22nd International Conference on Sustainable Energy Technologies
Kuala Lumpur, Malaysia, 13 to 15 August 2026 · ISBN 978-1-995850-00-9 · ISSN 2978-4387

CONFERENCE PAPER · AI & RENEWABLE SYSTEMS

Blockchain-Enabled Traceability: Bridging the Hydrogen Trade Gap between Europe and China

Sofya Morozova[1*], Omer Faruk Yakut[2], Arif Karabuga[3]

[1] Haliç University, International Trade and Business Department, Türkiye
[2] Ruby Cyber Labs Cybersecurity and Digital Forensics Laboratory, Türkiye
[3] Istanbul Aydın University, Faculty of Engineering, Türkiye

RECEIVED 12 February 2026 · REVISED 12 March 2026 · ACCEPTED 23 March 2026
PRESENTED 13 to 15 August 2026 · PUBLISHED 23 November 2026

ABSTRACT

The global energy transition is accelerating the development of hydrogen as a strategic low-carbon energy carrier, yet the international market remains structurally fragmented and lacks standardized verification. This study analyzes the current market structure of hydrogen through a comparative analysis of production capacity and national policy strategies in Europe and China. Specifically, it identifies the structural rift between Europe's regulatory-driven import model and China's industrial expansion strategy. To bridge this gap, the research evaluates the integration of a blockchain-based traceability platform designed to standardize "Certification Systems" and provide immutable proof of origin for green hydrogen. By addressing the technical barriers of cross-border trade, this study develops predictive scenarios for the evolution of international hydrogen trade through the future decades. The outlook evaluates how the deployment of such a traceability platform influences cost competitiveness, geopolitical alignment, and market integration. The results determine whether hydrogen will successfully evolve into a globally traded, transparently verified commodity or remain regionally structured in the long term.

KEYWORDS Hydrogen energy, Blockchain traceability, International trade, Market outlook 2050

1. Introduction

The European Union is undergoing a profound energy transition, driven by the dual imperatives of climate change mitigation and energy security. Renewable energy and hydrogen technologies are central to this transformation, with EU policies providing the framework for decarbonization and market integration. The transition is characterized by ambitious targets, technological innovation, and evolving policy responses to geopolitical and economic challenges, notably the Ukraine crisis and post-pandemic recovery. The interplay between renewables, hydrogen, and policy is shaping the EU's path toward carbon neutrality by 2050, but significant challenges remain in harmonizing national strategies and scaling up integrated systems (Cartier and Cazier 2024; Nhung 2024). While investment and policy support for hydrogen are increasing, the international market is characterized by structural fragmentation and a lack of standardized verification. This fragmentation is most visible in the diverging development models of major global actors: Europe, which focuses on a regulatory-driven import model, and China, which prioritizes a domestically oriented industrial expansion strategy.

A primary barrier to a unified global market is the heterogeneity in national strategies, which leads to regulatory complexity and differing certification schemes. In the European Union, the introduction of Renewable Fuels of Non-Biological Origin (RFNBO) certification systems is essential

* Corresponding author. Email address: sofyatoo1@gmail.com (Sofya Morozova)

© 2026 The Author(s).
Published by Caravel Press.

doi.org/10.65582/set.2026.029

for market growth, yet strict criteria can limit hydrogen availability and production (Machado *et al.* 2022; Eichner and Pethig 2019). To bridge the structural rift between these regional models, there is an urgent need for harmonized regulatory frameworks and digital tools that enhance transparency and trust.

This research evaluates the integration of a blockchain-based traceability platform as a technical solution to standardize certification systems and provide immutable "Proof of Origin" for green hydrogen. Such digital traceability tools are increasingly recommended to facilitate cross-border trade and unified market integration. By addressing these technical barriers, this study develops predictive scenarios to determine how infrastructure deployment and digital verification will influence future trade flows. While this study provides a strategic roadmap, it is limited by the rapid pace of technological innovation in water electrolysis and the inherent data heterogeneity across different national reporting systems. Additionally, the regional variability of non-technical barriers, such as public acceptance and safety perceptions, may affect the speed of platform scalability.

2. Hydrogen Trade

While the conceptualization of hydrogen as an energy carrier spans several decades, it was historically framed as a theoretical pillar of future energy systems rather than a practical reality. Early research characterized hydrogen as a versatile and clean vector with the unique capacity to bridge disparate sectors, such as transportation, heavy industry, and power generation. Despite this long-standing recognition, significant economic and technological hurdles historically stalled its large-scale deployment. Recently, however, hydrogen has undergone a major resurgence, driven by aggressive global climate policies and the accelerating energy transition. Current academic discourse emphasizes that hydrogen, particularly green or low-carbon variants, is now a critical instrument for decarbonizing industrial sectors. Beyond carbon reduction, it is increasingly valued for its ability to bolster energy security and provide the essential flexibility required to manage modern, renewable-heavy energy grids. The global landscape for hydrogen development is currently defined by two fundamentally different approaches: the European Union's regulatory-driven import model and China's industrial expansion strategy. While both regions view hydrogen as a cornerstone of the energy transition, their operational philosophies, timelines, and market mechanisms reflect distinct economic and geopolitical priorities.

