchain Hyperledger Sawtooth-Enabled Distributed Power Systems Chain of Operation and Control Node Privacy and Security	2021
Uyikumhe Damisa, Nnamdi Nwulu I	Blockchain-Based Auctioning for Energy Storage Sharing in a Smart Community	2022
Mousa Mohammed Khubrani, Shadab Alam	Blockchain-Based Microgrid for Safe and Reliable Power Generation and Distribution: A Case Study of Saudi Arabia	2023
Jalalud Din, Hongsheng Su, Sajad Ali, Muhammad Salman	Research on Blockchain-Enabled Smart Grid for Anti-Theft Electricity Securing Peer-to-Peer Transactions in Modern Grids	2024

In addition to peer-reviewed academic literature, this study incorporates a set of primary regulatory and institutional sources that define the legal and operational context of Guarantees of Origin within the European Union. These documents are not analyzed as empirical studies but are included to ensure regulatory accuracy and compliance alignment of the proposed system architecture.

Specifically, European legislation such as the Renewable Energy Directive (RED III), along with the European Energy Certificate System (EECS) Rules issued by the Association of Issuing Bodies (AIB), establish the formal requirements governing the issuance, transfer, and cancellation of GoOs. At the national level, the procedures defined by ERSE and EEGO provide the operational framework for GoO implementation in Portugal. Furthermore, horizontal regulations such as the General Data Protection Regulation (GDPR) and the NIS2 Directive introduce cross-cutting requirements related to data protection, cybersecurity, and system resilience. These regulatory sources inform the design constraints and compliance considerations discussed throughout the thesis and are all mentioned in Table 2.

Table 2 – Regulatory and Compliance Sources Relevant to Conceptual Framework

Source	Scope	Role in Thesis	Jurisdiction
Directive (EU) 2023/2413 (RED III)	Renewable energy policy	Defines legal basis of Guarantees of Origin	European Union
EECS Rules (AIB)	GoO issuance & transfer	Operational framework for GoO registries	European / Cross-border
ERSE / EEGO Manual of Procedures	National GoO implementation	Defines issuance, validation, and auditing procedures	Portugal
GDPR (EU 2016/679) / NIS2 (EU 2022/2555)	Data protection & cybersecurity	Compliance and risk constraints for digital platforms	European Union

2.3. Discussion

The literature reviewed in this chapter demonstrates that blockchain technologies are being explored across a wide spectrum of energy-sector applications, including peer-to-peer energy trading, decentralized flexibility markets, asset management, carbon accounting, and renewable-generation traceability. The diversity of use cases identified through the PRISMA methodology illustrates the strong academic interest in blockchain as an enabler of decentralized, transparent, and automated energy systems [4]. Yet, despite this breadth, the literature also reveals that most blockchain-energy applications remain conceptual, restricted to pilots, or constrained by regulatory, infrastructural, and market-design barriers [8].

A central insight emerging from the review is the contrast between high theoretical potential and limited practical deployment [24]. For example, peer-to-peer trading and transactive energy systems are often cited as ideal fits for blockchain, but their implementation is limited by tariff regulation, metering rules, and the technical requirements of grid stability [4]. Similarly, blockchain-based flexibility markets and automated grid balancing remain largely experimental due to interoperability challenges between grid operators and distributed energy resources. These findings suggest that only a subset of blockchain applications can realistically progress beyond pilot stages in the current regulatory and institutional landscape.

Within this broader context, renewable-energy certification and traceability emerge from the literature referred in this study as one of the most mature and viable domains for blockchain integration [21]. Studies consistently highlight that existing certification systems such as Renewable Energy Certificates (RECs), Guarantees of Origin (GoOs), and corporate ESG reporting mechanisms suffer from fragmentation, limited auditability, and delays in data synchronization, [25], [9]. Although these systems operate within clearly defined regulatory frameworks, their supporting infrastructures often rely on manual data handling, monthly aggregation cycles, and bilateral off-platform transactions that reduce real-time transparency and increase reconciliation work.

The Portuguese case is particularly aligned with these findings. EEGO ensures compliance with European directives and operates an effective issuance system, but still depends on REN's monthly metering aggregation, separate communication channels for commercial transactions, and centralized registry architecture that lacks automated verification[26]. Similar operational inefficiencies are documented in other European registries, contributing to risks of double counting, delays in certificate transfer recognition, and limited visibility for producers, auditors,

and corporate buyers. And these are some of the many concerns that industry experts interviewed for this research on the GoO commercial process [27].

At the same time, the literature identifies several challenges associated with blockchain adoption itself [8]. These include governance complexity, integration with legacy systems, data privacy concerns, and the need for permissioned consensus mechanisms that meet energy-sector performance and compliance requirements. Public blockchain models are generally unsuitable for sensitive certification and metering data, while permissioned models require coordinated institutional participation. These challenges reinforce the need for domain-specific, rather than generic, blockchain solutions.

Bringing these strands together, the review indicates that the GoO certification process represents the most appropriate and high-impact application area for blockchain among the alternatives explored. Unlike peer-to-peer trading or decentralized markets which face structural regulatory barriers, certificate issuance and verification already operate within a stable legal framework and rely heavily on data integrity, transparency, and auditability. Blockchain therefore has the potential to enhance an existing, widely adopted system, rather than requiring the creation of entirely new market structures. In addition, the literature shows that certificate-based mechanisms are increasingly important for corporate sustainability reporting, international energy claims, and consumer trust, reinforcing the relevance of improving their reliability [2].

For these reasons, this thesis focuses specifically on the blockchain-enabled transformation of the GoO issuance and verification process, rather than on broader blockchain-energy applications. This direction not only aligns with the gaps identified in both European and Portuguese certification infrastructures but also offers a realistic, institutionally anchored pathway for digital innovation. The insights from the literature thus form the basis for the design requirements and system architecture developed in Chapter 3 and Chapter 4.

Chapter 3. Industry Context and Opportunity Analysis

3.1. Context in the EU Market

The European renewable-energy sector has undergone a profound transformation over the past decade, driven by the objectives of the European Green Deal and the Renewable Energy Directive (RED III), which mandate that member states guarantee the traceability and authenticity of renewable electricity [28]. Within this framework, Guarantees of Origin (GoOs) have become the principal instrument for certifying that a given amount of electricity was generated from renewable sources. Each GoO corresponds to one megawatt-hour (MWh) of renewable energy, acting as an auditable proof of origin that underpins environmental claims, compliance reporting, and voluntary corporate sustainability targets.

Across Europe, the management of GoOs follows a harmonized model established by the Association of Issuing Bodies (AIB). National registries such as EEGO (*Entidade Emissora de Garantias de Origem*) in Portugal, CertiQ in the Netherlands, or Ofgem REGO in the United Kingdom, operate under the AIB's European Energy Certificate System (EECS). These entities are responsible for issuing, transferring, and cancelling certificates within their jurisdictions, while the AIB hub enables cross-border interoperability. The result is a decentralized but standardized European ecosystem in which energy producers, traders, utilities, and corporate consumers interact through a mixture of digital registries and bilateral commercial channels [29].

From the producer's perspective, GoOs constitute an additional revenue stream that complements electricity sales. Renewable generators, such as Greenvolt, participate by ensuring that their production data captured through certified IoT-enabled meters is accurately transmitted to the issuing authority.

Operational challenges expose structural limitations in the current design of national GoOs registries and suggest an opportunity for technological enhancement. Specifically, blockchain-based systems present potential to improve transparency, trust, and automation across the GoO lifecycle linking metering data, issuance records, and financial transactions within a tamper-proof, auditable framework.

3.2. Current RN Certificate Issuing Process from a Producer's Point of View

Talking from a producer point of view from the European Union , (Greenvolt) after gathering important data and insights from experts in the sector. In the Portuguese energy system, the issuance of Guarantees of Origin (GoOs) is centrally managed by REN (Rede Eléctrica Nacional),

acting through its internal entity EEGO (Entidade Emissora de Garantias de Origem). GoOs are digital certificates designed to verify the renewable origin of electricity and support claims such as 100% renewable energy consumption. For every 1 MWh of verified renewable electricity produced, one GoO is issued. Production values that do not reach a full MWh within a given issuance cycle are rounded down, with the fractional surplus (e.g., 0.3 MWh) accumulated and carried forward to the next issuance period.

From the perspective of a producer, such as Greenvolt, the GoO lifecycle begins with energy metering. REN/EEGO maintains direct, automated access to energy generation data through IoT-enabled meters installed at renewable facilities. Producers do not submit their readings manually; instead, REN retrieves them via telemetering protocols. These meters are certified and periodically audited by EEGO, ensuring data integrity at the source.

Each month, this platform calculates the total metered output per generation asset. Based on this data, the system issues the corresponding number of GoOs. For example, if a plant produces 100.3 MWh, EEGO issues 100 GoOs for that month, the residual 0.3 MWh remains in the system and is credited once it accumulates to a full MWh. Producers can access the EEGO interface to verify issuance totals, ensuring alignment with their internal production metrics.

However, issuance can be affected by site-specific constraints. Many renewable generation sites are in remote areas with limited mobile coverage. In such cases, delays in data transmission may prevent timely issuance. To maintain continuity in commercial operations, producers can request manual issuance of GoOs through the platform, a process guided by principles of reasonability and post-facto validation.

Once issued, GoOs reside within the producer's EEGO account. Producers then decide on a commercialization route typically selling the certificates to energy traders, utilities, or corporate buyers for ESG reporting purposes. These transactions occur off platform, often via bilateral agreements negotiated through email or brokered exchanges. After contractual terms are established (volume, period, price), the producer initiates a transfer on the EEGO platform, moving the GoOs to the buyer's account. If the transaction involves a cross-border party, the transfer is routed through the Association of Issuing Bodies (AIB) hub, which harmonizes GoO trading across European registries.

