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Enhancing Transparency and Efficiency in Green Hydrogen Logistics via Blochain and Smart contracts

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Abstract:

This research proposes a multi-layered blockchain-based framework designed to provide a decentralized and immutable ledger for GH2 logistics. By integrating Internet of Things (IoT) sensors for real-time monitoring and smart contracts for algorithmic execution, the architecture ensures that every hydrogen batch is linked to verifiable renewable inputs and specific sustainability criteria. The study adopts a design science research (DSR) approach, synthesizing evidence from a systematic literature review with the development of a conceptual architecture. The framework is benchmarked against international standards, including ISO 14687 and the EU's Renewable Energy Directive (RED II), to ensure regulatory and institutional alignment. The results demonstrate that the proposed framework provides enhanced end-to-end traceability, systematically preventing "greenwashing" through tamper-proof carbon accounting. By reducing transaction costs and providing a standardized layer of trust, this framework facilitates credible international trade and fosters a scalable global market for green hydrogen.

Keywords: Green Hydrogen (GH2), Blockchain, Smart Contracts.

JEL Classification: Q20, Q47

1. Introduction:

The global commitment to achieving carbon neutrality by 2050, as codified in the Paris Agreement, has accelerated the adoption of green hydrogen (GH2) as a primary energy vector for decarbonizing traditionally hard-to-abate sectors, including heavy industry, long-distance maritime transport, and aviation. Derived from renewable-powered water electrolysis, green hydrogen represents a zero-emission alternative to fossil fuels, positioning it as a fundamental pillar of the transition toward an environmentally responsible future. Despite its strategic ascent, the establishment of a functional hydrogen economy remains obstructed by significant structural and logistical complexities.

A critical analysis of existing GH2 supply chains reveals systemic limitations characterized by centralized data governance and fragmented information flows. Traditional logistics management is currently plagued by what has been described as a "metabolic disorder," where a patchwork of manual, paper-based, and siloed enterprise systems act like damaged nerve endings, resulting in high operational costs and persistent opacity. Furthermore, the current certification landscape for "Guarantees of Origin" (GO) is predominantly manual and susceptible to manipulation, creating a profound "lemons problem" where the lack of consensus on sustainability standards undermines stakeholder trust and deters large-scale investment. This transparency deficit facilitates the risk of "greenwashing," where sustainability claims regarding carbon intensity and renewable provenance cannot be independently validated, thus jeopardizing the integrity of the burgeoning market .

1.1. Research Problem:

How can a multi-layered framework integrating Blockchain technology, Internet of Things (IoT) sensors, and Algorithmic Smart Contracts be designed to provide immutable 'Guarantees of Origin' (GO), thereby enhancing transparency, operational efficiency, and safety across the Green Hydrogen logistics supply chain?

1.2. Sub-questions:

To critically analyze the primary research problem, the following three sub-questions are formulated:

1. How can the functional integration of real-time sensing capabilities with distributed ledgers transform traditional mass balance protocols into automated systems that ensure the absolute authenticity of sustainability claims across the hydrogen value chain?
2. To what extent do algorithmic smart contracts optimize economic performance by reducing transaction costs and restructuring supply chain governance through the substitution of manual verification with autonomous compliance and settlement mechanisms?,,
3. In what ways does a tamper-proof digital oversight system enhance logistical risk management and operational accountability by providing verifiable records of transport parameters that allow for the immediate determination of legal responsibilities?

1.3. Main Hypothesis: The research problem's components in the null form have served as the foundation for the following study hypotheses:

The integration of pervasive IoT sensing, a consortium blockchain ledger, and algorithmic smart contracts enables a mature, verifiable green hydrogen (GH2) market by providing immutable "Guarantees of Origin" (GO) that optimize transactional efficiency and mitigate operational risks.

1.4. **Sub-Hypotheses:**

H1: Real-time IoT-blockchain convergence facilitates an automated "Proof-of-Sustainability" system based on mass balance principles, eliminating the "lemons problem" and preventing greenwashing by establishing a direct cryptographic linkage between physical molecules and their digital records.

H2: The substitution of centralized auditing with autonomous smart contracts optimizes economic performance by minimizing *ex-ante* and *ex-post* transaction costs and eliminating administrative certification losses inherent in traditional systems.

