Blockchain-Based Trust Infrastructures for Sustainable Biomass Markets in Europe

Sustainable biomass markets in Europe depend on complex, multi-actor value chains that span production, certification, logistics, and regulatory oversight. Ensuring transparency, trust, and regulatory compliance across these distributed structures remains a persistent challenge. This paper explores blockchain-based trust infrastructures as an enabling foundation for reliable, auditable, and interoperable biomass markets. Following a Design Science Research approach, it combines distributed ledgers with smart contracts and continuously updatable metadata so that critical sustainability and compliance information can be securely documented and exchanged across organizational and national boundaries. Such infrastructures support tamper-resistant traceability, automate verification processes, and reduce administrative overhead in certification and reporting workflows. Drawing on early experimental implementations and conceptual system designs developed within the BBBio project, the paper discusses how blockchain-based approaches can enhance market integrity, improve cross-border interoperability, and support the scalable deployment of sustainable biomass systems in alignment with European policy and regulatory frameworks.

Keywords: *Blockchain in Supply Chains, Biomass, E-Governance, Sustainability Certification, Renewable Energy Directive (RED III)*

Introduction

The biomass sector occupies a central position in the European Union's renewable energy strategy, yet it is also one of the most fragmented and administratively demanding segments of the energy system. Solid, liquid, and gaseous biomass together constitute one of the largest sources of renewable energy consumed within the European Union, and biomass feedstocks travel through long, multi-actor value chains that connect agricultural and waste-based suppliers, scheme operators, biogas and biomethane plants, certification bodies, network operators, and national regulatory authorities before the associated energy or fuel reaches the market. The European Renewable Energy Directive (RED III) obliges member states to ensure that biomass feedstocks used to meet renewable energy targets satisfy defined sustainability and greenhouse gas emission-saving criteria, in line with requirements originally established under Directive 2009/28/EC and subsequently revised through Directive (EU) 2023/2413 (EUR-Lex 2023). Compliance with these criteria is verified through national registry and certification systems that record feedstock origin, chain-of-custody information, and greenhouse gas balances.

Although RED III establishes a common regulatory framework at the European level, its practical implementation is largely delegated to individual member states. This regulatory flexibility has produced a patchwork of national certification infrastructures that differ considerably in their technical maturity, degree of automation, and level of transparency. Many of these systems continue to rely on centralized databases, paper-based documentation, and manual verification steps, which increases the risk of inconsistent data, duplicated reporting effort, and delayed certification cycles. Differences in national regulatory approaches and market structures further complicate cross-border coordination and limit the integration of European biomass and renewable energy markets (Algarvio et al. 2019; Venizelou and Poullikkas 2024). Similar structural fragmentation has been observed more broadly across European electricity markets, where the absence of harmonized capacity mechanisms and coordinated adjustment markets continues to constrain full market integration (Höschle, Cadre, and Belmans 2018; Squicciarini et al. 2010; Zalzar et al. 2020).

These structural limitations reduce the operational efficiency of certification processes, hinder the development of transparent and integrated renewable energy markets, and create tangible costs for market participants. Biomass producers and plant operators must comply with reporting obligations to scheme operators, certification bodies, and national authorities, often through separate, non-interoperable channels, each with its own data formats, audit cycles, and documentation requirements. At the same time, public subsidies for renewable energy sources are gradually being reduced across several member states, while regulatory complexity and operational costs continue to rise. Under these conditions, technological innovations capable of improving transparency, automation, and interoperability in biomass certification systems are becoming increasingly important for the long-term competitiveness and stability of the sector, and for the broader credibility of the sustainability claims that underpin the European Green Deal and the “Fit for 55” package.

These developments also intersect with the European Union's wider digitalization and sustainability agenda. The European Green Deal and the accompanying “Fit for 55” legislative package rely heavily on the ability of market participants and regulators to monitor greenhouse gas savings and sustainability performance across supply chains in a consistent and verifiable manner. Digital tools that can document and share this information reliably across organizational and national boundaries are therefore not only an operational convenience for individual biomass producers, but also a precondition for the broader policy objective of verifiable, EU-wide progress tracking toward renewable energy and climate targets.

Distributed ledger technology has emerged as a promising candidate for addressing these challenges. Its core properties, decentralization, immutability, and cryptographically secured data integrity, align closely with the requirements of multi-actor certification environments in which no single participant should unilaterally control shared sustainability data (Hardjono, Lipton, and Pentland 2019; Cagigas et al. 2021). However, the specific design requirements for applying blockchain technology to the biomass certification domain, particularly under the concrete legal and operational constraints imposed by RED III, remain insufficiently explored in the existing literature, which has so far concentrated primarily on electricity trading and general public-sector use cases rather than on feedstock-level sustainability certification.