To enable better visualization of the current GoO lifecycle process, from Greenvolt's producing point of view, Figure 2 synthesizes every step of the process in chronological order.



Figure 2 – Lifecycle of a GoOs

3.3. Key Points, Challenges and Opportunities

The operational dynamics of the Guarantees of Origin in Portugal can be understood through the process illustrated in Figure 3, which depicts the full issuance and commercial trading workflow.

Figure 3 provides an overview of how GoOs are created by EEGO, held in producer accounts, and subsequently transferred to domestic or international buyers.

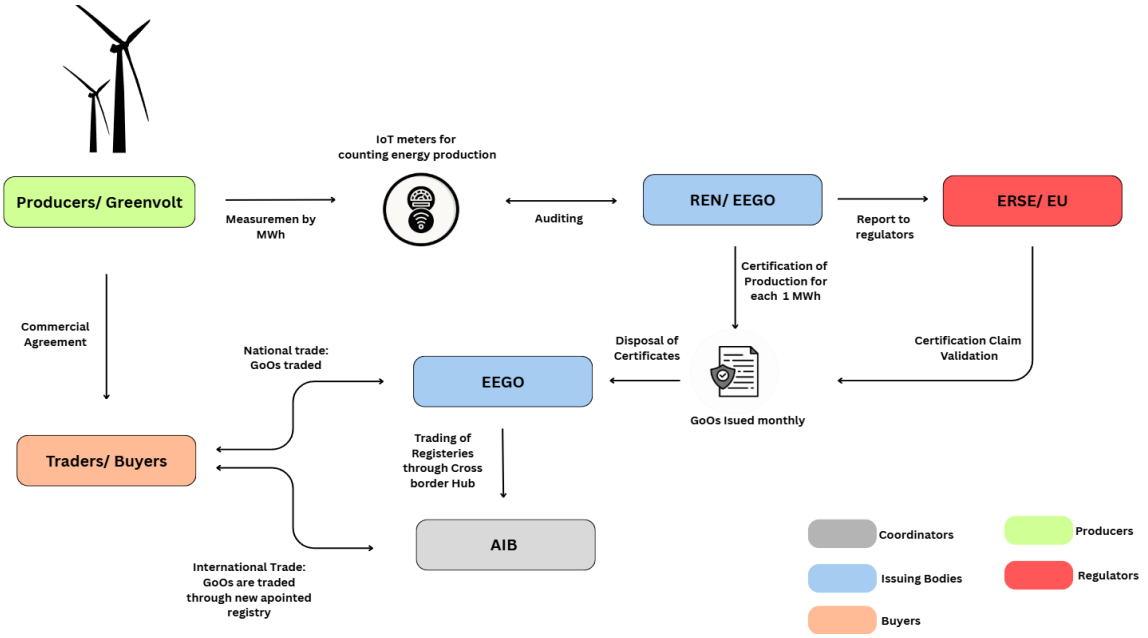


Figure 3 - GoO Issuance and Commercial Trading Workflow (Portugal Case Study)

Once issued, GoOs reside within the producer's EEGO account. Producers then decide on a commercialization route typically selling the certificates to energy traders, utilities, or corporate buyers for ESG reporting purposes. These transactions occur off-platform, often via bilateral agreements negotiated through email or brokered exchanges. After contractual terms are established (volume, period, price), the producer initiates a transfer on the EEGO platform, moving the GoOs to the buyer's account. If the transaction involves a cross-border party, the transfer is routed through the Association of Issuing Bodies (AIB) hub, which harmonizes GoO trading across European registries.

Despite this framework, the process is subject to several structural limitations:

- Fragmentation and Lack of Automation: EEGO records only technical transfers, not commercial terms, payment statuses, or legal obligations. This fragmentation forces producers to reconcile commercial and registry records manually, often through spreadsheets and email trails [5].
- Trust-Based Settlement: The over the counter (OTC) nature of GoO trading means that payment and delivery are not intrinsically linked. This absence of secure settlement mechanisms creates counterparty risk.
- Metadata Limitations: While GoOs contain essential data such as source type and issuance period (vintage), buyers increasingly demand more granular insights such as carbon

intensity, timestamped production logs, or ESG attributes [7]. The current registry schema does not support such extensions natively.

- Operational Frictions: Even routine issuance requires producer intervention in cases of delay, and reconciliation processes are non-standardized. This adds administrative overhead and slows down certificate monetization.

Taken together, these pain points reveal a structural misalignment between the growing strategic importance of GoOs and the limitations of existing registry and trading practices. Fragmented data management, trust-based settlement, limited metadata, and operational frictions all undermine the potential of renewable energy certification as a credible instrument for sustainable governance and ESG reporting. This context creates a clear opportunity for a more integrated, automation-ready, and audit-grade technological approach. A permissioned blockchain framework, designed in alignment with REN/EEGO, AIB EECS, and RED III requirements, can address these challenges by providing tamper-evident records of the GoO lifecycle, enabling secure delivery-versus-payment logic, enriching certificates with granular sustainability metadata, and offering unified interfaces for producers, traders, regulators, and corporate consumers. The conceptual framework developed in Chapter 4 is explicitly shaped by these challenges and aims to respond to them in a way that is both technologically feasible and institutionally realistic.

Chapter 4. Conceptual Framework Design

4.1. Architecture

4.1.1. Design Science Research Methodology Application

The choice of DSRM is justified by its emphasis on creating and evaluating artefacts that address identified, real-world problems. In this case, the problem is the lack of transparent, tamper-evident, and interoperable systems for the issuance, trading, and retirement of GoOs.

In this research, GoOs were chosen as the focal point for building the conceptual artifact to solve the problems stated in this dissertation while applying the current methodology [11]. While other applications were considered, these renewable energy certificates remain a regulated mechanism still affected by inefficiencies in the EU. Focusing here allows the artifact to address a concrete real-world challenge with clear potential for greater transparency, trust and efficiency.

The process begins with problem identification and motivation, which highlights inefficiencies in the current GoOs process, including centralized registries, delays in issuance, and risks of double counting. Building on this, the objectives of the solution are defined: the artefact must deliver end-to-end traceability, automate certificate lifecycle events, support auditability, and align with regulatory frameworks while remaining energy-efficient and interoperable with existing registries.

The design and development phase produces the conceptual framework. This includes the architectural layers (data, blockchain, application, governance), smart contract logic for issuance, transfer, and retirement of certificates, and mechanisms for integrating IoT and oracles to ensure reliable data input. Tokenization is used to represent each certificate as a unique digital asset, embedding metadata such as source, timestamp, and carbon intensity [9].

The demonstration phase applies the framework to use-case scenarios that reflect real-world operations in renewable energy markets regarding the GoOs emitting process and management. These scenarios cover the lifecycle process of this type of certificate, from energy production data capture, through automated issuance and transfer, to retirement and audit. Demonstration highlights how blockchain smart contracts can automate these processes while ensuring transparency and preventing fraud. For instance, a use case might simulate a wind farm producing electricity, triggering the automatic issuance of tokenized GoOs, their peer-to-peer trade on a digital marketplace, and their retirement once claimed by a corporate buyer for ESG reporting.

Finally, the evaluation of the artefact is based on criteria of integrity, transparency, prevention of double counting, scalability, and compliance with regulatory standards. While a full empirical

evaluation will take place later in Chapter 5, the design choices are already aligned with literature insights and stakeholder expectations, ensuring that the framework is both theoretically sound and practically relevant.

To summarize, the six steps of the Design Science Research Methodology are explicitly mapped onto the document structure:

- Problem identification and motivation: Addressed in Chapter 1 (Sections 1.1 and 1.2), which describe the limitations of current GoO certification mechanisms and the need for more transparent, tamper-evident, and interoperable solutions.
- Definition of objectives of the solution: Developed in Section 1.3, which formulates the main objectives of the thesis, and further refined through the research questions presented in Section 1.5.
- Design and development: Realized in Chapter 4, where the conceptual blockchain framework is specified, including stakeholder analysis, requirements, architectural layers, consensus design, information flows, and smart contract logic.
- Demonstration: Illustrated in Section 4.2.3 and 4.2.4 through system application designs, dashboard mockups, and simulated use-case flows that show how the framework would operate in practice for GoO issuance, validation, transfer, and retirement.
- Evaluation: Conducted in Chapter 5, which reports on expert interviews and a structured criteria-based assessment, analysing the validity, utility, technology fit, completeness of requirements, workflow accuracy, and robustness of the proposed framework.
- Communication: Achieved through this thesis itself and through the potential dissemination of its findings to academic and professional audiences in the renewable energy and digital innovation domains.

This mapping ensures that the research adheres to the principles of DSRM, linking problem analysis, artifact design, demonstration, and evaluation in a coherent and traceable manner [11].

4.1.2. Stakeholder Analysis

Before the identification of stakeholders, a structured stakeholder analysis was conducted to understand the institutional, operational, and regulatory actors involved in the Guarantees of Origin (GoO) lifecycle. The purpose of this analysis was to ensure that the proposed blockchain-based framework reflects the real governance structure of the Portuguese and European GoO

system, rather than introducing an abstract or technology-driven model disconnected from practice.

The stakeholder identification and classification process followed a qualitative, design-oriented approach aligned with the Design Science Research Methodology. Stakeholders were identified based on their formal role in the GoO issuance, transfer, validation, and auditing processes, as well as their decision-making power and influence over regulatory compliance and system adoption.