H3: A tamper-proof digital oversight system enhances logistical safety and accountability by maintaining an auditable record of critical physical parameters (e.g., pressure, purity) throughout the transport lifecycle, providing a robust evidentiary base for the determination of legal responsibilities

1.5. Importance of the Study:

1. We propose a decentralized framework that utilizes a consortium blockchain and IoT sensors to provide an immutable ledger for GH2 data management, ensuring that every batch is cryptographically linked to verifiable renewable inputs.
2. The framework utilizes Smart Contracts to automate the issuance, transfer, and cancellation of digital GO tokens (Proof-of-Sustainability), thereby streamlining the certification process and reducing the administrative burden on producers and regulators.
3. Enhanced Operational Safety and Accountability by enabling real-time monitoring of storage conditions and transport logistics, the proposed system mitigates safety risks associated with hydrogen's high flammability and ensures clear accountability across the supply chain.

1. Literature Review

1. 1. Green Hydrogen (GH2) Supply Chain Challenges: Logistics, Safety, and Economic Constraints

The transition to a hydrogen-based economy is fundamentally constrained by the physical and thermodynamic properties of the hydrogen molecule. Hydrogen is characterized as an "ultralight gas" with a density of merely 0.082 kg/m³ and an exceptionally broad flammability range when mixed with air, which necessitates complex and high-cost handling procedures (Wappner T & al, 2024). From a logistical perspective, distribution remains the primary cost driver, with studies estimating that between 40% and 75% of total supply chain expenses are incurred during the delivery of the molecule from producer to consumer (Wappner T & al, 2024).

Furthermore, the "low volumetric energy density" of GH2 requires significantly larger storage infrastructure compared to conventional hydrocarbons (Alavi-Borazjani & al, , 2025). For maritime applications, vacuum-insulated cryogenic tanks are two to three times more expensive than Liquefied Natural Gas (LNG) tanks and occupy 87% more space per

unit of energy, forcing a trade-off between fuel capacity and cargo volume (Alavi-Borazjani & al, , 2025). Beyond infrastructure, operational safety presents a severe barrier; hydrogen's "low ignition energy" of just 0.02 mJ renders it highly susceptible to fire and explosion in enclosed spaces, necessitating the development of globally standardized safety protocols to ensure system integrity(Alavi-Borazjani & al, 2025). Economic analysis suggests that while hydrogen-powered vessels offer a path toward zero tank-to-wake emissions, the total cost of ownership (TCO) remains prohibitive, with fuel expenses currently accounting for approximately 87% of the TCO for large-scale container transport (Alavi-Borazjani & al, , 2025).

1. 2. Blockchain in the Energy Sector

The deployment of Distributed Ledger Technology (DLT) in the energy sector has facilitated a shift from centralized utility models to decentralized "prosumer" ecosystems. Blockchain enables the creation of peer-to-peer (P2P) energy marketplaces where individuals can trade surplus renewable electricity directly, utilizing smart contracts to automate settlement and eliminate costly intermediaries (Nwulu N. & al, 2025). A prominent application is the use of Ethereum-based architectures to track energy generation and consumption within microgrids, providing a "single, tamper-proof transaction record" accessible to all stakeholders.

Beyond market transactions, blockchain provides a transformative mechanism for "Guarantees of Origin" (GO). By linking Renewable Energy Certificates (RECs) to digital tokens, the technology simplifies carbon accounting and prevents the pervasive risk of "double-counting". This ensures that the environmental premium paid for carbon-free energy is accurately attributed to the correct investor, effectively digitizing the value of green energy claims (De Blasio, N., & C. Hua, 2021).

1. 3. The Intersection of Blockchain and Hydrogen

While the literature on blockchain-enabled hydrogen supply chains is growing, current research often suffers from significant conceptual and technical gaps. Most existing studies remain confined to "theoretical proof-of-concepts" or isolated technical modules, failing to provide a cohesive framework for the entire GH2 value chain (Grünewald A., T & al, 2026).

A critical deficiency in current models is the "lack of consensus" in defining "green" hydrogen across diverging international certification schemes, which creates interoperability barriers for cross-border trade (Schmid J., et al, 2024). Moreover, many proposed frameworks ignore the "garbage in, garbage out" problem; blockchain can ensure the immutability of data, but it cannot independently verify the physical reality of the data fed into the system via oracles without robust external verification mechanisms (Schmid J., et al, 2024).