The EU's hydrogen market is designed to evolve through a structured progression, moving from an initial start-up phase into development and, eventually, full-scale growth. This maturation is supported by regulatory actions specifically tailored to the requirements of each stage to ensure legal certainty and coordinated infrastructure development (Dejonghe *et al.* 2023; Hasan and Fuentes 2025). A key element of this operationalization is the use of auction-based support mechanisms via the European Hydrogen Bank. These auctions are strategically utilized to incentivize electrolyzer capacity and critical infrastructure investment, as they provide more precise and effective investment signals compared to traditional price guarantees (Hasan and Fuentes 2025). To facilitate this import-heavy model, the EU places significant emphasis on infrastructure regulation, focusing on the development of cross-border pipelines, storage facilities, and harmonized certification systems. These technical standards, including strict "Proof of Origin" requirements, are essential for seamless market integration and the verification of imported low-carbon energy. However, the model faces persistent operational challenges, such as a highly complex policy landscape and stringent certification barriers. Overcoming these hurdles will require diversifying funding sources beyond centralized mechanisms to ensure long-term market fluidity and energy security (Dejonghe *et al.* 2023).

Table 1. Comparison of EU and Chinese hydrogen market structure.

	European Union (Regulatory-Driven Import Model)	**People's Republic of China (Industrial Expansion Strategy)**
Governance Style	Centralized, market-mechanism based; high legal certainty via top-down regulation.	Decentralized; local experimentation with central coordination and regional pilots (Gong 2025; Zhang and Yang 2022)
Objectives	Energy security, cross-border market integration, and standardized certification.	Rapid domestic scale-up, industrial decarbonization, and technology breakthroughs (Dejonghe *et al.* 2023)
Traceability & Blockchain	Essential for immutable "Proof of Origin" to meet strict RFNBO sustainability criteria.	A tool for overcoming regional fragmentation and ensuring standards across diverse pilot (Mojsiejewska and Rogowska 2024; Li *et al.* 2025)
Policy Instruments	EU ETS II, RED III, European Hydrogen Bank auctions, and RFNBO certification.	Three-stage national roadmaps, local subsidies, and regional industrial clusters (Graczyk *et al.* 2025; Liu *et al.* 2025)
Infrastructure Focus	Cross-border pipelines (European Hydrogen Backbone) and storage for import terminals.	Domestic pipeline networks, refueling stations, and renewable-grid integration (Kountouris *et al.* 2024; Zhao *et al.* 2026)
Incentive Mechanisms	Competitive auctions providing precise investment signals for electrolyzer capacity.	Direct subsidies, policy-driven industrialization, and R&D for water electrolysis (Wolf 2025)
Challenges	Regulatory complexity, high certification barriers, and import dependency risks.	Regional protectionism, high capital costs, and fragmented local regulations (Song *et al.* 2026)

In contrast, China's approach is characterized by decentralized, local experimentation combined with significant central oversight. While this model fosters rapid innovation and technological breakthroughs, it also leads to regulatory fragmentation and local protectionism (Gong 2025; Zhang and Yang 2022). China's roadmap is governed by a rigorous three-stage strategy 2021–2035 prioritizing rapid domestic scaling. The initial phase 2021–2025 emphasizes the expansion of hydrogen fuel cell vehicles and refuelling stations through regional pilot projects. This is followed by a scale-up phase 2026–2030 where the focus shifts to massive green hydrogen production and infrastructure connectivity. By the final phase 2031–2035, the strategy aims to broaden application scenarios across all industrial sectors to achieve significant CO_2 reductions. Operationally, China relies on a combination of technological innovation, particularly in water electrolysis and biohydrogen, and regional adaptation. Despite achieving rapid industrial growth, the model continues to navigate challenges such as high capital costs, immature technology subsets, and localized infrastructure gaps. These issues are currently being addressed through aggressive policy support and key technological breakthroughs in pipeline transportation and hybrid system fault detection (Zhao *et al.* 2026).

Despite regulatory efforts, the primary barrier to cross-border hydrogen trade is not only policy fragmentation but also the absence of reliable, standardized, and interoperable data systems. Hydrogen, unlike traditional commodities, requires verification of its production pathway, carbon intensity, and energy source. This creates a multidimensional data challenge, where information must be consistently tracked, validated, and shared across jurisdictions. Existing certification schemes remain fragmented, non-interoperable, and vulnerable to information asymmetry, limiting trust between trading partners. In addition to regulatory and technological differences, the global hydrogen market is still in an early stage of price formation and lacks a unified pricing mechanism

comparable to conventional energy commodities. Hydrogen prices remain highly dependent on production methods, regional electricity costs, and infrastructure availability, leading to significant price disparities across markets. Unlike oil or natural gas, where benchmark pricing systems provide transparency and stability, hydrogen markets are characterized by bilateral agreements and project-specific pricing structures. This limits market liquidity and slows the development of large-scale international trade. The emergence of standardized certification and traceability systems is therefore closely linked not only to verification, but also to the creation of transparent pricing mechanisms and more efficient market signals.

3. The Traceability Platform

Blockchain technology offers a decentralized and tamper-resistant infrastructure capable of recording hydrogen production data, certification attributes, and transaction flows in a transparent and verifiable manner. Unlike conventional databases, blockchain enables multiple stakeholders to access a shared ledger without relying on a central authority, thereby reducing information asymmetry and enhancing trust. Hydrogen proof of origin certificates (HPOCs), also known as Guarantees of Origin (GOs), are emerging as critical instruments in the global energy transition. They provide verifiable evidence of the production method and environmental attributes of hydrogen, enabling market differentiation between renewable, low-carbon, and fossil-based hydrogen (Gallegos 2024). In Figure 1, the consortium blockchain network is illustrated as the core infrastructure enabling secure and coordinated hydrogen certification and trade across multiple jurisdictions. The network is designed as a permissioned system, where participation is restricted to authorized institutional actors, ensuring controlled access, data confidentiality, and regulatory compliance. As shown in the figure, the network is composed of multiple stakeholder nodes, including EU regulators, Chinese authorities, certification bodies, trade and exchange organizations, energy and industry associations, and accredited entities such as laboratories and inspectors. These participants jointly maintain the distributed ledger and contribute to transaction validation, forming a decentralized yet governed ecosystem. At the center of the consortium network, smart contracts are depicted as the primary execution layer, responsible for managing the lifecycle of hydrogen certificates. As indicated in the diagram, these contracts automate key functions such as certificate issuance, transfer, revocation, compliance verification, and access control. This ensures that regulatory rules are consistently enforced across all participating entities. The figure further demonstrates how data integrity is preserved through cryptographic mechanisms, where production data is hashed and recorded on-chain. Each transaction is stored as an immutable record with a timestamp, enabling full traceability and auditability of hydrogen certification and ownership history. Additionally, the network structure shown in the figure highlights its role in facilitating cross-border regulatory alignment, particularly between the European Union and China. By enabling shared validation processes and standardized data exchange, the consortium blockchain supports interoperability between different regulatory frameworks and reduces fragmentation in the hydrogen market.