The information used to build the architecture and the analytics work to plan it was collected from three complementary sources:

- Academic literature reviewed in Chapter 2, particularly studies addressing renewable energy certification, governance, and blockchain-based traceability;
- Regulatory and institutional documentation, including ERSE and EEGO manuals of procedures, the AIB EECS rules, and the Renewable Energy Directive (RED III);
- Semi-structured interviews conducted with Greenvolt professionals involved in energy management, asset management, IT/security, and risk management, which provided empirical insight into operational roles and constraints.

These inputs were triangulated to ensure that each stakeholder included in the analysis corresponds to an existing actor in the current GoO ecosystem, with clearly defined responsibilities and authority.

This analysis provides an overview of the main actors involved in the ecosystem of GoOs and their relation to the potential adoption of a blockchain-based framework. In Table 3 we can see each stakeholder present in the GoO certification process and lifecycle and their role in this process, applied to a Portuguese producer point of view: Greenvolt.

Table 3 – Stakeholder Identification

Stakeholder	Role in Guarantees of Origin (GO)	Influence & Power	Relevance for Blockchain Solution
Greenvolt (Producer)	Generates renewable energy (solar, wind) and requests GoOs issuance from REN.	High as a producer with own parks, central in issuance and sale.	Could benefit from automated, tamper-proof issuance & transfer of GoOs, reducing manual REN platform operations.
Issuing Body: REN (Rede Elétrica Nacional), EEGO	Issues GoOs for renewable generation; operates national platform.	Very High – regulator and sole issuer in Portugal.	Blockchain can support REN's transparency, auditing, and compliance reporting.
European Traders / Market Participants	Buy GOs in auctions from producers like Greenvolt.	Medium–High, depending on trading volume.	Blockchain enables transparent secondary trading and prevents duplication.
Corporate Consumers: Electro-intensive industries, Property Managers, Hotels, etc.	Purchase GOs to meet ESG targets or regulatory obligations.	Medium – drive demand, but dependent on regulation.	Blockchain adds trust layer, making reporting and auditing more robust.
Regulators: DG ENER; ESRE Coordinating Bodies: AIB	Define legal framework for GoOs and renewable energy compliance.	Very High can enforce adoption or block innovation.	Blockchain offers alignment with EU goals for transparency and digitalization.
Technology Providers	Offer blockchain platforms or digital certification systems.	Medium influence depends on REN/producer uptake.	Provide technical backbone for the GO-blockchain integration.

The identified stakeholders range from producers, issuing bodies, traders, and consumers, to regulators and technology providers. Each plays a distinct role in the functioning of the GO market and carries different levels of influence, as well as specific motivations and expectations.

This analysis is crucial for the development of the proposed blockchain framework, as it highlights whose needs must be prioritized, which interests drive adoption, and where potential resistance may emerge. By identifying these dynamics early in the process, the design of the artifact can better align with real-world requirements and address challenges that are both technical and institutional. These stakeholder roles justify a governance model in which validation privileges

and data visibility are role-based, balancing transparency and auditability with confidentiality and institutional accountability.

Stakeholder Interests and Objectives:

- Producers (e.g., Greenvolt): Secure efficient issuance of GoOs, monetize renewable generation, and access wider European markets.
- REN/ EGGO (issuing body): Guarantee the credibility of GoOs, maintain a secure and transparent system, and comply with EU regulations.
- Traders/Market participants: Facilitate liquidity, ensure fair transactions, and maximize value in GoOs trading.
- Corporate consumers: Demonstrate compliance with renewable energy targets, strengthen ESG credentials, and mitigate reputational risk.
- Regulators and Coordinating Bodies: Regulate market integrity, prevent fraud or double counting, and promote EU decarbonization objectives. Also coordinate interoperability in the EU market validating exchange between member countries.
- Technology providers: Expand adoption of blockchain or digital platforms by aligning with market needs and regulation.

Potential Barriers and Concerns:

- Producers: May be resistant to adopting new systems if they add cost or complexity; skepticism around blockchain's practical utility.
- REN: Potential reluctance to integrate blockchain if it challenges their role or conflicts with existing regulatory structures.
- Traders: Concerns about market disruption, compatibility with existing trading practices, and transaction costs.
- Corporate consumers: Wary of additional costs and technical requirements for ESG reporting integration.
- Regulators and Coordinating Bodies: Risk-averse to untested solutions; strict compliance needed with EU directives and national law.
- Technology providers: Dependence on regulatory approval and market uptake, creating uncertainty about return on investment.

4.1.3. Requirement Analysis

Operational challenges and stakeholder insights identified in the current GoOs certification process were converted into a comprehensive set of functional and non-functional requirements guiding the development of the blockchain-based framework. These requirements were organized and structured numerically as you can see in Table 4 and Table 5 [11].

The functional requirements outline the system's capabilities to address specific inefficiencies observed in the issuance, management, and transfer of GoOs.

Table 4 – Functional Requirements

ID	Problem	Requirement
FR1	EEGO/REN collects meter data manually through internal processes with limited automation and visibility for producers.	The solution must automatically link metered energy data with GoO issuance, reducing manual intervention and errors.
FR2	The current GoO registry depends on trust and manual checks, which can lead to inconsistencies or double issuance.	The solution must ensure each GoO is uniquely and immutably registered, preventing duplication.
FR3	Producers lack visibility of issuance timestamps and confirmation when GoOs are created.	The solution must timestamp and record every issued GoO on a distributed ledger for transparent verification.
FR4	Transfers between producers and traders rely on manual contracts and trust-based payments.	The solution must enable smart-contract-based transfer and settlement of GoOs to automate delivery-versus-payment.
FR5	No continuous, end-to-end tracking exists from issuance to retirement.	The solution must record the complete GoO lifecycle (issuance → transfer → retirement) for full traceability.
FR6	The EEGO platform operates as a closed system with limited interoperability.	The solution must integrate with REN/EEGO systems via APIs or oracles to synchronise data.
FR7	Current GoOs store minimal information, limiting traceability and ESG reporting.	The solution must enrich GoOs with metadata such as energy source, production date, and carbon intensity.
FR8	Stakeholders lack a unified interface to monitor transactions and balances.	The solution must provide dashboards tailored to each stakeholder (producers, traders, regulators).
FR9	Manual emission corrections by REN are necessary when meter data is delayed.	The solution must include a transparent manual override function for verified adjustments.

In parallel, the non-functional requirements shown in Table 5 define broader principles that ensure the framework's reliability, compliance, and scalability within the European regulatory context. These include interoperability with existing certification systems, adherence to legal and governance standards, and the adoption of secure, energy-efficient technological practices. Together, these requirements ensure that the proposed solution responds to real operational needs while maintaining consistency with the strategic and regulatory expectations of producers, issuing bodies, traders, and regulators.

Table 5 – Non-functional Requirements

ID	Problem	Requirement
NFR1	Lack of digital governance standards limits legal acceptance of blockchain systems.	The solution must be designed to align with EU RED III and EEGO regulations for legal validation of GoOs.
NFR2	National registries are isolated, reducing cross-border recognition.	The solution must ensure interoperability with AIB's EECS infrastructure for EU-level compatibility.
NFR3	The current system relies on internal trust rather than cryptographic assurance.	The solution must guarantee data integrity and authenticity using cryptographic mechanisms.
NFR4	Rising GoO volumes could cause delays or inefficiencies in registry management.	The solution must maintain scalability and performance even under high transaction loads.
NFR5	Energy-intensive consensus mechanisms contradict renewable principles.	The solution must adopt low-energy consensus protocols such as Proof of Authority or PBFT.
NFR6	Audits depend on manual reconciliation between REN and producers.	The solution must enable regulators to audit GoO records directly through a transparent ledger.
NFR7	Some transaction details are commercially sensitive.	The solution must protect confidentiality using permissioned access controls.

The identified requirements provide a structured foundation for the development of the blockchain framework, ensuring that each design element directly addresses a concrete limitation of the current GoO system. By linking every technical and governance feature to specific operational problems, the framework aims to strengthen transparency, trust, and efficiency across the entire

certification process. Beyond improving traceability and automation, it also establishes the necessary conditions for regulatory alignment and cross-border interoperability, reinforcing the credibility and long-term sustainability of renewable energy certification in the European context.

4.2. Framework Architecture

4.2.1. Infrastructure and Requirements Alignment

For RN certification issuing system to operate securely and transparently on a blockchain infrastructure, it is essential to evaluate the consensus mechanisms that underpin data integrity, immutability, and operational efficiency. In this context, the consensus layer determines how different network participants, such as EEGO/REN, regulators, and renewable-energy producers agree on the validity and sequence of issuance records.

Given that the current Portuguese to EU GoOs issuing and sales process already functions under a trusted national authority (EEGO within REN), the blockchain design must complement this structure rather than replace it. Therefore, the analysis focuses on permissioned and low-energy mechanisms that preserve institutional control while ensuring tamper-proof traceability and compliance with EU regulations (RED III and the AIB EECS framework).

Recent European initiatives, notably the TRINITY project (Horizon 2020, 2022), have demonstrated the viability of blockchain-based GoO issuance platforms using a Federated Byzantine Agreement (FBA) model [30]. This approach enables secure, near-real-time validation and cross-border interoperability between national registries. Building upon these insights, Table 6 compares several consensus mechanisms [31]: FBA/ Stellar SCP, PBFT/ IBFT, Public PoS, and Raft against key criteria such as tamper-proofing, energy efficiency, scalability, and governance fit.

In the context of blockchain-based certification systems, the FBA model implemented in the Stellar Consensus Protocol (SCP), represents a highly efficient and reliable approach for ensuring tamper-proof recordkeeping in multi-stakeholder environments [30]. Unlike public proof-of-work or proof-of-stake systems that rely on anonymous validators and probabilistic finality, FBA operates through quorum slices, where each trusted institution (such as EEGO, ERSE, or a producer) participates in the validation process within a defined federation.