Furthermore, there is a distinct lack of research addressing "technical scalability." Current blockchain infrastructures often struggle to process the high-frequency, real-time data generated by IoT sensor networks in industrial settings, which can lead to system congestion (Schmid J., et al, 2024). Additionally, there is a strategic tension regarding information distribution: while decentralization improves consensus quality, it can inadvertently facilitate "tacit collusion" among sellers by making aggregate market data visible to competitors, potentially harming consumer surplus (Cong L. W., & He, Z, 2018). Finally, advanced security features like Zero-Knowledge Proofs (ZKPs), while beneficial for privacy, currently carry high transaction costs that conflict with the goal of reducing the overall cost of hydrogen (Schmid J., et al, 2024).

2. Proposed Multi-layered Blockchain Management

The structural complexity of green hydrogen (GH2) logistics requires a sophisticated digital twin that mirrors physical molecules through a decentralized information system. This study proposes a multi-layered architecture designed to synchronize energy production data with market certification protocols.

2. 1. The Layers of the Architecture

- **Physical/Perception Layer:** At the foundational level, this layer consists of the "IoT Sensors Asset Network," which integrates smart meters and sensors directly into electrolyzers, storage tanks, and transport vehicles (Tetouani A., et al, 2025). These devices capture granular operational metrics, including hydrogen flow rates, pressure, temperature, and electricity input patterns from renewable sources (Schmid J., et al, 2024).
- **Network Layer:** Serving as the "Hydrogen Blockchain Service Network," this layer manages the data transmitted from the perception layer via secure IoT gateways (Tetouani A., et al, 2025). We propose a consortium blockchain model governed by pre-selected authorized nodes—such as regulators and Transmission System Operators (TSOs)—to maintain a shared, immutable ledger while ensuring data privacy(Schmid J., et al, 2024). This layer facilitates identity management and consensus (e.g., Proof of Authority) to validate transactions efficiently(Schmid J., et al, 2024).
- **Application/Service Layer:** This top-tier layer provides the interface for stakeholders to access "Guarantees of Origin" (GO) and digital product passports. It includes modules for hydrogen management, data analytics, and automated reporting to ensure compliance with international directives like RED II (Tetouani A., et al, 2025).

2. 2. Smart Contracts for Automated Governance

Smart contracts function as "autonomous reflexes" within the architecture, translating institutional rules into executable code (Kilinc, N. U., "The Integrated Bio-Digital Maritime Organism: A Scientific Analysis of Green Smart Ports, Autonomous Vessels, and Synchro-modal Logistics," 2025, p. 19). They are designed to automate payments and the issuance of GO tokens upon verifying that hydrogen batches meet specific criteria. When IoT sensors relay data confirming the required purity levels and quantities (e.g., 1 MWh energy equivalent), the smart contract triggers a "REST API Request" to execute financial settlements or token transfers without human intervention (Tetouani A., et al, 2025).

3. Analysis and Discussion

3. 1. Transparency, Trust, and the Mitigation of "Greenwashing"

The primary obstruction to a functional green hydrogen (GH2) economy is the "lemons problem," wherein information asymmetry regarding production methods allows fraudulent actors to mimic authentic producers (Cong L. W., & He, Z, 2018). By implementing the proposed architecture, the industry can transition from a "book and claim" concept to a mass balance-based "Proof-of-Sustainability" system, which requires a direct cryptographic linkage between the physical hydrogen output and its digital certificate (Schmid J., et al, 2024). The framework effectively addresses "greenwashing" by utilizing an immutable ledger to ensure that sustainability claims are accurate, reliable, and fraud-proof ((Wappner T & al, 2024). Through the tokenization of energy certificates, the architecture guarantees that for every unit of sustainable energy, only one "Guarantee of Origin" (GO) is created, systematically preventing the risk of double-counting (Wappner T & al, 2024).

3. 2. Economic Trade-offs

The transition to hydrogen-powered logistics involves significant financial barriers, particularly a Total Cost of Ownership (TCO) that remains higher than conventional diesel alternatives (Alavi-Borazjani & al, , 2025). However, a critical longitudinal analysis reveals that the initial capital expenditure (CAPEX) for technology integration—estimated at approximately USD 4 million to USD 5 million—is offset by the elimination of "certification losses" and logistics inefficiencies (Tetouani A., et al, 2025). By removing costly intermediaries such as banks and brokers and automating settlement triggers through smart contracts, the framework facilitates a 43.6% increase in cumulative five-year net gains compared to traditional, manual certification baselines (Tetouani A., et al, 2025).