This paper therefore investigates how blockchain-based trust infrastructures can improve transparency, traceability, and interoperability in biomass certification systems within European energy markets. More specifically, the paper addresses the following research question: which architectural and governance design principles allow a blockchain-based infrastructure to satisfy the sustainability, auditability, and cross-border interoperability requirements of RED III-compliant biomass certification, while remaining compatible with the operational realities of existing national registry systems? The scope of the paper is conceptual and design-oriented: it draws on an ongoing applied research project, presents a system architecture, and reflects on its implications, rather than reporting a large-scale empirical validation across multiple national markets.

The remainder of this paper is organized as follows. The next section reviews the relevant literature on blockchain technology, its application in the energy sector, and the structural challenges of European energy market integration, and positions the present study within this body of work. The third section describes the Design Science Research methodology adopted for developing and evaluating the proposed artifact. The fourth section presents the results of this design process, including the proposed blockchain-based architecture, its governance model, and its prototypical implementation within the BBBio project. The fifth section discusses the implications, limitations, and open challenges of the proposed approach in light of the existing literature. The final section concludes the paper and outlines directions for future research.

Literature Review

Foundations of Blockchain Technology

Blockchain technology provides a decentralized, append-only ledger in which transactions are cryptographically linked and replicated across a network of participating nodes. Once recorded, entries cannot be altered without changing all subsequent entries and gaining consensus from the network, which gives the technology its characteristic tamper-resistance. Hardjono, Lipton, and Pentland (2019) argue that these properties make blockchain particularly suitable as an interoperability layer for autonomous, multi-organizational systems, since it allows independent actors to share verifiable state without relying on a single trusted intermediary. Their proposed architecture for blockchain autonomous systems distinguishes between the technical interoperability of ledgers and the organizational interoperability of the institutions that operate them, a distinction that proves directly relevant to the biomass certification context examined in this paper, where technical connectivity alone would not resolve the underlying governance fragmentation between national authorities.

Cagigas et al. (2021), in a systematic review of blockchain applications in the public sector, similarly conclude that the technology's core value for public administration lies in its capacity to increase transparency and auditability of records that are jointly maintained by multiple, only partially trusting stakeholders, such as public registries, land titles, or certification schemes. Their review further identifies a recurring implementation pattern across successful public-sector blockchain projects: technical decentralization is typically combined with a restricted, permissioned set of validating nodes operated by accountable public authorities, rather than with fully open, permissionless participation. Both studies emphasize, however, that realizing these benefits in practice requires careful attention to governance design, since technical decentralization does not automatically translate into organizational trust or regulatory acceptance.

Blockchain Applications in the Energy Sector

Within the energy domain specifically, Bao et al. (2020) provide a broad survey of blockchain applications, identifying peer-to-peer energy trading, grid management, electric vehicle charging, and certificate-of-origin tracking as the most actively researched use cases. Their review highlights that most existing energy-sector blockchain applications remain at the pilot or proof-of-concept stage, and that scalability, regulatory uncertainty, and integration with legacy metering and registry infrastructure represent the most significant barriers to production deployment. They further note that certificate-of-origin and guarantee-of-origin systems, which share important structural similarities with biomass sustainability certification, are among the use cases where blockchain's auditability advantages are most clearly demonstrated, since they typically involve verifying claims made by one party against evidence held by another.

Boumaiza (2024) presents a more targeted design and implementation study of a blockchain-enabled transactive energy market, demonstrating that permissioned blockchain architectures can support automated settlement and verification of energy transactions while satisfying the access-control requirements of regulated market participants. This work is particularly relevant to the present study, as it illustrates that permissioned, rather than fully public, blockchain designs are often better suited to regulated energy markets, where participation must be restricted to authorized and identifiable actors such as certification bodies and national authorities. Boumaiza's implementation also demonstrates the practical feasibility of combining smart contracts with automated compliance checks in a regulated market context, providing a proof of concept for the smart-contract-based verification mechanisms proposed later in this paper.