This model is particularly well-suited for the GoO ecosystem, where national authorities must maintain operational sovereignty while ensuring interoperability across European borders. Each node in the federation validates transactions independently but reaches consensus through Byzantine fault-tolerant voting, achieving finality within seconds and without the need for energy-

intensive mining. Transactions are digitally signed, timestamped, and permanently anchored in the distributed ledger, guaranteeing immutability and traceability from issuance to cancellation.

Table 6 – Relevant Consensus Mechanisms [30]

Criterion	FBA / Stellar SCP (permissioned federation)	BFT (PBFT/IBFT/Tendermint) (permissioned)	Public PoS (Ethereum L2/L3 app)	Raft (non-Byzantine)
Tamper-proof & finality	Strong tamper-evidence + fast finality via quorum slices; no miners; append-only ledger; signed ops.	Strong finality under f < 1/3 faulty; deterministic commits. (General property of BFT)	Economic finality; strong immutability but probabilistic settlement and MEV exposure.	Crash-fault tolerant only; not Byzantine-fault tolerant weak against adversarial actors.
Energy & cost profile	Negligible energy; micro-fees deter spam; suitable for high-throughput registries.	Efficient vs PoW; validator ops overhead higher than FBA.	Low energy but gas/fees volatile and external to sector governance.	Very low, but at the cost of weaker threat model.
Latency / throughput	Ledger closes ~2–5s; high scalability noted in TRINITY GoO case.	Low seconds to sub-second depending on config; throughput good for registry ops.	Variable (congestion, L2 bridges); settlement may rely on sequencer trust.	Excellent performance, but not BFT.
Fit to GoO workflows	Already demonstrated for issuing, transfer, cancellation with EECS alignment and market adapters in TRINITY.	Good fit; would require bespoke adapters; no sector-specific reference in your corpus.	Possible via smart contracts; governance/interop with national registries is harder.	Requires trust assumptions that do not match GoO multi-party markets.
Interoperability with AIB/EECS	Designed to be compatible with EECS, with issuing body platform + T-RES/T-MARKET flows.	Possible, but no direct template in your sources.	Possible at app layer; cross-border acceptance uncertain.	Not aligned to cross-border, audit-grade ledgers.
Governance model	Federated: REN/EEGO, regulator, producers, market operator run nodes; quorum slices encode trust.	Consortium: fixed validator set under MoU; mature ops practice.	Public governance external to sector stakeholders.	Central/operator-led; undermines multi-party trust.
Security against current pain points	Addresses OTC counterparty risk via atomic transfer flows + on-chain proofs (as per TRINITY transfer/cancel patterns).	Also strong; needs more custom work to mirror TRINITY patterns.	Strong base layer but settlement links to fiat still off-chain; governance misaligned.	Weak vs adversarial behaviour (Byzantine actors).
Implementation risk (per your sources)	Lowest: prior GoO reference design exists (TRINITY).	Medium: solid tech, but no GoO exemplar in your corpus.	Higher: regulatory acceptance & fee volatility risks.	Conceptually misaligned for tamper-proof in adversarial setting.

The selection of the FBA model, implemented through the Stellar Consensus Protocol (SCP), directly aligns with the functional and non-functional requirements identified for the blockchain-based GoO issuance framework. Designed to enable fast, tamper-proof, and energy-efficient consensus among trusted institutions, this model offers the ideal balance between technological decentralization and regulatory governance. In a context such as the Portuguese energy system where the issuing authority, EEGO, already acts as a central and trusted entity the FBA model provides the opportunity to enhance automation, transparency, and data integrity without compromising institutional control or compliance with European regulation.

From a functional perspective, the architecture supports seamless automation and traceability throughout the issuance workflow. By connecting IoT-based metering systems directly to the permissioned blockchain through oracle interfaces, the FBA model allows for real-time validation and registration of production data, eliminating manual input and reducing the risk of errors. Each Guarantee of Origin is cryptographically unique, timestamped, and recorded immutably across all participating nodes, thereby ensuring transparency and preventing duplication. Furthermore, the ledger structure accommodates enriched metadata such as energy source, production period, and carbon intensity, enhancing the value of each certificate for future ESG reporting. Secure API integration also enables interoperability with EEGO's existing systems, allowing blockchain records to mirror official registry data while maintaining consistency and auditability.

From a non-functional standpoint, the model satisfies critical requirements relating to compliance, scalability, sustainability, and confidentiality. Because the FBA operates as a permissioned federation, it remains fully consistent with the RED III and the AIB's European Energy Certificate System (EECS), both of which emphasize traceability, national sovereignty, and interoperability. Its consensus process achieves deterministic finality in seconds, guaranteeing strong performance even under high transaction loads. The model is also inherently low-energy, as it relies on federated voting rather than mining or staking, thus aligning with the renewable-energy principles that define the GoO scheme. Moreover, permissioned access ensures that transaction visibility is limited to authorized participants (e.g., EEGO, ERSE, and producers), thereby balancing transparency with commercial confidentiality.

Functional Requirements Alignment (FR1–FR9):

- Automates the linkage between metering data and issuance through oracles, reducing manual intervention and improving data accuracy.
- Guarantees the uniqueness and immutability of each GoO via cryptographic validation and Byzantine fault-tolerant consensus.

- Provides real-time timestamping of issuance events, ensuring transparent verification by both producers and regulators.
- Enables metadata enrichment for each certificate, supporting ESG and carbon-intensity reporting.
- Integrates seamlessly with existing EEGO systems through secure APIs and supports authorized manual corrections that remain fully auditable.
- Establishes a foundation for future expansion of smart contracts, allowing delivery-versus-payment and lifecycle tracking to be added later without altering the core governance structure.

Non-Functional Requirements Alignment (NFR1–NFR7):

- Ensures compliance with EU legal frameworks (RED III, EECS) by maintaining a permissioned and regulator-governed network.
- Supports interoperability with other national registries through the AIB hub, following the same model successfully demonstrated in the TRINITY pilot.
- Guarantees cryptographic integrity, scalability, and deterministic finality through federated Byzantine consensus.
- Consumes negligible energy compared to Proof of Stake or Proof of Work systems, ensuring sustainability alignment.
- Provides native auditability for regulators and secure, role-based access control to protect commercially sensitive information.

In summary, the Federated Byzantine Agreement model provides a strong conceptual basis to satisfy the technical, regulatory, and operational requirements of a blockchain-based GoO issuance framework [30]. By combining tamper-proof consensus, regulatory compliance, and energy efficiency, it establishes a solid foundation for a transparent and trustworthy certification process under the EEGO/REN system while remaining interoperable with the broader European Guarantees of Origin ecosystem.

4.2.2. Information Flows

To complement the architectural definition and consensus of the conceptual model previously discussed, it is necessary to establish how information flows through the proposed blockchain-based system. The information flow model illustrates the logical movement of data and

transactions across the different entities involved in the GoO lifecycle, from data generation by producers to certification, verification, and final auditing by regulatory authorities.

The design of this process was guided by the DSRM and by the principles of system interoperability and transparency required under the EECS. The flow begins at the data source layer, where verified energy production data is automatically captured from IoT-enabled meters operated under the supervision of REN/EEGO. This data is transmitted through secure oracles into the blockchain layer, where it is validated and recorded by federated nodes participating in the consensus network. Once verified, smart contracts execute issuance rules, creating a unique, timestamped GoO token that is permanently stored in the distributed ledger [32].

The conceptual architecture of the proposed blockchain-based GoO issuance system is structured into four interdependent layers that together ensure transparency, security, and traceability across the entire certification process as you can see clearly on Figure 4.

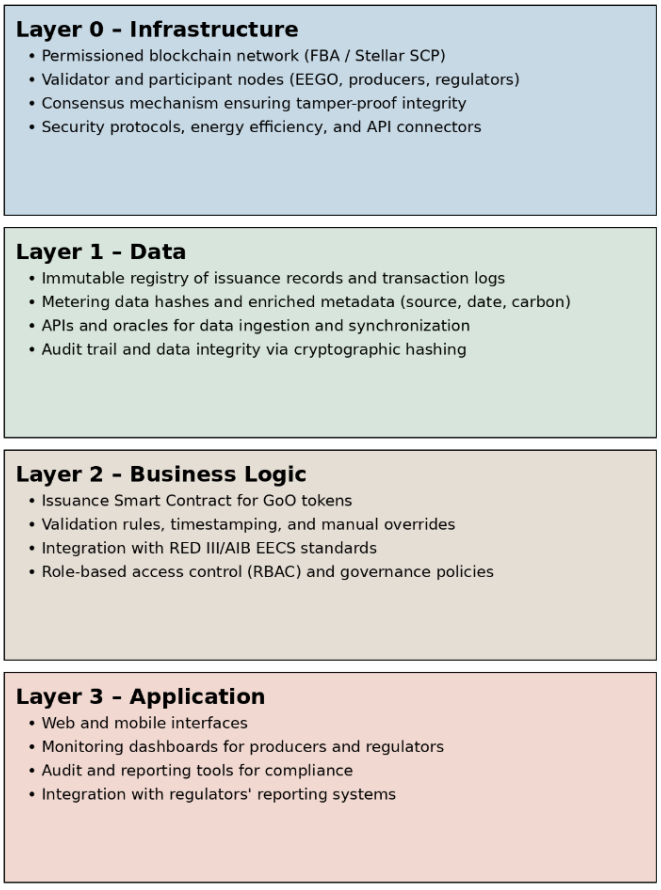


Figure 4 – Conceptual Model Layer Structure

This layered configuration allows the system to operate modularly, with each layer performing a distinct role while maintaining integration with the others. Such a design not only enhances technical robustness and governance clarity but also guarantees alignment with existing national infrastructures, such as EEGO, and with the EECS coordinated by the AIB.