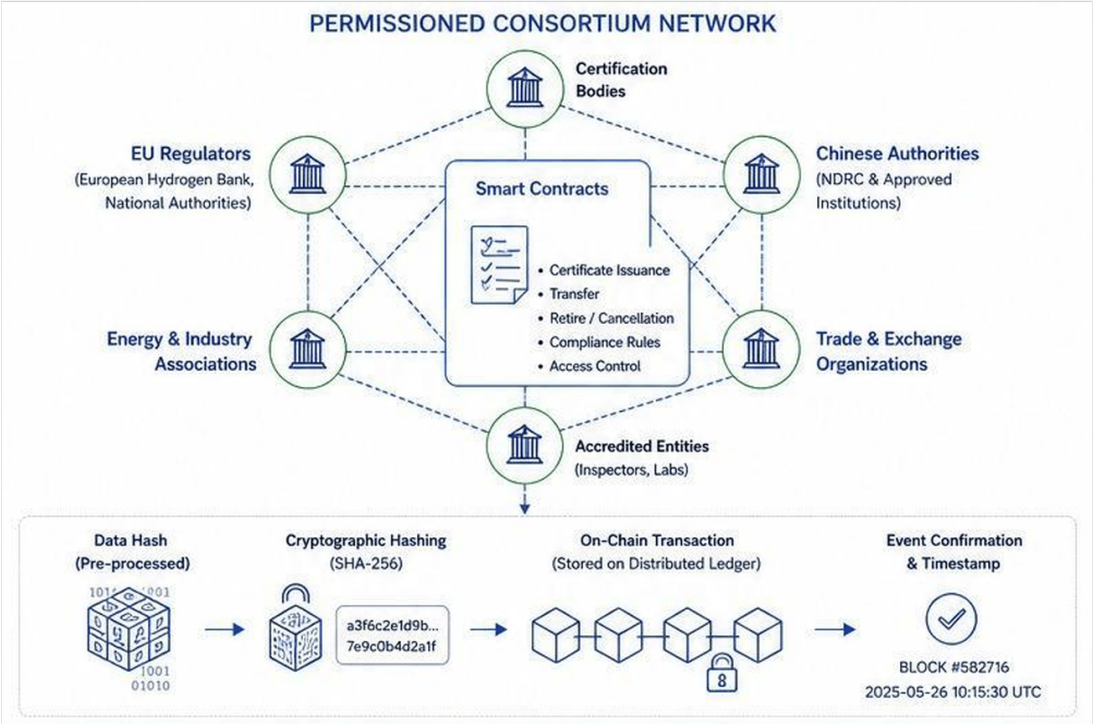

Figure 1. Consortium network diagram.

3.1. Technical Architecture and Blockchain Selection

The platform employs a consortium blockchain built on Hyperledger Besu, an enterprise-grade Ethereum client architecture, which is uniquely suited to the institutional requirements of cross-border hydrogen trade. Unlike public blockchains, which are resource-intensive, introduce high transaction fee volatility, and lack governed membership, or private blockchains, which reintroduce single points of failure and centralized trust, a consortium model distributes authority among a defined set of permissioned nodes operated by verified actors. The platform architecture is structured across three functional layers as mapped out in Figure 2:

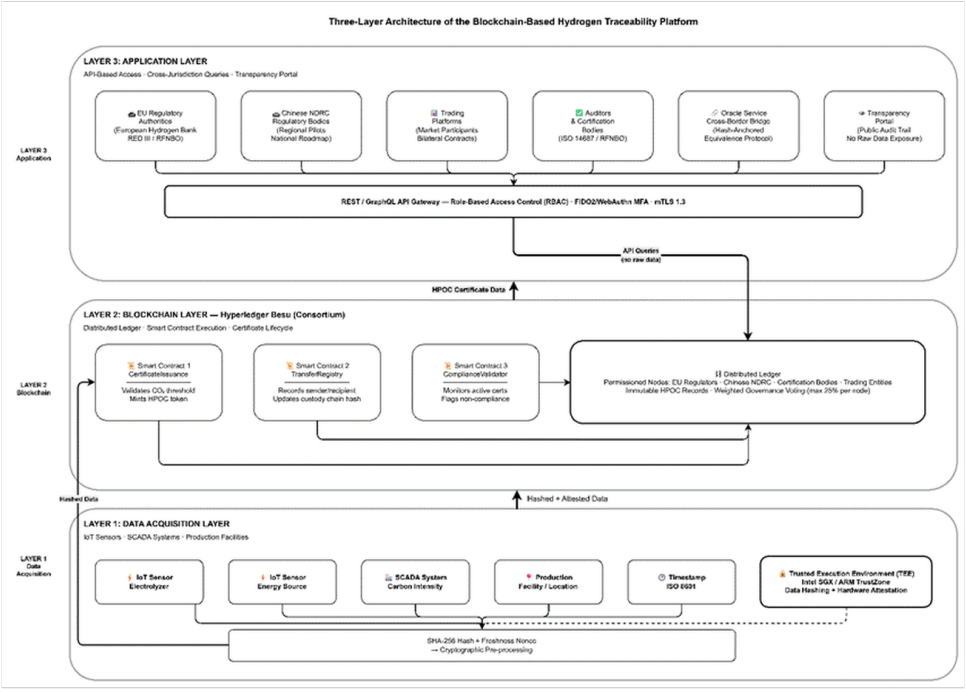

Figure 2. Three-layer architecture of the proposed blockchain-based hydrogen traceability platform.