Structural Challenges of European Energy Market Integration

A parallel and long-standing strand of literature addresses the structural obstacles to European energy market integration independently of blockchain technology. Squicciarini et al. (2010) trace the evolution of European electricity market integration from a regional to a pan-European model, noting that full harmonization has remained elusive despite successive legislative packages, in part because member states retain significant discretion over the design of their national market rules. Höschle, Cadre, and Belmans (2018) show that inefficiencies persist specifically because national capacity mechanisms are not harmonized across interconnected electricity markets, leading to distorted price signals and suboptimal cross-border capacity allocation, an outcome the authors attribute directly to the absence of a shared, mutually verifiable data layer between national market operators.

More recently, Venizelou and Poullikkas (2024) analyze trends in cross-border electricity trading across the pan-European network and find that, although trading volumes have increased, technical and regulatory interoperability gaps continue to limit the efficiency gains that a fully integrated market could deliver. Zalzar et al. (2020) model the impact of an integrated European adjustment market for electricity under a high share of renewables and demonstrate that better-coordinated balancing mechanisms could substantially reduce system costs, underlining the economic value of interoperability. Algarvio et al. (2019) extend this discussion specifically to variable renewable energy sources, showing that regulatory design choices at the national level have measurable effects on the integration of renewables into the broader European internal market. Taken together, this literature establishes that the interoperability problems observed in biomass certification are not an isolated phenomenon but a specific manifestation of a broader, well-documented pattern of fragmented governance in European energy markets, a pattern that has so far been analyzed mainly in economic and regulatory terms rather than from the perspective of the underlying information infrastructure.

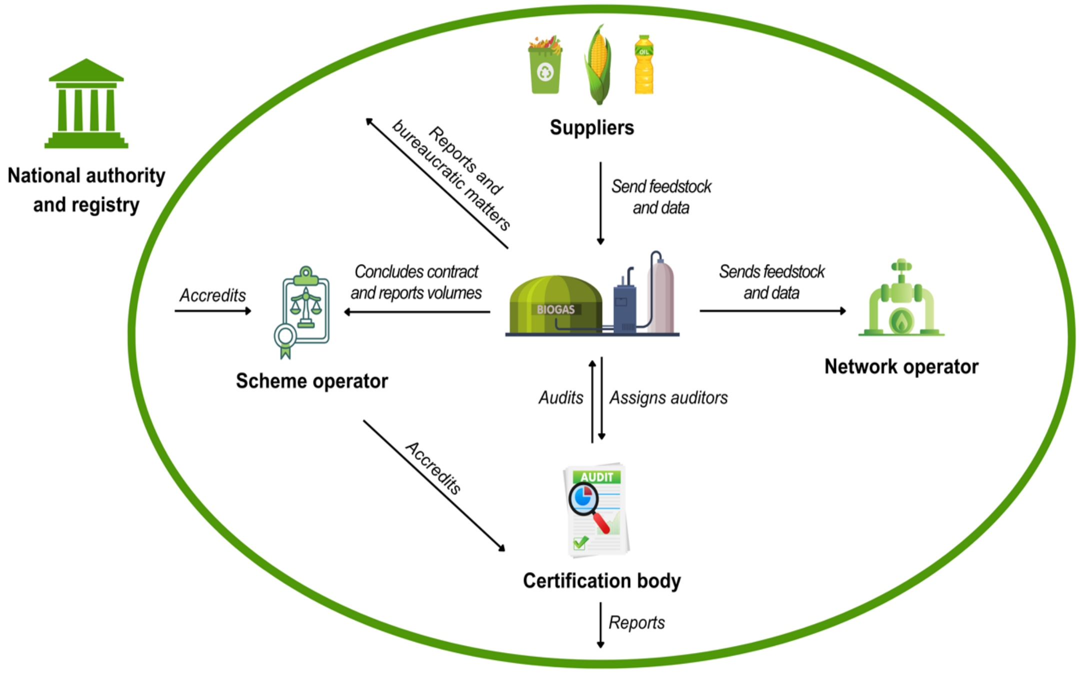
Digital Governance and the Interoperability Gap

Read jointly, the two strands of literature reviewed above point to a specific, underexplored gap. The blockchain and public-sector literature (Hardjono, Lipton, and Pentland 2019; Cagigas et al. 2021; Bao et al. 2020; Boumaiza 2024) demonstrates that distributed ledgers can technically support shared, auditable records among multiple regulated actors, while the energy-market-integration literature (Squicciarini et al. 2010; Höschle, Cadre, and Belmans 2018; Algarvio et al. 2019; Venizelou and Poullikkas 2024; Zalzar et al. 2020) demonstrates that the persistent obstacle to European market integration is precisely the absence of such a shared, mutually verifiable data layer across national institutions. Despite this apparent complementarity, few studies to date have examined how a blockchain-based digital governance layer could be designed specifically for the biomass certification workflows mandated by RED III, which combine the multi-stakeholder trust problem addressed in the public-sector blockchain literature with the cross-border harmonization problem addressed in the energy-market-integration literature.