3. 3. Scalability and the Energy Consumption Paradox

A central critique of blockchain implementation within "green" projects is the energy intensity of the technology itself. To justify this integration, the proposed framework rejects energy-intensive Proof-of-Work (PoW) consensus mechanisms in favor of Proof-of-

Authority (PoA) (Schmid J., et al, 2024). PoA is characterized by "low" energy consumption and "high" scalability, making it suitable for industrial-scale energy markets without undermining the project's net-zero objectives (Schmid J., et al, 2024). To further enhance scalability, the framework proposes linking transactions to 1 MWh batches rather than infinitesimal sensor data streams, thereby optimizing data throughput and preventing system congestion while maintaining the integrity of the "digital pulse" across the value chain (Tetouani A., et al, 2025).

4. Challenges and Future Directions

The structural maturation of a green hydrogen (GH2) economy is currently impeded by three interconnected systemic barriers: regulatory fragmentation, technical friction with legacy infrastructures, and the prohibitive capital intensity of digital integration.

4. 1. Regulatory Hurdles and Cross-Border Standardization

The primary obstacle to a liquid global hydrogen market is the profound lack of consensus regarding international certification standards and the qualitative definition of "green" provenance (Schmid J., et al, 2024). Incompatible certification schemes—such as the divergence between the EU's CertifHy and Australia's Zero Carbon Certification—create significant interoperability barriers that deter cross-border trade (Wappner T & al, 2024). Furthermore, within federal systems like Australia, fragmented regulatory responsibilities across states increase compliance complexity and discourage large-scale investment (Wong P. Y. L & al, , 2025). Legal conflicts also persist between the immutable nature of distributed ledgers and the European General Data Protection Regulation (GDPR), specifically regarding the "right to be forgotten" (Khan S. N & al., , 2021).

4. 2. Technical Interoperability and the "Oracle Problem"

Integrating blockchain technology with established industrial infrastructures presents severe technical challenges, particularly when interfacing with legacy Enterprise Resource Planning (ERP) systems (Beriwal S, 2025). These traditional systems often function as "application islands," resulting in a "metabolic disorder" characterized by siloed information flows (Kilinc N. U, 2025). Moreover, the "oracle problem"—the necessity of trusted third-party intermediaries to feed off-chain sensor data into the blockchain—introduces potential single points of failure and risks of data manipulation (Schmid J., et al, 2024). Scalability also remains a concern, as current blockchain infrastructures struggle to process the high-frequency, real-time data generated by expansive IoT sensor networks (Tetouani A., et al, 2025).

4. 3. Prohibitive Infrastructure and IoT Costs

The capital-intensive nature of green hydrogen logistics represents a formidable economic constraint. For example, the establishment of a single hydrogen refueling station requires an estimated investment of USD 1 million to USD 2 million (Sayeed M. A., & Manikandan, K, 2024).Comprehensive technological integration for a medium-scale demonstration project—encompassing both IoT sensor networks and private blockchain infrastructures—carries an estimated capital expenditure (CAPEX) of approximately USD 5.5 million (Tetouani A., et al, 2025). These high initial costs are further exacerbated by the energy requirements of cryogenic storage and the necessity for specialized, hydrogen-compatible materials to prevent embrittlement (Alavi-Borazjani & al, , 2025).

5. Conclusion

This research demonstrates that the integration of blockchain technology and the Internet of Things (IoT) provides a transformative solution for the green hydrogen supply chain by mitigating information asymmetry and establishing a tamper-proof mechanism for "Guarantees of Origin" (GO). The main findings indicate that the proposed multi-layered architecture effectively addresses the "lemons problem" in energy markets, ensuring that sustainability claims are accurate and verifiable. By automating compliance through algorithmic smart contracts and real-time IoT monitoring, the framework significantly reduces transaction costs and eliminates the risk of "greenwashing".

The value of this framework lies in its ability to synchronize the physical movement of hydrogen molecules with an immutable digital twin, fostering stakeholder trust and market scalability. Based on these insights, the following policy recommendations are proposed:

1. **Standardization and Harmonization:** Energy regulators must develop a unified national regulatory structure that aligns with international ISO standards (e.g., ISO 14687 and ISO 19880) to facilitate seamless interstate and international trade.
2. **Regulatory Sandboxes:** Governments should implement regulatory sandboxes to provide controlled environments for testing blockchain-based certification and IoT integration without the immediate burden of full-scale compliance.
3. **Incentivized Digitalization:** Policymakers should provide financial incentives, such as tax credits or grants, to offset the high CAPEX of IoT and blockchain adoption, particularly for smaller market participants.
4. **Integrated Lifecycle Accounting:** Industry practitioners should adopt a "cradle-to-gate" or "well-to-wheel" boundary definition for carbon accounting to ensure true environmental integrity across the entire value chain.

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