1. Data Acquisition Layer (Layer 1): This layer interfaces directly with physical production facilities (such as PEM or alkaline electrolyzers) via internet-of-things (IoT) sensors and Supervisory Control and Data Acquisition (SCADA) systems. It captures real-time operational data including electrolysis operational parameters, energy source attribution metrics, carbon intensity data, location coordinates, and timestamps. To secure this data at the ingestion point, the platform utilizes hardware-based Trusted Execution Environments (TEEs) such as Intel SGX or ARM TrustZone to perform data hashing and hardware attestation directly at the production facility, applying a SHA-256 cryptographic hash and a freshness nonce to prevent replay or data-tampering attacks.
2. Blockchain Layer (Layer 2): Operating on the Hyperledger Besu consortium framework, this layer maintains the immutable distributed ledger and executes the smart contract logic. The ledger ensures full auditability via cryptographic security and consensus mechanics, restricting weighted governance voting rules (e.g., maximum 25% voting power per individual node category) to maintain cross-border neutrality between trading jurisdictions.
3. Application Layer (Layer 3): The application layer provides secure, role-based access control (RBAC) via REST and GraphQL APIs protected by FIDO2/WebAuthn multi-factor authentication (MFA) and mutual TLS (mTLS 1.3) encryption. This allows regulatory authorities, trading platforms, and external auditors to query certificate statuses and verify compliance without exposing raw, commercially sensitive industrial production data.

Unlike public blockchains, which are resource-intensive and lack governed membership, or private blockchains, which reintroduce centralized trust, a consortium model distributes authority among a defined set of permissioned nodes operated by verified actors such as certification bodies, energy regulators, and trading entities. For the European Union context, this aligns with the institutional roles of the European Hydrogen Bank and national regulatory authorities operating under RED III and RFNBO frameworks. On the Chinese side, designated nodes can be administered by entities approved under China's National Development and Reform Commission (NDRC) hydrogen guidelines. The platform architecture is structured across three functional layers. The data acquisition layer interfaces with production facilities through IoT sensors and SCADA systems, capturing real-time operational data including electrolysis parameters, energy source attribution, and carbon intensity metrics. This data is pre-processed and cryptographically hashed before transmission to the blockchain layer. The blockchain layer maintains the distributed ledger and executes the smart contract logic governing certificate issuance, transfer, and retirement. The application layer provides API-based access for regulatory authorities, trading platforms, and auditors, enabling cross-jurisdiction data queries without direct access to raw underlying production data.

3.1.1. Comparative Justification of Consortium Blockchain

The selection of a consortium blockchain is evaluated against four alternative architectures that could support hydrogen certificate verification. Table 2 provides a conceptual comparison across six criteria relevant to EU–China hydrogen trade. The comparison concerns institutional control and certificate lifecycle management rather than measured implementation performance.

Table 2. Comparison of five digital certificate architectures across six EU–China trade criteria.

Approach	Trust model	Tamper resistance	Cross-border use	Sovereignty	Transfer / custody	Regulatory automation
Centralized registry	Single recognized operator	Auditable, but operator has privileged control	Requires agreement on a common operator	Low if one jurisdiction controls the registry	Possible within registry	High if centrally configured
Federated database	Cooperating data stewards	Depends on controls and synchronization	Requires shared schemas and dispute rules	Distributed, but coordination-sensitive	Possible; conflicting status risk	Possible via shared services
Digitally signed certificates	Trusted issuer and public keys	Signature detects modification	Portable if issuers/keys accepted	High issuer autonomy	No common ownership/ status ledger	Limited without extra services
Verifiable credentials	Accredited issuer / verifier	Cryptographic proof and optional disclosure	Promising with shared schemas	High issuer autonomy	Needs external status / transfer registry	Possible via extra services
Consortium blockchain	Jointly authorized validators	Consensus-backed audit trail	Shared, jointly governed network	Shared control across jurisdictions	Common status and custody ledger	Smart-contract rules

A centralized registry can provide effective lifecycle tracking and automated validation, but it places control with one operator; neither the European Union nor China can be assumed to accept unilateral oversight by the other. Federated databases preserve local data stewardship, yet require additional arrangements for synchronization, resolving conflicting certificate states, and recognizing an authoritative transfer history. Digital signatures authenticate certificates but do not, alone, prevent subsequent duplicate claims or transfers. Verifiable credentials support cryptographic attribute verification and selective disclosure, making them suitable for representing HPOC attributes, but require an external status and transfer mechanism. By contrast, a permissioned consortium blockchain can maintain a shared certificate-status and chain-of-custody ledger while accredited entities independently operate validator nodes. Smart contracts can encode agreed issuance, transfer, retirement, and compliance checks, reducing the need to trust one foreign system operator. Consequently, the proposed Hyperledger Besu model is preferable for the particular governance problem of bilateral hydrogen verification, provided the parties agree on membership, access, audit rights, and data standards. This architectural choice does not itself establish regulatory equivalence or guarantee the correctness of off-chain production measurements.