Current Biomass Certification Landscape in Europe

Under RED III, sustainable biomass feedstocks must be certified from the point of origin, enabling accurate greenhouse gas footprint calculations and supply chain traceability (EUR-Lex 2023). In current national implementations, this typically involves a workflow in which suppliers deliver feedstock and accompanying data to a biogas or biomethane plant; the plant operator concludes contracts and reports volumes to a scheme operator, who in turn accredits both the plant and an independent certification body; the certification body conducts audits, commissioned through auditors assigned by the scheme operator, and reports outcomes to the national authority and registry, which retains overall regulatory and bureaucratic oversight (see Figure 1). Each arrow in this workflow represents a distinct, largely manual reporting or verification relationship, typically supported by separate, non-interoperable information systems on each side of the exchange.

Figure 1. *RED III Biomass Stakeholder Workflow on a National Level*



Source: Author's own illustration, BCCM Mittweida (2026).

This workflow illustrates why the fragmentation identified in the broader energy market literature is especially pronounced in biomass certification: the same feedstock batch may need to be reported, in slightly different formats, to a scheme operator, a certification body, a network operator, and a national registry, with limited ability to verify that these independently maintained records remain consistent over time. Existing digitalization efforts largely automate individual reporting relationships rather than establishing a shared, verifiable data layer across all stakeholders, which is precisely the gap that blockchain-based trust infrastructures are positioned to address. Building on the technical foundations described above and the structural challenges documented in this section, the remainder of this paper investigates how a blockchain-based architecture can be designed to close this gap within the constraints of the existing RED III certification workflow.

Methodology

This study follows a Design Science Research (DSR) approach to develop and evaluate a technological artifact that addresses the transparency and interoperability challenges identified in biomass certification systems. Design Science Research, as a research paradigm, focuses on the creation and rigorous evaluation of purposeful artifacts, such as models, methods, or system architectures, that solve practical problems while simultaneously contributing generalizable design knowledge to the scientific literature. The research process therefore combines theoretical analysis with iterative system development, rather than relying exclusively on either purely conceptual reasoning or purely empirical observation, and treats the resulting architecture as a design artifact whose value must be justified both by its practical relevance and by its grounding in the existing knowledge base reviewed in the previous section.

The DSR process applied in this study proceeds through four interrelated activities. First, structural challenges in biomass certification and cross-border energy market integration were identified through the review of the academic literature summarized in the previous section, together with an analysis of the regulatory framework established by RED III and its national implementations, and through the reconstruction of the current, largely manual certification workflow depicted in Figure 1. Second, based on these insights, a system architecture was conceptualized to directly address the identified limitations related to transparency, automation, and interoperability, while remaining compatible with the roles and responsibilities of existing stakeholders shown in Figure 1, rather than proposing an entirely new institutional structure. Third, the proposed architecture was refined through iterative prototyping, in which design decisions regarding the choice of ledger technology, the governance model for network participation, and the treatment of dynamic sustainability attributes such as CO2 footprints were evaluated against the operational requirements of the domain and against the design patterns identified in the literature review, particularly the preference for permissioned architectures in regulated markets. Fourth, the resulting artifact was evaluated conceptually against the design objectives of transparency, auditability, automation, and regulatory compliance, and reflected upon in light of the related work discussed above.

Particular attention throughout this process was given to aligning the technological design with the operational requirements of the relevant stakeholder groups identified in the literature review and in Figure 1, namely biomass producers and suppliers, scheme operators, certification bodies, network operators, and national regulatory authorities. Each design decision, including the choice of a permissioned rather than public ledger, the batch-level treatment of dynamic metadata, and the use of open application programming interfaces for external connectivity, was evaluated against this stakeholder map to ensure that the proposed architecture could plausibly be adopted without requiring a wholesale replacement of existing institutional roles. The proposed architecture and its prototypical implementation, described in the following section, constitute the primary design artifact produced by this research process; its properties are evaluated against the requirements derived from the literature and from the regulatory context, rather than through a controlled field experiment, which is identified as a direction for future research in the discussion section.