At the foundation lies the infrastructure layer, which constitutes the technological backbone of the framework, it encompasses the permissioned blockchain network based on the FBA consensus mechanism, implemented through the SCP. It ensures network stability, low energy consumption, and fault tolerance across the validator nodes operated by EEGO REN's GoO issuing platform, regulators, and authorized producers. The infrastructure layer also includes secure APIs and cryptographic mechanisms that enable interoperability with REN's existing data systems and the AIB's cross-border registry environment [6]. In essence, it provides the computational environment within which all validation, consensus, and communication processes occur, safeguarding the network's integrity and operational efficiency [14].

Above this foundation, the data layer manages the acquisition, validation, and immutable storage of production and certification data [33]. It integrates directly with IoT-enabled metering devices through oracles that collect, verify, and transmit energy data in real time. Each data point is cryptographically hashed and timestamped before being recorded on the distributed ledger, ensuring accuracy and eliminating the risk of manipulation or duplication. This layer also structures the metadata associated with each GoO including the energy source, production timestamp, and carbon intensity, thereby enriching the certificates with additional traceability attributes. By acting as a secure repository of verified production data, this layer serves as the single source of truth upon which all higher-level operations depend.

Building upon these technical foundations, the business logic layer defines the operational rules that govern the issuance and validation of Guarantees of Origin. It hosts the smart contract architecture that automates the creation of digital certificates according to predefined criteria. Each Issuance Smart Contract (ISC) executes when verified data corresponding to one megawatt-hour (MWh) of renewable electricity is received, minting a unique and timestamped GoO token in compliance with EU RED III and EECS standards. The same layer accommodates controlled manual interventions, enabling EEGO to issue verified corrections when metering data is delayed or requires validation adjustments. This ensures that operational flexibility is maintained without compromising transparency or auditability. Furthermore, the business logic layer anticipates future extensions of the framework, such as automated Delivery-versus-Payment (DvP) settlement or retirement of certificates for ESG reporting, all while preserving governance consistency.

Finally, the application layer constitutes the user-facing dimension of the system, enabling stakeholders to interact with the blockchain environment through intuitive and secure interfaces. It provides web-based dashboards for producers and regulators, offering real-time visibility into issuance volumes, transaction histories, and compliance indicators. For auditors and regulatory authorities, the same layer offers direct access to immutable records through dedicated APIs, facilitating continuous monitoring and compliance verification. In addition, the architecture supports integration with external sustainability and reporting systems, ensuring that verified data from the blockchain can be seamlessly incorporated into corporate ESG disclosures or national energy reports. The application layer therefore transforms the technical capabilities of the underlying blockchain infrastructure into practical tools that enhance transparency and accountability within the renewable energy ecosystem.

In this configuration, information flows vertically through the layers, beginning with metering data at the infrastructure level and culminating in the delivery of verifiable information to end users through the application layer. Each component reinforces the integrity of the one above it: the infrastructure ensures security, the data layer ensures reliability, the business logic layer enforces regulatory compliance, and the application layer delivers accessibility and usability. Collectively, these interlinked layers establish a cohesive and tamper-proof environment that supports the issuance and governance of Guarantees of Origin in accordance with both Portuguese and European regulatory frameworks.

Figure 5, below drafts the proposed conceptual architecture workflow, which introduces a blockchain-enabled issuance framework that digitalizes and automates the current process of GoO issuance and certification to sale from a producer’s point of view in Portugal.

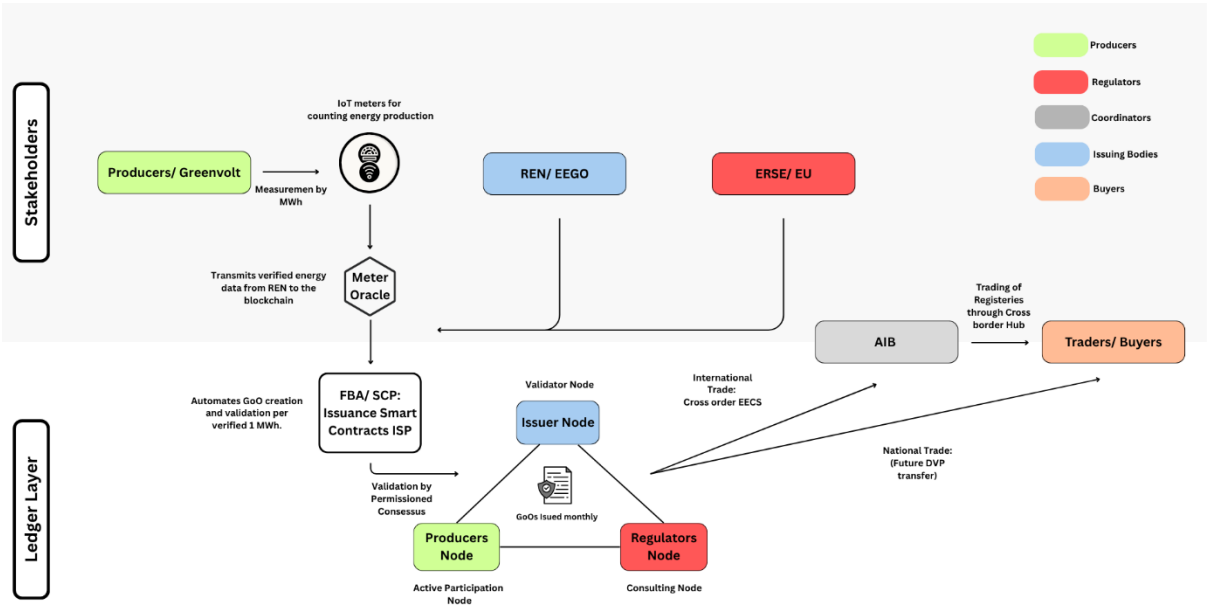


Figure 5 – Conceptual Framework for Blockchain-Based GoO Issuance Process

The conceptual model builds upon the existing EEGO/REN infrastructure and extends it with blockchain components to ensure tamper-proof data recording, automated issuance, and transparent validation. This design follows a hybrid approach, in which data acquisition and initial verification remain partially off-chain through IoT-based metering and REN supervision, while issuance, timestamping, and lifecycle management are executed on a permissioned blockchain governed collaboratively by REN/EEGO, regulatory bodies, and selected renewable energy producers.

The process begins at the production site, where renewable energy facilities such as those operated by Greenvolt generate electricity that is measured by certified IoT-enabled meters. These devices continuously record production in real time and communicate readings directly to the Issuing Body's infrastructure. In accordance with the existing national procedures, the measurements are expressed in MWH, and only audited, regulator-approved meters are authorized to transmit data into the system. This ensures that the energy production data entering the certification process is both accurate and compliant with existing technical standards.

To enable interoperability between off-chain metering systems and the blockchain network, the framework integrates a Meter Oracle, a trusted middleware responsible for securely transmitting verified production data to the blockchain [6]. Once REN has validated the readings through its internal telemetry mechanisms, the oracle packages and forwards the verified data to the blockchain layer, where it triggers the issuance process. In this way, the oracle acts as the technical

bridge between the physical measurement infrastructure and the blockchain environment, ensuring that every issuance event originates from authenticated, regulator-approved data.

Upon reception of these verified meter inputs, the Issuance Smart Contract (ISC**)** implemented under the FBA / SCP automatically executes the issuance logic.

For every full 1 MWh of validated renewable generation, the contract mints a unique GoO token containing essential metadata, which includes:

- Producer identity, linking the certificate to the verified energy generator.
- Energy source and location, specifying the renewable technology and origin of production.
- Timestamp and verification signature, ensuring temporal accuracy and regulatory endorsement.
- Associated carbon intensity or emission factor, enabling traceable sustainability reporting.

This structure guarantees that each certificate is unique, immutable, and traceable throughout its lifecycle. Technically, this setup allows for continuous token issuance as soon as production thresholds are reached. Nevertheless, in alignment with existing regulatory procedures, the aggregation and formal validation of these certificates remain on a monthly cycle, ensuring compatibility with the EEGO's established governance structure.

Once created, each GoO undergoes validation and recording on a permissioned distributed ledger maintained by three principal types of validator nodes. The Issuer Node, managed by REN/EEGO, acts as the primary validation authority responsible for registering issued tokens. The Producers Node, operated by authorized renewable producers such as Greenvolt, serves as an active participant in the consensus process, verifying the provenance and accuracy of production data. The Regulators Node, representing entities such as ERSE and the European Commission, functions as a consulting or observer node with audit-level privileges. Through the permissioned consensus mechanism, these nodes collectively reach agreement on the authenticity of each transaction before it is permanently committed to the ledger. This consensus-driven validation process effectively replaces the existing reliance on manual verification and trust-based reconciliation with cryptographic assurance and distributed governance, significantly enhancing system reliability and transparency.

Following validation, the issued GoOs can be synchronized with external registries to enable both national and cross-border trading. For domestic operations, the framework anticipates future integration with Delivery-versus-Payment (DvP) mechanisms to automate secure and simultaneous transfer of certificates and payments between producers and buyers. For

international transactions, interoperability with the AIB and its EECS hub allows the Portuguese system to exchange and recognize certificates across EU member states, ensuring full compliance with European renewable energy market standards. In both cases, corporate buyers and traders gain direct access to verified GoOs, which can be retired to substantiate renewable energy consumption claims in environmental, social, and governance ESG reporting.