3.2. Hydrogen Certificate Data Model

Each HPOC recorded on the platform constitutes a structured digital object containing a comprehensive set of production and compliance attributes. The certificate includes a unique identifier, the producer identity represented by a keyed, pseudonymized hash to preserve commercial confidentiality, the production method (e.g., PEM or alkaline electrolysis, steam methane reforming with carbon capture), the primary energy source, measured carbon intensity expressed in kilograms of CO_2 equivalent per kilogram of hydrogen, the geolocation and timestamp of production, applicable regulatory standards such as RFNBO under RED III or ISO 14687, and a chain-of-custody

hash linking the certificate to prior transfer records. Table 3 provides data description. This data model directly responds to the multilevel verification requirements that distinguish hydrogen from conventional energy commodities. The carbon intensity field is essential for compliance with the European Commission's delegated regulation defining RFNBO thresholds, which requires that hydrogen production emit no more than 3.38 kg CO_2eq/kg H_2 on a lifecycle basis. By embedding this parameter in an immutable on-chain record, the platform eliminates reliance on self-reported declarations and third-party intermediaries, reducing verification costs and the risk of certification fraud.

Table 3. HPOC certificate data model: on-chain fields, data types, and regulatory basis.

Field	Type	Description	Regulatory Basis
certificate_id	UUID (String)	Globally unique certificate identifier	—
producer_hash	HMAC-SHA-256 (keyed)	Pseudonymized producer identifier (privacy-preserving)	GDPR / data privacy
production_method	Enum	PEM Electrolysis / Alkaline / SMR-CCS / Bio	ISO 14687
energy_source	Enum	Wind / Solar / Hydro / Grid-balanced	RED III, Annex IX
carbon_intensity	Float (kg CO_2eq/kg H_2)	Lifecycle GHG intensity of production batch	RFNBO ≤ 3.38 kg CO_2eq/kg H_2
production_timestamp	ISO 8601	Date and time of production batch	—
facility_location	ISO 3166	Country / region code of production site	—
electrolysis_efficiency	Float (%)	Energy conversion efficiency of electrolyzer unit	—
standard_compliance	Array [String]	List of applicable regulatory standards met	RFNBO/RED III; ISO 14687
custody_chain_hash	SHA-256	Cryptographic link to prior transfer record	—
certificate_status	Enum	ACTIVE / TRANSFERRED / RETIRED	EU GO Registry equiv.

3.2.1. Producer Identity Protection and Regulatory Access

A plain SHA-256 digest of a producer identifier does not provide anonymity. Because SHA-256 is deterministic and the universe of possible hydrogen producers may be relatively small, an observer could hash likely identifiers and compare them with on-chain values. The platform therefore treats producer identifiers as pseudonymized personal or commercially sensitive data rather than as irreversibly anonymized records. This distinction is especially relevant when an identifier can be associated with a natural person under the GDPR.

The producer_hash field is generated with a keyed and salted construction: producer_hash = HMAC-SHA256(key_R, producer_id || salt), where key_R is a secret key held within the designated regulator-controlled key-management service and salt is a randomly generated value maintained with the off-chain identity record. Knowledge of the public ledger and candidate producer identifiers is insufficient for straightforward dictionary matching without the secret key. Key rotation, salt management, and access logging form part of the proposed operating procedures.

The association between the pseudonym and the verified legal identity is maintained in an encrypted off-chain registry, protected by a hardware security module (HSM) or trusted execution environment (TEE). Only the keyed pseudonym, not the legal identity or the secret key, is written to the consortium ledger. Authorized verification services can resolve the mapping under predefined purpose, retention, and role-based access restrictions; a blockchain record alone cannot reveal the protected identity.

Re-identification for legitimate supervisory purposes requires multi-signature or threshold authorization from the designated oversight parties, for example joint approval by authorized European and Chinese representatives. The identity-mapping service checks that approval before

disclosing records; each request and decision is recorded as a tamper-evident on-chain audit event without publishing the identity itself. These controls specify a proposed governance mechanism and would require concrete implementation and bilateral legal arrangements.

The custody_chain_hash field serves a different purpose from producer_hash: it uses SHA-256 to link successive certificate-transfer records and detect subsequent alteration of their content, not to hide an individual's identity. The keyed producer identifier remains pseudonymized because an authorized mapping process permits re-identification. Table 4 distinguishes this mechanism from anonymization and clarifies the limits of its privacy guarantees.

Table 4. Anonymization versus pseudonymization in the proposed certificate data model.

Parameter	Anonymization	Pseudonymization in proposed platform
Identity link	Not reasonably recoverable by available means	Recoverable through controlled off-chain mapping
On-chain value	No retained identifying link	HMAC-SHA-256 keyed producer_hash
Mapping / keys	No re-identification mapping retained	Salt and key management kept off-chain; access restricted
Regulatory access	No intended way to restore identity	Threshold-authorized disclosure with audit trail
Data-protection treatment	Not personal data when truly anonymous	May remain personal data under GDPR

3.3. Smart Contract Logic and Automated Compliance Verification

The platform operationalizes compliance enforcement through a set of interdependent smart contracts deployed on the consortium blockchain. The certificate issuance contract validates incoming production data against predefined compliance thresholds before minting an HPOC. If a production batch fails to meet the carbon intensity threshold or the required energy additionality criteria, the contract rejects issuance and logs the non-compliance event immutably. This automated gate function replaces the manual review processes currently employed by certification bodies, reducing processing time from weeks to minutes.