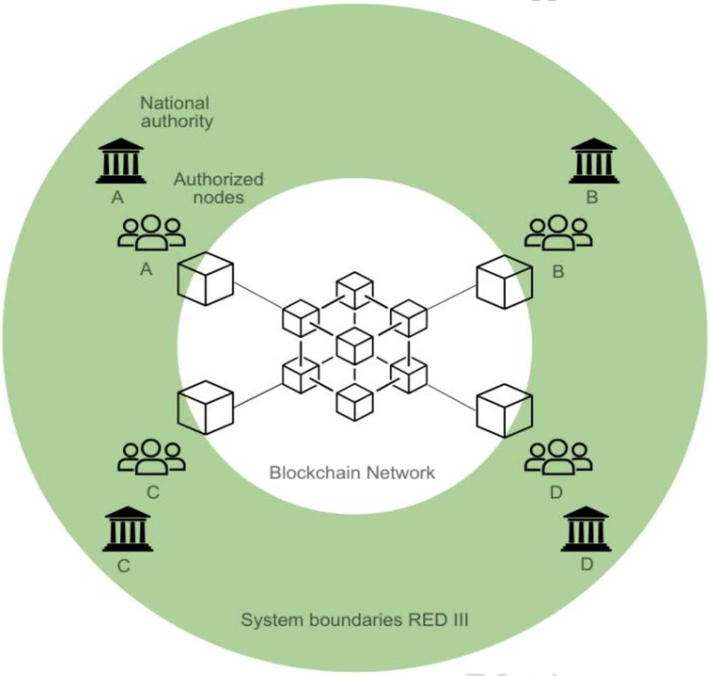
Results

Proposed System Architecture

To address the structural limitations identified in existing biomass certification systems, this study proposes a blockchain-based digital infrastructure designed to enhance transparency, interoperability, and automation across certification and trading processes. A central design principle of the proposed system is bottom-up traceability, which enables biomass feedstocks to be tracked from their point of origin throughout the entire value chain shown in Figure 1. This approach allows comprehensive monitoring of sustainability attributes and enables accurate calculation of CO2 footprints associated with biomass production and utilization, directly addressing the traceability requirements imposed by RED III.

Blockchain technology provides the core infrastructure for secure and tamper-resistant data management within this architecture. The distributed ledger ensures the integrity and immutability of certification records, allowing transparent auditing and reliable verification of sustainability information across the biomass supply chain, consistent with the properties described by Hardjono, Lipton, and Pentland (2019) and Cagigas et al. (2021) in the literature review.

Figure 2. *RED III Blockchain-Based E-Governance Approach*



Source: Author's own illustration, BCCM Mittweida (2026).

Figure 2 illustrates the proposed blockchain-based e-governance architecture for biomass certification and cross-sector data integration. The system connects the key stakeholders identified in Figure 1, including biomass producers, certification authorities, national regulatory bodies, and market participants, through a decentralized blockchain network. Authorized nodes operated by national authorities maintain system integrity and ensure compliance with European regulatory requirements, while the underlying blockchain infrastructure enables secure data exchange across relevant sectors such as biomass production, logistics, energy generation, and regulatory monitoring. Each of the four authorized-node clusters shown in Figure 2 corresponds conceptually to a national authority together with its accredited market participants, illustrating how the architecture could, in principle, be extended from a single-country prototype to a multi-country network without changing its underlying governance logic.

Integration Layer and Certification Workflow

A message broker functions as an integration layer between sector-specific databases and the blockchain network, enabling seamless communication between existing information systems, such as those already operated by scheme operators and certification bodies, and the distributed ledger. This design deliberately avoids requiring stakeholders to replace their existing internal systems; instead, the message broker translates relevant events, such as a reported delivery volume or a completed audit, into blockchain transactions, so that legacy systems can continue to operate largely unchanged while still contributing to a shared, verifiable record. Certification authorities utilize blockchain data to generate product graphs, issue sustainability certificates, and ensure traceability of biomass feedstocks throughout the supply chain. By enabling automated verification and real-time monitoring, the architecture reduces administrative effort and strengthens regulatory oversight compared to the manual, multi-channel reporting workflow shown in Figure 1.