Regulatory oversight is enhanced through a read-only access layer that enables institutions such as ERSE to audit issuance activities directly on the blockchain, in real time and without the need for intermediary reporting. This feature ensures full traceability of each GoO, linking it to the original production data and the corresponding issuance transaction. The outcome is a tamper-proof chain of custody that guarantees the authenticity and provenance of renewable energy certificates, in line with the transparency and interoperability principles defined under the EU Renewable Energy Directive (RED III) and the AIB's EECS framework.

In the context of the previously defined functional and non-functional requirements, the proposed architecture satisfies the system's operational needs through automation, data integrity, and interoperability.

Functional requirements such as automated linkage with metered data, prevention of duplication, and real-time timestamping are fulfilled through the interaction between the Meter Oracle and the Issuance Smart Contract, which together eliminate manual data reconciliation. Non-functional requirements including compliance with RED III, interoperability with AIB's EECS framework, and energy-efficient consensus are addressed using a permissioned blockchain and a low-energy consensus model (FBA/SCP) [28]. When compared to the traditional EEGO framework, which relies on manual batch issuance and post-facto validation, the blockchain-based system significantly improves efficiency by enabling near-real-time data processing, transparent validation, and immutable record-keeping. These features reduce administrative overhead, accelerate issuance cycles, and enhance both system reliability and auditability.

Overall, this architecture introduces a significant evolution in the way GoOs are issued, verified, and audited in Portugal. By combining automated data collection, blockchain-based issuance, and distributed validation, it establishes a transparent and efficient system capable of reinforcing trust in renewable certification processes, enhancing regulatory oversight, and paving the way for seamless cross-border integration within the European energy market.

4.2.3. System Application Design

This section presents the application design and simulated use cases of the proposed blockchain-based GoO issuance framework. The objective is to translate the conceptual architecture into a

functional model, illustrating how stakeholders interact with the system through its main modules. By visualizing the system through user interfaces and process mockups, the model demonstrates how blockchain technology can enhance transparency, auditability, and efficiency in the GoOs issuance process.

The overall logic of stakeholder interaction and data movement is depicted in Figure 6 shown below. This diagram, provides a visual summary of the end-to-end process, linking the physical energy-measurement layer to the digital certification environment.

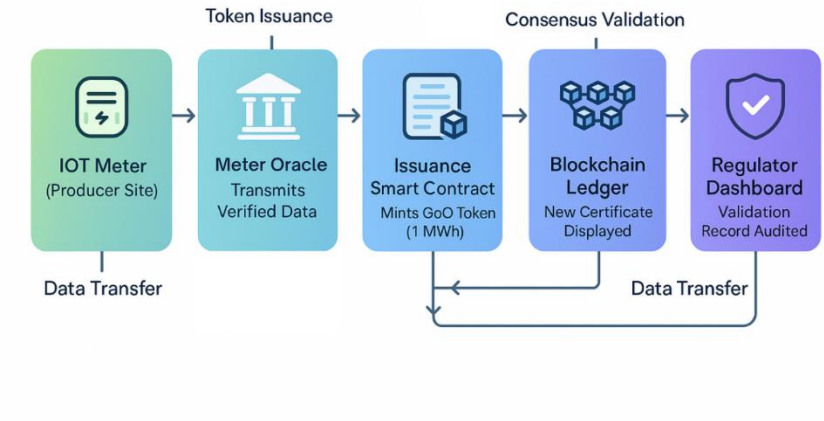


Figure 6 – Use-Case Flow Diagram (Functional Overview)

Verified data from IoT meters are transmitted through a trusted Meter Oracle to the Issuance Smart Contract, which mints a GoO token once 1 MWh of renewable energy is validated.

The transaction is registered on the blockchain ledger and subsequently displayed across the relevant dashboards each tailored to a specific stakeholder:

- The producer interface for certificate creation and tracking.
- The regulator interface for validation and auditing.
- The registry panel for cross-border synchronization within the European Energy Certificate System (EECS).

Together, these interfaces represent the system's application layer and operational demonstration phase under the DSRM.

The producer dashboard shown as an example in Figure 7, demonstrates how a renewable-energy generator such as Greenvolt interacts with the blockchain-based system to monitor energy production and certificate issuance. Real-time metering data validated by REN are automatically reflected on the interface, eliminating manual reporting [14].

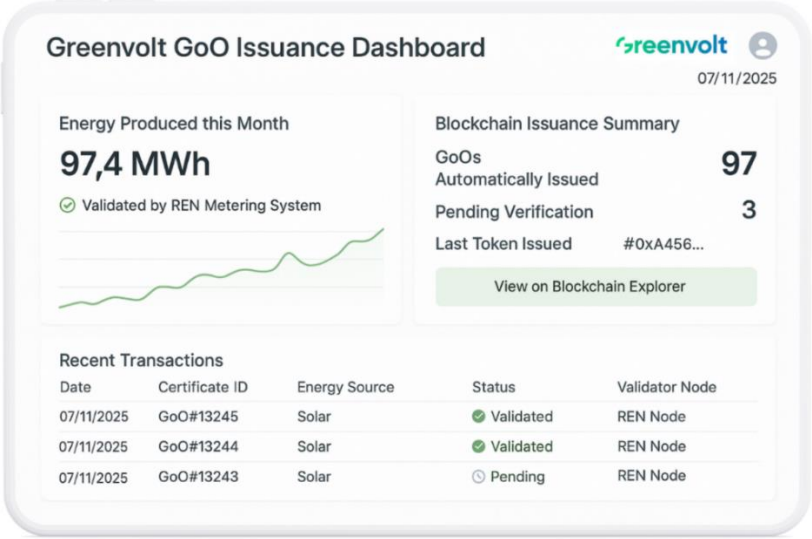


Figure 7 – Producer's Dashboard, (Greenvolt point of view)

The dashboard displays the monthly energy total (97.4 MWh e.g.) and blockchain issuance summary, indicating both automatically issued and pending verifications.

Each certificate includes a unique identifier, timestamp, and validator node reference, which correspond to immutable on-chain records.

The option "View on Blockchain Explorer" links the user directly to the public record of each GoO, reinforcing transparency and traceability.

Functionally, this interface operationalizes, FR1–FR3, (automatic linkage with metered data, prevention of duplication, and transparent timestamping) while satisfying non-functional requirements related to auditability and usability.

On the other hand, the regulator dashboard represented in Figure 8 represents the control and audit perspective of entities such as ERSE.

Through this interface, regulators access real-time aggregated data on total certificates audited, active producers, and cross-border validations.

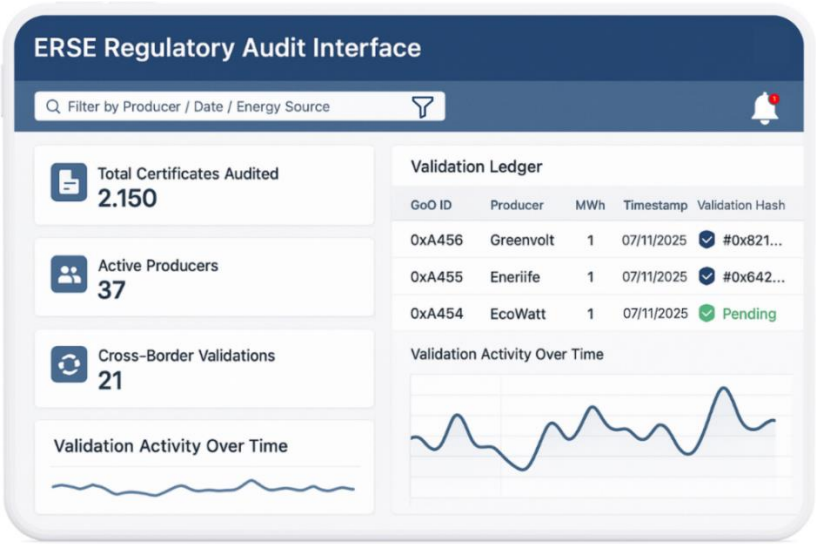


Figure 8 – Regulator Dashboard

The Validation Ledger provides granular traceability, displaying each GoO ID, producer, MWh, timestamp, and validation hash, indicating whether a transaction has been confirmed or remains pending. Interactive graphs further allow regulators to monitor validation activity over time, identifying anomalies or delays.

By granting read-only access to the blockchain ledger, this dashboard ensures independent verification without intermediary reporting, thereby addressing FR5 and NFR6, (direct auditability and compliance transparency) on the requirement analysis in section 4.1.3. It exemplifies the transition from manual audits to continuous, blockchain-enabled oversight.

Lastly, the panel on Figure 9, illustrates interoperability with the AIB's EECS framework.

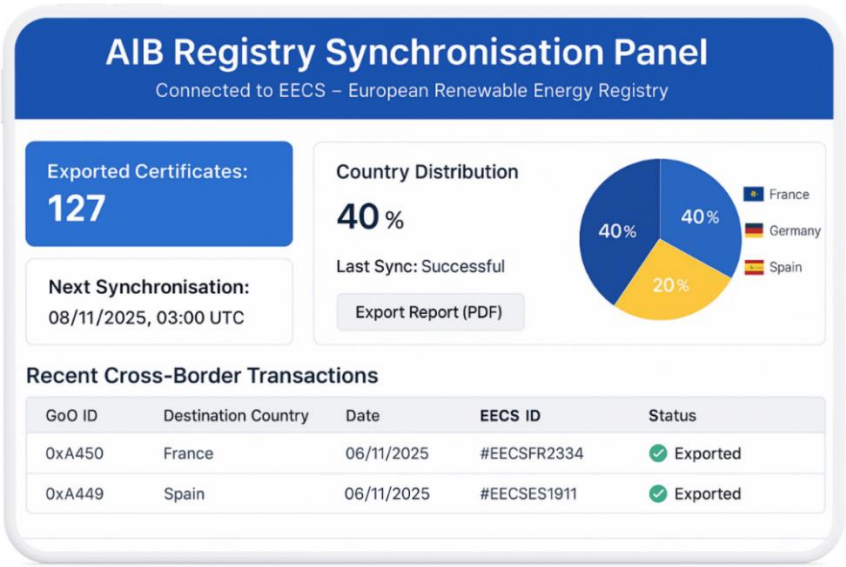


Figure 9 – Registry Integration Panel (AIB Synchronization)

This respective user interface enables the automatic export of validated GoOs to the European registry, displaying the number of certificates synchronized, their country distribution, and the status of recent cross-border transactions.