The transfer registry contract governs the exchange of HPOCs between trading counterparties. Each transfer event records the sender, recipient, transaction volume, price reference, and the regulatory framework under which the transfer is recognized. This produces an auditable chain of custody that supports dispute resolution and market surveillance by competent authorities. A third compliance validation contract continuously monitors the state of active certificates against evolving regulatory thresholds. As frameworks are updated (for example, if the RFNBO carbon intensity limit is revised under a RED IV amendment), the validator contract can be upgraded through the consortium governance protocol, automatically flagging certificates that no longer meet the new standard without invalidating prior compliant transfers.

3.4. Cross-Border Interoperability Layer

The most structurally significant feature of the proposed platform is its cross-border interoperability layer, designed to bridge the divergent certification ecosystems of the European Union and China. Current EU certification relies on the European GO Registry and RFNBO-compliant national schemes, while China operates its own hydrogen certification pilots under regional standards that lack mutual recognition with European frameworks (Mojsiejewska and Rogowska 2024; Li *et al.* 2025). This incompatibility constitutes the primary technical barrier to EU–China hydrogen trade, as neither party can independently verify the sustainability attributes of the other's certificates. The interoperability layer addresses this through a hash-anchored certificate equivalence protocol. When a Chinese producer submits an HPOC for recognition in the EU market, the interoperability layer deploys an off-chain oracle service that retrieves and validates the corresponding production data

from the Chinese certification record, translates the relevant attributes into the EU compliance schema, and submits a verification proof to the consortium blockchain. The resulting EU-recognized certificate is cryptographically linked to its Chinese counterpart, preserving an auditable lineage while operating within each jurisdiction.

3.5. Governance and Trust Model

The long-term viability of the platform depends on a robust multi-stakeholder governance framework that balances institutional authority with operational resilience. The consortium governance model assigns node operation rights to three categories of verified participants: regulatory authorities, including EU member state hydrogen agencies and Chinese NDRC-affiliated bodies, accredited certification organizations, and licensed trading entities. Decision-making authority over protocol upgrades, compliance threshold adjustments, and node admission is distributed through a weighted voting mechanism, preventing any single jurisdiction from unilaterally modifying the shared infrastructure. Trust is further reinforced through periodic on-chain audit trails published to a transparency portal accessible to regulators and market participants, without exposing commercially sensitive transaction details. This transparency mechanism is essential for building the institutional confidence required to transition from bilateral contractual arrangements toward the open, liquid hydrogen market envisioned in the globally integrated scenario of this study's outlook framework. As mutual recognition agreements mature through bilateral diplomacy, the governance architecture can be progressively upgraded to reduce oracle overhead and enable direct certificate portability across jurisdictions. Table 5 demonstrates comparative analysis under the platform system.

Table 5. Comparative analysis of the proposed platform against existing hydrogen certification systems.

Feature	CertifHy	EU GO Registry	Proposed Platform
Architecture	Centralized	Centralized	Consortium Blockchain
Geographic scope	EU (partial)	EU only	EU + China (extensible)
Smart contract automation	No	No	Yes (3 contract layers)
Real-time verification	No	No	Yes (IoT/SCADA integration)
Cross-border bridge	No	No	Yes (oracle-based equivalence)
Producer privacy	Partial	Partial	HMAC-SHA-256 keyed hash (pseudonymized)
Carbon intensity tracking	Yes	Yes	Yes (immutable on-chain)
Governance model	Bilateral agreements	EU institutional	Weighted consortium voting
Interoperability protocol	Limited	EU only	Hash-anchored equivalence
Regulatory update mechanism	Manual re-certification	Manual update	Automated via ComplianceValidator

3.6. Security Architecture and Threat Mitigation

The platform attack surface spans IoT hardware, smart contract logic, oracle bridges, and governance mechanisms; a layered security architecture aligned with OWASP Smart Contract Security and NIST SP 800-82 addresses each layer systematically.

4. Outlook and Scenarios

To evaluate the future evolution of international hydrogen trade, this study develops a scenario-based framework extending to 2050. The scenarios are constructed based on key structural variables, including infrastructure development, cost competitiveness, regulatory alignment, and the implementation of certification and traceability systems. Particular emphasis is placed on the role of

digital verification technologies in enabling market integration. Rather than predicting a single outcome, the scenario approach captures alternative pathways reflecting different levels of technological adoption and policy coordination.

4.1. Scenario 1: Fragmented Regional Markets

In this scenario, international trade remains hampered by non-technical barriers and divergent standards. Without a unified digital verification layer, European importers continue to face high administrative costs to ensure compliance with strict RFNBO certification. Simultaneously, China's domestic focus leads to localized infrastructure that lacks the transparency required for global markets, resulting in "cost fragmentation" and regional protectionism. By 2050, hydrogen remains a regional resource rather than a global commodity.

4.2. Scenario 2: Partially Integrated Certification-Based Trade

In this scenario, the gradual deployment of digital traceability platforms by 2035 facilitates partial market convergence. Blockchain-based systems support the automation of "Proof of Origin" processes, enabling more efficient verification of hydrogen production data across jurisdictions. This reduces administrative burdens and improves trust between trading partners, particularly between export-oriented and import-dependent regions. However, differences in regulatory frameworks and infrastructure development persist, limiting full interoperability. As a result, hydrogen trade expands significantly, but remains structured around regional alliances rather than a fully global market.

4.3. Scenario 3: Globally Integrated Digital Hydrogen Market

This scenario envisions a highly integrated global hydrogen market supported by advanced digital traceability and coordinated policy frameworks. In this context, traceability platforms evolve into multilateral governance tools, enabling consistent lifecycle emissions accounting and facilitating mutual recognition of certification systems across regions. While complete standardization remains challenging, increased alignment allows for greater price transparency and more efficient allocation of hydrogen resources globally. As a result, hydrogen emerges as a widely traded energy carrier, playing a central role in the decarbonization of industrial sectors and global energy systems.