Smart Contract Layer and Automated Verification

Smart contracts are implemented to automate certification workflows and enforce predefined sustainability rules, such as minimum greenhouse gas emission-saving thresholds or feedstock eligibility criteria under RED III. When a new transaction, for example a reported feedstock delivery or an audit result, is submitted to the network, the relevant smart contract automatically checks it against these predefined rules before the transaction is accepted into the ledger, reducing the scope for manual review to genuine exceptions rather than routine compliance checks. These programmable mechanisms reduce manual intervention, minimize operational errors, and improve overall process efficiency. To ensure system robustness, the architecture incorporates cryptographic mechanisms for secure data validation and access control while complying with the requirements of the EU Renewable Energy Directive.

Within the proposed architecture, dynamic attributes such as CO_2 footprints are managed at the batch level rather than being permanently linked to individual, immutable tokens. This design choice enables incremental updates through additional blockchain transactions, for example when new laboratory measurements or logistics data become available, while preserving a complete, auditable history of prior values. As a result, transparency, auditability, and regulatory compliance are significantly improved while reducing the administrative effort compared to traditional, document-based certification systems.

Prototype Implementation and the BBBio Project

The blockchain artifact described above is currently being developed within the BBBio project (Blockchain-based Biomass Certification), funded by the German Federal Ministry of Education and Research (BMBF) under the "WIR! – Wandel durch Innovation in der Region" initiative. The project aims to address inefficiencies in biomass certification by integrating blockchain technology, smart contracts, and Internet-of-Things (IoT) data sources, and provides the applied research context in which the architecture presented in this paper is being iteratively developed and tested together with regional biomass producers and certification stakeholders.

The prototype implementation is based on Hyperledger Fabric, a modular and scalable enterprise-grade permissioned blockchain framework. Hyperledger Fabric restricts network participation to authorized entities, ensuring secure access control while supporting the transaction throughput required for energy market applications, in line with the permissioned-design recommendation derived from Boumaiza's (2024) work on transactive energy markets. Its modular architecture allows adaptation to national regulatory requirements, while the pluggable consensus mechanism ensures scalability and fault tolerance as the number of participating authorities and market actors grows. The choice of Hyperledger Fabric over a public, permissionless blockchain reflects the governance requirements identified in the literature review: since certification authorities must be identifiable and legally accountable, the network's validating nodes are restricted to organizations formally accredited under the applicable national scheme.

To ensure interoperability with existing certification infrastructures, the system integrates open application programming interfaces (APIs) that enable connectivity with external platforms, including trading systems and market participants. This architecture facilitates cross-border data exchange and supports regulatory harmonization across the European Union, addressing the interoperability gap identified throughout the literature review.

Table 1 summarizes the main differences between the currently prevailing, largely centralized biomass certification approach and the blockchain-based architecture proposed in this paper, structured along the design dimensions that motivated this research. Across these dimensions, the transition from a centralized to a blockchain-based design is not simply a technology substitution but a shift in where and how trust is established: in the current landscape, trust rests largely on the diligence of individual scheme operators and certification bodies and on periodic manual audits, whereas in the proposed architecture, trust is additionally anchored in the cryptographic and procedural guarantees of the shared ledger itself, which reduces, without fully eliminating, the reliance on any single organization's internal controls.

Table 1. *Comparison of Centralized and Blockchain-Based Biomass Certification Systems*

Design Dimension	Current Centralized Approach	Proposed Blockchain-Based Approach
Data management	Siloed, organization-specific databases	Shared, synchronized distributed ledger
Traceability	Manual, document-based chain of custody	Automated, bottom-up batch traceability
Verification	Periodic manual audits	Continuous, smart-contract-based verification
Interoperability	Limited, bilateral data exchange	Open APIs and shared data layer across actors
Dynamic sustainability data (e.g., CO2)	Static, periodically re-issued documents	Batch-level, incrementally updatable metadata

Administrative effort	High, duplicated reporting	Reduced through automation

Source: Author's own compilation (2026).

By combining decentralized data management, automated certification processes, and interoperable digital infrastructures, the proposed system provides a scalable design response to the transparency, efficiency, and regulatory compliance challenges identified in European biomass certification systems (Cagigas et al. 2021; Hardjono, Lipton, and Pentland 2019). The proposed architecture therefore provides a practical foundation for implementing decentralized certification infrastructures in European biomass markets.