Each exported GoO is linked to its corresponding EECS identifier, ensuring full traceability between the national and European systems. Periodic synchronization times and the ability to export PDF reports enhance administrative efficiency and standardized reporting.

This dashboard demonstrates compliance with NFR2 (interoperability) and FR6 (integration with external registries) referenced on the requirement analysis in section 4.1.3, providing evidence that the proposed framework extends beyond national boundaries to support seamless European wide certificate exchange.

The three simulated interfaces collectively validate the applicability and usability of the blockchain-based issuance conceptual framework. They illustrate how automation and transparency can coexist with regulatory control, ensuring that each stakeholder: from producer to regulator and finally to European registry, interacts within a unified, tamper-proof ecosystem.

This demonstration phase, in accordance with the DSRM, confirms that the proposed solution satisfies the operational requirements and provides a viable pathway for real-world implementation.

4.2.4. Smart Contracts and Tokenization

Following the demonstration of the system interfaces, it is necessary to conceptualize the underlying blockchain mechanisms that enable automation and trust within the GoO framework.

In this context, smart contracts and tokenization constitute the logical foundation of the proposed system. Although not implemented in this study, these concepts define how transactions would be autonomously executed and permanently recorded within the blockchain environment, replacing several manual verification and registry steps present in the current EEGO/REN process.

Smart contracts are self-executing digital agreements that operate based on predefined conditions stored within the blockchain. In the proposed architecture, smart contracts would govern key events such as GoO issuance, validation, and cross-border transfer [17], [30].

Once the Meter Oracle transmits validated metering data to the blockchain (as described in Section 4.2.3 and shown in Figure 5), the smart contract triggers the automatic creation of a digital token representing one megawatt-hour of renewable energy. Tokenization refers to the process of representing real-world assets or units of value as digital tokens on a blockchain network.

In the proposed framework, each GoO is minted as a non-fungible token (NFT-like structure), as each certificate is unique to a specific producer, time, period, and energy source. This ensures that certificates are non-duplicable, traceable, and easily transferable between stakeholders within the network.

The system follows a "one token per MWh" logic, providing full alignment between physical energy generation and digital certificate issuance. From an operational perspective, the tokenization process enables:

- Tamper-proof verification of GoO ownership and authenticity.
- Transparent traceability of certificate history (issuance, validation, and transfer).
- Efficient interoperability with external registries (AIB/EECS) through token metadata.

This approach addresses one of the central challenges mentioned in the Greenvolt interviews: the lack of transparency and trust in off-chain GoO trading processes.

By representing each certificate as a verifiable digital asset, the system reduces counterparty risk and enhances market confidence [9].

Each token embodies a unique certificate: immutable, time-stamped, and associated with specific metadata such as producer identity, energy source, and generation timestamp.

The digital artifact in the design foresees three primary smart contracts: Issuance, Validation, and Transfer. Which together establishes the automated logic of the proposed framework:

- Issuance Smart Contract: triggered automatically when validated metering data are received from REN via the Meter Oracle. This contract mints a unique GoO token representing one megawatt-hour of renewable energy, assigns it to the producer's blockchain address, and embeds essential metadata such as producer identity, energy source, timestamp, and emission factor.
- Validation Smart Contract: verifies the authenticity of each issuance event through consensus among validator nodes, REN/EEGO, ERSE, and authorized producers. Upon successful validation, the GoO status is updated from Pending to Validated within the blockchain ledger, and regulatory bodies are notified through the ERSE Audit Interface, ensuring transparent oversight.
- Transfer Smart Contract: governs the secure exchange of validated GoOs between producers, traders, and international registries. It locks and releases tokens based on

payment confirmation or regulatory approval and synchronizes transaction records with the AIB Registry Synchronization Panel to maintain cross-border consistency under the EECS framework.

Collectively, these mechanisms automate the lifecycle of GoOs issuance, validation, and transfer eliminating manual reconciliation while supporting full traceability, auditability, and regulatory compliance within a trustless and permissioned environment.

In line with European directives (RED III and AIB EECS standards), the smart contract logic would remain permissioned. Allowing only authorized entities (REN, ERSE, and accredited producers) to execute or validate transactions this ensures that blockchain automation does not compromise regulatory oversight.

The use of a FBA/SCP consensus reinforces this control by enabling distributed validation while maintaining energy efficiency and governance alignment.

In conclusion, the proposed framework combines a permissioned FBA/SCP-based infrastructure, structured information flows, and a set of tailored application and smart contract components that collectively implement the functional (FR1–FR9) and non-functional (NFR1–NFR7) requirements identified in Section 4.1.

The next chapter evaluates this conceptual artifact with domain experts, assessing its validity, perceived usefulness, technological fit, and potential impact on traceability, certification processes, and sustainable governance in the renewable energy sector.

Chapter 5. Evaluation

5.1. Evaluation Method

The evaluation method followed in this chapter examined whether the proposed blockchain-based framework effectively supports traceability, certification, and sustainable governance in the renewable energy sector. The study pursued four objectives:

- First, it verified the completeness and relevance of the functional and non-functional requirements derived from the literature and stakeholder input.
- Second, it assessed the feasibility, scalability, and interoperability of the architecture when interfacing with existing infrastructures such as EEGO, the AIB hub, and grid metering operated by REN.
- Third, it investigated perceived usefulness and acceptability among domain experts who are familiar with certification processes and energy market operations.
- Finally, it identified limitations and potential improvements that would facilitate pilot deployment and regulatory alignment.

The evaluation followed a DSRM orientation and combined semi-structured interviews with seven industry experts with a structured criteria-based assessment. The following people that were part of the conceptual framework and its efficiency evaluation process, built in this project were:

- Bernardo Roque, Director of Energy Management, Greenvolt: Provided operational insights into the daily management of renewable energy production and the current GoO issuance process.
- David Silva, Head of Asset Management, Greenvolt: Contributed detailed knowledge of the company's asset performance, data acquisition, and GoO sales operations and market in a EU and Portugal context.
- Edmund Freitas, Head of Financial Risk Management, Greenvolt: Offered a financial perspective, assessing how the blockchain framework in this study could influence transaction transparency, market trust, and counterparty risk mitigation.

- João Catana, Head of IT and Cybersecurity, Greenvolt: Contributed expertise in system architecture, digital infrastructure, and information security.

The instruments consisted of an interview guide that explored relevance, utility, feasibility, scalability, transparency, interoperability, and regulatory compliance, and a complementary evaluation matrix that captured ordinal judgements on a five-point Likert scale [11]. Each evaluation criterion was answered only by the expert whose domain of expertise directly relates to that criterion. This ensures a role-specific, context-aware assessment and aligns with the DSRM principle of evaluation by knowledgeable stakeholders.

Table 7 shows the process of mapping each stakeholder to the relevant areas on evaluation of the conceptual framework developed in the project.

Table 7 - Mapping of Evaluation Criteria to Expert Roles

Evaluation Dimension	Criterion	Expert Responsible	Evaluation Focus
Goal	Validity	Director of Energy Management	Does the framework effectively support traceability, certification, and sustainable governance?
Environment	Utility (Organizational Fit)	Head of Asset Management	Is the system applicable and beneficial to Greenvolt's operational reality and the national GoO process?
Environment	Technology Fit	Head of IT & Cybersecurity	Does the blockchain architecture (FBA/SCP, smart contracts, oracles) align with REN / EEGO / AIB infrastructures?
Structure	Completeness	Director of Energy Management + Asset Management	Are all functional and non-functional requirements addressed by the design?
Activity	Accuracy	Asset Management	Are the proposed workflows (issuance, validation, transfer) logically consistent and technically feasible?
Evolution	Robustness / Scalability	Head of Financial Risk Management	Is the framework scalable, secure, and adaptable to future EU regulatory changes?

5.2. Performance Discussion and Feedback

Following the mapping of evaluation criteria to expert roles, this section presents the performance assessment of the proposed blockchain-based framework using a role-specific Likert evaluation model. In accordance with the DSRM the goal of this stage is to determine whether the conceptual artifact fulfils the objectives defined during the design phase and whether it demonstrates practical utility for stakeholders engaged in Guarantees of Origin certification.

To ensure methodological rigor and domain relevance, each evaluation criterion was assessed exclusively by the expert whose organizational role and expertise correspond to that dimension. This avoids generic or uninformed assessments and aligns with DSRM's principle that artifacts should be evaluated by knowledgeable stakeholders [11]. The result is a targeted and context-aware performance assessment across operational, technical, financial, and regulatory perspectives as you can see on Table 8.