The quantitative ranges presented in Table 6 are grounded in projections from the International Energy Agency (IEA 2024; IEA 2025), which indicate that global hydrogen demand reached approximately 100 Mt in 2024 and is expected to increase substantially under decarbonization pathways. In net-zero scenarios, total demand could reach between 400 and 500 Mt by 2050, driven by industrial transformation, transport, and energy system integration. As production becomes geographically concentrated in regions with low-cost renewable resources, international trade is projected to play an increasingly important role, with estimates suggesting that approximately 20–30% of hydrogen demand could be met through cross-border flows. Early market signals already reflect this trend, with a growing share of announced hydrogen projects designed for export, potentially exceeding 16 Mt annually by 2030. These projections support the scenario differentiation, where variations in trade volumes, pricing structures, and market integration depend primarily on the development of infrastructure, regulatory alignment, and the adoption of digital traceability systems.

Table 6. Scenario projections of hydrogen trade adoption.

Factor	Scenario 1 (2025–2050)	Scenario 2 (2030–2050)	Scenario 3 (2040–2050)
Global hydrogen demand	120–200 Mt	200–350 Mt	350–500 Mt
Share of hydrogen traded internationally	<10%	10–25%	25–40%
Trade volume (Mt/year)	10–30 Mt	50–120 Mt	150–250 Mt
Infrastructure development	Limited regional pipelines (20,000 km)	Expanding corridors (20,000–50,000 km)	Global network (50,000 km + shipping routes)
Average hydrogen cost (USD/kg)	3.5–6.0	2.0–4.0	1.5–2.5
Certification coverage	30% of traded hydrogen verified	50–70% verified	80–90% verified
Blockchain adoption	10% of transactions	30–60%	70–90%
Market liquidity	Low (bilateral contracts)	Medium (regional hubs emerging)	High (global trading platforms)
Carbon Intensity (kg CO_2/kg H_2)	5–10 (mixed sources)	2–6	<1–2 (mostly green hydrogen)
Market outcome by 2050	Regional market	Regional blocks	Global commodity market

5. Conclusion

This study demonstrates that the evolution of hydrogen into a globally traded energy commodity is not solely dependent on production capacity or infrastructure expansion, but critically on the establishment of reliable, interoperable, and transparent certification systems. The comparative analysis of the European Union and China highlights a fundamental structural divergence, where differing regulatory approaches and market strategies create fragmentation and limit cross-border trade potential. The proposed platform, utilizing a consortium blockchain architecture, addresses the core challenge of information asymmetry by establishing a shared, decentralized ledger among verified institutional actors. By automating the lifecycle of HPOCs through smart contracts, the platform ensures that strict regulatory requirements such as the EU's RFNBO sustainability criteria are immutably verified against real-time production data. This digital verification layer reduces the high administrative and compliance costs that currently hamper international trade, shifting the market toward a more liquid and efficient state.

The scenario analysis further confirms that the degree of digital traceability adoption is a decisive factor in shaping future trade structures. In the absence of such systems, hydrogen markets are likely to remain regionally constrained. Conversely, the widespread implementation of blockchain-enabled certification mechanisms enables higher levels of market integration, price transparency, and cross-border coordination. Over time, this contributes to the emergence of hydrogen as a standardized, verifiable, and globally tradable commodity.

Compared with a centralized registry, federated databases, signed certificates, and standalone verifiable credentials, the proposed consortium blockchain provides a jointly governed certificate-status and custody ledger better aligned with the cross-border sovereignty constraints of EU-China trade. Producer confidentiality is addressed through HMAC-SHA-256-based pseudonymization, restricted off-chain identity mapping, and threshold-controlled regulatory disclosure, rather than through claims of irreversible anonymity.

In conclusion, the proposed platform should not be viewed as a supplementary technological tool, but as a foundational market infrastructure necessary for the development of international hydrogen trade. Its ability to connect production, certification, and trading systems across jurisdictions positions it as a critical component in achieving a scalable, transparent, and efficient global hydrogen economy by 2050.

Declarations

Author contributions. Sofya Morozova: Investigation, Formal analysis, Writing (original draft), Visualization, Resources. Omer Faruk Yakut: Visualization, Software. Arif Karabuga: Methodology, Conceptualization, Data curation, Writing (review and editing), Validation, Supervision, Project administration, Resources.

Funding. This research received no specific funding.

Conflicts of interest. The authors declare no competing interests.

Data availability. The data that support the findings of this study are available from the corresponding author upon reasonable request.

References

Cartier, V.; Cazier, E. A. (2024) 'Hydrogen technology development during a revolutionary era in Europe', *7th International Conference on Nuclear and Renewable Energy Resources, NURER 2024 Conference Proceedings*. Available at: https://www.scopus.com/pages/publications/105010227821

Dejonghe, Marie; Van de Graaf, Thijs; Belmans, Ronnie (2023) 'From natural gas to hydrogen: Navigating import risks and dependencies in Northwest Europe', *Energy Research & Social Science*, 106, pp. 103301. Available at: https://doi.org/10.1016/j.erss.2023.103301

Eichner, Thomas; Pethig, Rüdiger (2019) 'EU-type carbon regulation and the waterbed effect of green energy promotion', *Energy Economics*, 80, pp. 656-679. Available at: https://doi.org/10.1016/j.eneco.2019.01.019

Gallegos, Francisca (2024) 'Bridging the Gap: Certification Schemes for Sustainable Hydrogen in Global Trade', *Journal for European Environmental & Planning Law*, 21(3-4), pp. 239-273. Available at: https://doi.org/10.1163/18760104-21030005