Discussion

The results presented above suggest that blockchain-based trust infrastructures can meaningfully address several of the structural limitations identified in the literature review, particularly the coexistence of multiple, non-interoperable reporting relationships shown in Figure 1. By replacing bilateral, document-based exchanges with a shared, cryptographically verifiable data layer, the proposed architecture reduces the need for redundant reporting and enables certification bodies and national authorities to verify sustainability claims without relying solely on the self-reported figures of upstream actors. This is consistent with the broader claim in the public-sector blockchain literature that shared ledgers are most valuable precisely in settings with multiple, only partially trusting stakeholders (Cagigas et al. 2021), and it extends that claim to a domain, biomass sustainability certification, that has so far received comparatively little attention in the blockchain literature relative to electricity trading and certificate-of-origin schemes (Bao et al. 2020).

At the same time, the case of biomass certification illustrates a design tension that is only partially addressed in the general blockchain literature: the need to reconcile the immutability of the ledger with the inherently dynamic nature of sustainability data, such as CO2 footprints, which are revised as new information becomes available throughout a product's lifecycle. The batch-level, incrementally updatable metadata design adopted in this study represents one possible resolution of this tension, but alternative designs, for example based on versioned off-chain data anchored periodically on-chain, may offer different trade-offs between transparency, storage cost, and auditability, and warrant further comparative investigation in future work.

The choice of a permissioned blockchain architecture based on Hyperledger Fabric also reflects a broader pattern observed in the energy-sector literature, where regulated market contexts consistently favor permissioned over fully public designs (Bao et al. 2020; Boumaiza 2024). This design choice, however, introduces its own governance question: unlike public blockchains, permissioned networks require an explicit, trusted process for admitting and authorizing participating nodes, which in the biomass certification context would likely need to be defined jointly by national authorities across member states in order to genuinely support the cross-border interoperability envisioned in this paper. Without such a coordinated governance agreement, there is a risk that multiple, mutually incompatible national blockchain infrastructures could emerge, effectively reproducing the fragmentation problem described by Höschle, Cadre, and Belmans (2018) and Squicciarini et al. (2010) in a new technological form rather than resolving it. This risk echoes a broader observation in the energy-market-integration literature, namely that technical capability alone rarely resolves fragmentation problems that are ultimately rooted in diverging national institutional arrangements (Squicciarini et al. 2010; Venizelou and Poullikkas 2024).

The stakeholder-oriented design approach adopted in the methodology section also has implications for the adoption prospects of the proposed architecture. Because the message-broker integration layer allows existing scheme operator and certification body systems to remain largely unchanged, the transition cost for individual stakeholders is likely to be lower than for architectures that require a full replacement of legacy systems, which may partly explain why comparable message-broker-based integration patterns have proven successful in other public-sector blockchain deployments (Cagigas et al. 2021). Nevertheless, adoption ultimately depends on national authorities agreeing to recognize blockchain-recorded certification events as legally equivalent to existing paper-based or centralized-database records, a regulatory question that lies beyond the scope of the technical design presented here but that will need to be addressed jointly by policymakers and standardization bodies if the approach is to move beyond the pilot stage represented by the BBBio project.

It is also worth situating the proposed blockchain-based design against the alternative of further centralizing existing certification databases, for instance through a shared EU-level registry operated by a single institution. Such a centralized alternative could, in principle, achieve similar levels of data consistency, but it would require member states to cede direct control over sensitive national certification data to a central operator, a governance step that has proven politically difficult in comparable European market-integration efforts (Squicciarini et al. 2010). The permissioned blockchain design proposed in this paper offers a middle path: it achieves a shared, mutually verifiable data layer without requiring any single institution to act as the sole custodian of the data, since every authorized national node retains a full, synchronized copy of the ledger and participates in validating new entries.

Several limitations of the present study should be acknowledged. First, the proposed architecture has so far been evaluated conceptually and through prototypical implementation within a single national research project (BBBio); a systematic, multi-country pilot involving several scheme operators and certification bodies would be required to validate the interoperability claims made in this paper under real regulatory heterogeneity. Second, this paper does not provide a quantitative performance evaluation of the Hyperledger Fabric implementation, such as transaction throughput or latency under realistic certification volumes; such an evaluation is a necessary next step before broader deployment can be recommended. Third, questions of data protection and confidentiality, particularly the extent to which commercially sensitive volume and pricing data can be shared on a distributed ledger accessible to multiple stakeholders, have not been fully resolved in the current design and require closer engagement with European data protection requirements. Finally, regulatory uncertainty regarding the legal recognition of blockchain-based certification records under national implementations of RED III remains an open issue that lies partly outside the scope of a purely technical design study.