Table 8 - Evaluation Results (Likert and Interpretation)

Evaluation Criterion	Expert Responsible	Score (1–5)	Interpretation
Validity of the Artifact	Director of Energy Management	**5**	The framework accurately represents the GoO lifecycle and strengthens traceability and certification reliability.
Organizational Utility (Fit to Operations)	Head of Asset Management	**4**	The architecture aligns well with Greenvolt's operational workflows; minor adjustments may be needed for REN integration timing.
Technology Fit (Blockchain + Existing Systems)	Head of IT & Cybersecurity	**3**	The proposed permissioned blockchain model (FBA/SCP) and smart contracts are technically feasible; integration with REN/EEGO requires interface design. But there are some concerns about familiarity and expertise with blockchain technology in the company and also current markets.
Completeness of Requirements	Director of Energy Management & Head of Asset Management	**4**	All key functional and non-functional requirements are addressed, covering issuance, validation, and transfer.
Accuracy of Workflow Logic	Head of Asset Management	**4**	The workflow accurately reflects real processes of issuance, correction, and validation; monthly aggregation logic is consistent with current practice.
Robustness / Scalability / Risk	Head of Financial Risk Management	**4**	The system enhances transparency and reduces counterparty risk; scalability is promising but depends on regulatory adaptation. Also, high costs of implementation pose a challenge.

The evaluation results presented in Table 8 provide a consolidated view of how the proposed blockchain-based framework is perceived across different organizational domains within Greenvolt. As recommended in the DSRM, each evaluation dimension was assessed by the expert most qualified to judge its relevance and feasibility, ensuring a context-specific and methodologically rigorous assessment. The combination of Likert scoring and qualitative interpretation enables a balanced evaluation of both the conceptual soundness of the artifact and its potential applicability in a real operational environment.

Overall, the results indicate high performance across all evaluation dimensions, with scores ranging from 3 to 5. The validity of the artifact received the highest score (5), reflecting strong alignment between the proposed design and the actual GoO lifecycle described by the Director of Energy Management. This confirms that the conceptual model accurately captures the key stages of issuance, validation, and certification, and effectively addresses traceability concerns highlighted during the interviews.

The assessment of organizational utility (score 4) suggests that the system is well aligned with Greenvolt's internal workflows, particularly those related to energy metering, certificate issuance, and operational data handling. Feedback from the Head of Asset Management indicates that the automation of issuance and validation could reduce manual reconciliation and mitigate minor delays currently observed in REN's monthly aggregation process. However, the expert also noted that full alignment may require adjustments in data timing and onboarding procedures.

In terms of technology fit, the Head of IT & Cybersecurity assigned a score of 3, signaling cautious optimism. While the use of a permissioned blockchain architecture (FBA/SCP) and smart contracts is viewed as technically feasible, concerns remain regarding internal familiarity with blockchain technologies and the readiness of supporting systems, especially those managed externally by REN and EEGO. This suggests that additional technical capacity-building, integration testing, and interface standardization would be necessary before deployment.

The completeness of requirements received a strong score, (4), from both the Energy Management and Asset Management departments. Their joint assessment confirms that the artifact successfully addresses all core functional, (automatic issuance, prevention of duplication, traceability, auditability) and non-functional requirements (security, transparency, interoperability). The experts emphasized that the system reflects the real operational constraints of renewable asset management, particularly the monthly issuing cycle and audit checks.

The accuracy of workflow logic was also rated highly (score 4), validating that the proposed workflows for issuance, correction, and validation accurately mirror current practices. The Head

of Asset Management confirmed that the model captures both automated and manual contingencies, including fallback procedures for delayed data transmission or exceptional corrections.

Lastly, the assessment of robustness, scalability, and risk received a score of 4 from the Head of Financial Risk Management. This reflects a positive view of blockchain's potential to reduce counterparty risk, improve transaction trust, and support future scaling as certificate volumes grow. Nonetheless, the expert raised concerns regarding regulatory uncertainties, cross-border harmonization, and the financial implications of implementing and maintaining a distributed ledger system.

Taken together, the evaluation demonstrates that the proposed framework is conceptually sound, operationally relevant, and technically feasible, while also revealing key areas requiring further consideration before real-world implementation. These include integration with REN's systems, internal blockchain expertise, and alignment with evolving regulatory frameworks such as RED III and AIB EECS standards. The feedback validates the artifact within the DSRM evaluation stage and provides a clear foundation for future refinement, prototyping, and potential pilot deployment.

Chapter 6. Conclusion and Future Work

6.1. Conclusion

This thesis investigated the potential of permissioned blockchain technologies to support the traceability, certification, and governance of renewable energy Guarantees of Origin within the European regulatory context. Through a structured review of the literature and the application of Design Science Research Methodology, a requirements-driven conceptual framework was developed and assessed through expert-based evaluation.

Rather than delivering a fully implemented system, the contribution of this work lies in the conceptual design, architectural reasoning, and governance alignment of a blockchain-enabled GoO framework, grounded in real operational practices and regulatory constraints.

This section revisits the research objectives defined in Chapter 1 and evaluates the extent to which they were achieved throughout the study. The conclusion integrates both the design process and the expert-based evaluation results, following the structure recommended by the Design Science Research Methodology. Table 9 summarizes the degree of accomplishment for each objective.

Table 9 - Assessment of Thesis Objectives

Thesis Objectives	Summary of Findings
1. Verify the completeness and relevance of the functional and non-functional requirements.	Requirements were mapped, validated, and judged complete by domain experts (Energy Management and Asset Management), receiving a high evaluation score.
2. Assess feasibility, scalability, and interoperability of the proposed blockchain architecture.	The architecture (FBA/SCP, smart contracts, oracles) was evaluated as feasible with moderate integration challenges; scalability and security confirmed by Risk and IT experts.
3. Investigate perceived usefulness and acceptability among domain experts.	Experts confirmed strong operational relevance, automation benefits, and improved traceability; high Likert scores for validity and utility.
4. Identify limitations and areas for improvement regarding deployment and regulatory alignment.	Concerns were raised regarding REN integration, internal blockchain familiarity, implementation costs and regulatory harmonization. Recommendations were formulated.

The first objective, to verify the completeness and relevance of the functional and non-functional requirements, was achieved at the conceptual design and expert-validation level. The requirements were systematically derived from literature, aligned with regulatory constraints, and validated through expert review. Feedback from Energy Management and Asset Management confirmed that the proposed framework addresses all core operational processes involved in the Guarantees of Origin lifecycle.

The second objective, to assess the feasibility, scalability, and interoperability of the proposed architecture, was achieved and showed strong potential. The technical evaluation conducted by the Head of IT & Cybersecurity acknowledged the suitability of a permissioned FBA/SCP blockchain and smart-contract logic. However, integration with REN's metering infrastructure and broader European mechanisms (EEGO and AIB) would require targeted interface development and organizational adaptation.

The third objective, to investigate perceived usefulness and acceptability among experts, is achieved at the conceptual design and expert-validation level. Domain specialists emphasized the expected improvements in traceability, automation, and risk reduction. The high validity and organizational fit scores demonstrate strong acceptance of the conceptual artifact and its practical relevance to Greenvolt's operations.

Finally, the fourth objective, to identify limitations and improvement opportunities, was achieved with clear insights. Experts pointed to challenges related to regulatory harmonization, internal blockchain expertise, and potential implementation costs. These limitations form the basis for the recommendations and future work outlined at the end of this chapter.

Overall, the evaluation confirms that the conceptual blockchain-based framework designed in this thesis is valid, relevant, and feasible, while also identifying the necessary conditions for future refinement and deployment. The results demonstrate that the proposed solution meaningfully contributes to improving traceability, certification integrity, and sustainable governance in the renewable energy sector.

6.2. Further Work and Implementation

Although the proposed blockchain-based framework demonstrates conceptual feasibility and operational relevance, several areas require further technical work before full implementation. The following points outline the key directions for future work:

- Prototype Development and Technical Validation: Developing a functional prototype represents the first step toward implementation, allowing the core blockchain components such as the permissioned FBA/SCP network, smart contract logic, and simulated Meter Oracle to be tested in practice. A prototype would enable verification of performance, data flow, and security behavior under controlled conditions [15].
- Integration Testing with Existing Energy-Sector Systems: Further work should examine how the proposed architecture would interface with national and European infrastructures,

namely REN's metering telemetry, EEGO's issuance platform, and the AIB EECS Hub. Understanding these integration requirements is essential for ensuring interoperability and managing dependencies on external systems [30].

- Regulatory and Governance Alignment: The regulatory dimension requires detailed analysis, particularly concerning alignment with RED III, national legislation, and AIB certification standards. Future work should also define governance structures for validator-node operations, smart contract updates, and dispute-handling processes to ensure regulatory and operational trust [29].
- Organizational Readiness and Capacity Building: Expert feedback indicates a need for greater internal familiarity with blockchain technologies. Future efforts should therefore focus on training operational and IT teams, running workshops to evaluate process changes, and developing a gradual adoption roadmap that minimizes disruption to existing workflows.
- Security, Privacy, and Risk Assessment: Prior to deployment, a comprehensive cybersecurity and risk evaluation is required. This includes penetration testing of blockchain nodes and oracle mechanisms, assessment of compliance with NIS2 and GDPR [27], and financial risk modelling for blockchain-based GoO trading and settlement processes [6].
- Economic Feasibility and Cost–Benefit Analysis: Further research should explore the long-term economic viability of adopting a blockchain-based certification system. This involves analyzing implementation and maintenance costs, assessing efficiency gains from automation, and evaluating potential changes in GoO market dynamics and pricing behavior.
- Pilot Deployment with a Limited Asset Portfolio: The final phase of future work would involve a controlled pilot project using a small subset of Greenvolt's assets. A pilot would enable empirical observation of the issuance, validation, and cross-border transfer mechanisms, providing real-world data to validate the conceptual design before considering broader deployment.

In summary, while the conceptual framework has been validated as technically coherent and operationally relevant, its full deployment requires incremental development, regulatory alignment, and extensive testing. The future work outlined above provides a structured pathway

from conceptual design to empirical implementation, following the iterative refinement principles of the DSRM.

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