Gong, Xiaohan (2025) 'A comparative study of China and the EU's experimental approaches to creating hydrogen markets', *Review of European, Comparative & International Environmental Law*, 34(3), pp. 641-660. Available at: https://doi.org/10.1111/reel.70016

Graczyk, Andrzej; Brusiło, Paweł; Graczyk, Alicja Małgorzata (2025) 'Hydrogen as a Renewable Fuel of Non-Biological Origins in the European Union—The Emerging Market and Regulatory Framework', *Energies*, 18(3), pp. 617. Available at: https://doi.org/10.3390/en18030617

Hasan, Shahid; Fuentes, Rolando (2025) 'Designing effective hydrogen Markets: Policy recommendations from electricity and gas market reform', *Energy Policy*, 207, pp. 114816. Available at: https://doi.org/10.1016/j.enpol.2025.114816

IEA (2024) *Global Hydrogen Review 2024*. Available at: https://iea.blob.core.windows.net/assets/89c1e382-dc59-46ca-aa47-9f7d41531ab5/GlobalHydrogenReview2024.pdf

IEA (2025) *Global Hydrogen Review 2025*. Available at: https://iea.blob.core.windows.net/assets/a6c466dd-b6f0-44bd-a60a-6940eccfb1c3/GlobalHydrogenReview2025.pdf

Kountouris, Ioannis; Bramstoft, Rasmus; Madsen, Theis; Gea-Bermúdez, Juan; Münster, Marie; Keles, Dogan (2024) 'A unified European hydrogen infrastructure planning to support the rapid scale-up of hydrogen production', *Nature Communications*, 15(1). Available at: https://doi.org/10.1038/s41467-024-49867-w

Li, Jiaqing; Liang, Huilong; Zheng, Zhiye; Teng, Lin; Zhang, Zhuwu; Gao, Ziqiao; Luo, Yu; Zhang, Che; Jiang, Lilong (2025) 'A critical review of China's hydrogen supply chain and equipment', *International Journal of Hydrogen Energy*, 180, pp. 151737. Available at: https://doi.org/10.1016/j.ijhydene.2025.151737

Liu, Qian; Gao, Shuang; Hou, Yanan; Liu, Jianfeng; Yuan, Qianqian; Wang, Ai-Jie; Ren, Nanqi; Huang, Cong (2025) 'AI- and Biotechnology-Driven Digital Design of Biohydrogen-Producing Microbiota', *Engineering*, 62, pp. 296-302. Available at: https://doi.org/10.1016/j.eng.2025.09.027

Machado, Júlia T. M.; Flynn, Brendan; Williamson, Ian (2022) 'The national shaping of Europe's emerging hydrogen strategies: Cooperative or competitive hydrogen Politics?', *Competition and Regulation in Network Industries*, 23(1), pp. 77-96. Available at: https://doi.org/10.1177/17835917221082935

Mojsiejewska, Katarzyna; Rogowska, Delfina (2024) 'Wymagania wobec wodoru RFNBO [Requirements for RFNBO hydrogen]', *Nafta-Gaz*, 80(2), pp. 96-101. Available at: https://doi.org/10.18668/ng.2024.02.04

Nhung, Nguyen Hong (2024) 'The European Union's Green Energy Transition and Its Impact on Vietnam', *EAI/Springer Innovations in Communication and Computing*. Springer Nature Switzerland, pp. 33-56. Available at: https://doi.org/10.1007/978-3-031-60154-5_3

Song, Yuxia; Feng, Yihang; Li, Yuwei; Kong, Ruiqi; Xiao, Shiyu (2026) 'Evolutionary patterns and future trends of China's hydrogen energy industry policy', *Energy Reports*, 15, pp. 108966. Available at: https://doi.org/10.1016/j.egyr.2025.108966

Wolf, Andre (2025) 'Public support for the roll-out of renewable hydrogen in Europe: A real options perspective', *International Journal of Hydrogen Energy*, 97, pp. 1440-1452. Available at: https://doi.org/10.1016/j.ijhydene.2024.11.471

Zhang, Max; Yang, Xiaonan (2022) 'The Regulatory Perspectives to China's Emerging Hydrogen Economy: Characteristics, Challenges, and Solutions', *Sustainability*, 14(15), pp. 9700. Available at: https://doi.org/10.3390/su14159700

Zhao, Shangxin; Wang, Weibin; Li, Yuxing; Liu, Cuiwei (2026) 'Pipeline transportation strategy and key technological breakthroughs for high-quality development of hydrogen energy industry under the dual carbon goals', *Journal of Pipeline Science and Engineering*, 6(2), pp. 100391. Available at: https://doi.org/10.1016/j.jpse.2025.100391

HOW TO CITE THIS PAPER

Morozova, S., Yakut, O. F. and Karabuga, A. (2026). Blockchain-Enabled Traceability: Bridging the Hydrogen Trade Gap between Europe and China. In: *Proceedings of the 22nd International Conference on Sustainable Energy Technologies (SET2026)*, Kuala Lumpur, Malaysia, 13 to 15 August 2026. Caravel Press, pp. 329–342. ISBN 978-1-995850-00-9. ISSN 2978-4387. https://doi.org/10.65582/set.2026.029

COPYRIGHT AND LICENCE

© 2026 The Author(s). This is an open access paper distributed under the terms of the Creative Commons Attribution (CC BY 4.0) licence, which permits unrestricted use, distribution and reproduction in any medium, provided the original work is properly cited.

WSSET World Society of Sustainable Energy Technologies Organised by the World Society of Sustainable Energy Technologies. Published by Caravel Press.