Despite these limitations, the discussion above indicates that blockchain-based trust infrastructures offer a coherent and technically grounded response to the transparency and interoperability problems documented throughout the literature on both biomass certification specifically and European energy market integration more broadly. The design principles identified in this study, bottom-up traceability, batch-level dynamic metadata, permissioned network governance, and open API-based interoperability, provide a starting point for further research and for policy discussions on how blockchain-based infrastructures might be coordinated at the European rather than purely national level.

Conclusions

Blockchain technology has the potential to address several structural challenges within the European renewable energy sector, in particular the fragmented certification systems, inefficient manual procedures, and limited interoperability between national markets documented throughout this paper. Through decentralized data management, immutable transaction records, and automated smart contracts, blockchain-based trust infrastructures can significantly improve transparency and operational efficiency within biomass supply chains, while remaining compatible with the roles of existing stakeholders such as scheme operators, certification bodies, and national authorities.

This paper has followed a Design Science Research approach to develop such an architecture, presenting its governance model, its treatment of dynamic sustainability metadata, and its prototypical implementation on Hyperledger Fabric within the BBBio project. The literature review situates this contribution within two previously separate bodies of work, the general literature on blockchain applications in energy and public administration, and the long-standing literature on structural barriers to European energy market integration, and argues that biomass certification represents a particularly clear case in which these two problems intersect and in which a blockchain-based digital governance layer can plausibly address both simultaneously.

However, several challenges must be addressed before such systems can be widely adopted. Regulatory uncertainty remains a key issue, particularly with regard to the legal recognition of blockchain-based records and the alignment of national legislation with European policy frameworks. Furthermore, balancing transparency with data protection requirements requires careful technical and legal consideration, and additional challenges include ensuring scalability, maintaining system security, and enabling interoperability with existing digital infrastructures across member states.

Despite these challenges, blockchain-based certification systems have the potential to enhance market efficiency, strengthen regulatory compliance, and improve transparency across renewable energy supply chains. Future research will therefore focus on evaluating the technical performance and practical applicability of the proposed system architecture in real-world, multi-country energy markets, on conducting a systematic performance evaluation of the underlying Hyperledger Fabric network, and on developing the cross-border governance arrangements that would be required to operate a shared blockchain infrastructure across national certification authorities. The results presented here highlight the potential of blockchain-based trust infrastructures as a foundational element for next-generation digital governance in the European energy sector.

References

Algarvio H, Lopes F, Couto A, Santana J, Estanqueiro A (2019) Effects of regulating the European Internal Market on the integration of variable renewable energy. Wiley Interdisciplinary Reviews: Energy and Environment. https://doi.org/10.1002/wene.346.

Bao J, He D, Luo M, Choo KKR (2020) A survey of blockchain applications in the energy sector. IEEE Systems Journal 15(3): 3370–3381. https://doi.org/10.1109/JSYST.2020.2998791.

Boumaiza A (2024) Design and implementation of a blockchain-enabled transactive energy market. IEEE Access 12: 143118–143130. https://doi.org/10.1109/ACCESS.2024.3440180.

Cagigas D, Clifton J, Díaz-Fuentes D, Fernández-Gutiérrez M (2021) Blockchain for public services: A systematic literature review. IEEE Access 9: 13904–13921. https://doi.org/10.1109/ACCESS.2021.3052019.

EUR-Lex (2023) Directive (EU) 2023/2413 of the European Parliament and of the Council. Brussels: Publications Office of the European Union.

Hardjono T, Lipton A, Pentland A (2019) Toward an interoperability architecture for blockchain autonomous systems. IEEE Transactions on Engineering Management 67(4): 1298–1309. https://doi.org/10.1109/TEM.2019.2920154.

Höschle H, Cadre H, Belmans R (2018) Inefficiencies caused by non-harmonized capacity mechanisms in an interconnected electricity market. Sustainable Energy, Grids and Networks 13: 29–41. https://doi.org/10.1016/j.segan.2017.11.002.

Squicciarini G, Cervigni G, Perekhodtsev D, Poletti C (2010) The integration of the European electricity markets at a turning point: From the regional model to the Third Legislative Package. https://hdl.handle.net/1814/14294.

Venizelou V, Poullikkas A (2024) Trend analysis of cross-border electricity trading in pan-European network. Energies. https://doi.org/10.3390/en17215318.

Zalzar S, Bompard E, Purviņš A, Masera M (2020) The impacts of an integrated European adjustment market for electricity under high share of renewables. Energy Policy 136: 111055. https://doi.org/10.1016/j.enpol.2019.111055.