

# From Macro to Micro: Fractional Guarantees of Origin and Their Integration into Accountable Economic Units. A New Paradigm of Sustainable Organizational Design through Compliance-as-a-Service Architectures

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## Abstract

*The European Union's mandatory sustainability reporting framework reveals a structural inadequacy in the current Guarantees of Origin system: certificates issued at 1 MWh granularity decouple from physical energy flows and enable greenwashing through temporal mismatching. This paper introduces Fractional Guarantees of Origin, a paradigm leveraging Distributed Ledger Technology to tokenize renewable energy at kWh resolution with cryptographically anchored compliance. Through qualitative case study validation of VoltVert, an ISO 20022-native registry, and H2Secure, a smart contract framework for RED III hydrogen compliance, we demonstrate that fractional attribution eliminates double-counting risk and substantially reduces compliance costs. Integration with government infrastructure, specifically Romania's Central Virtual Resource under PNRR Target 415, establishes a Compliance-as-a-Service architecture where Scope 2 emissions become auditable in near-real-time rather than post-factum estimates. Applying the Jabbour organizational design framework, we find that technology adoption alone is insufficient: organizations concurrently addressing awareness, formalization, measurement, governance, and resource allocation achieve significantly higher environmental performance. Sectoral replication is demonstrated across sustainable mobility and real estate. This research bridges technological feasibility and organizational reality, positioning Fractional Guarantees of Origin as both a regulatory necessity and a competitive advantage in the post-2025 energy transition.*

*Keywords: Guarantees of Origin, Distributed Ledger Technology, Scope 2 accounting, CSRD automation, organizational design, Compliance-as-a-Service, European sustainability infrastructure.*

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## 1. Introduction

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The European Green Deal, operationalized through the Fit for 55 legislative package and its successor directives, has created an unprecedented density of regulatory obligations around corporate sustainability accountability. The Corporate Sustainability Reporting Directive (CSRD) and its accompanying European Sustainability Reporting Standards (ESRS) mandate that large enterprises audit Scope 2 greenhouse gas emissions with financial-audit rigor, effective from 2025 onward (European Commission, 2022; Hummel and Jobst, 2024). Concurrently, the Renewable Energy Directive III (RED III, Directive 2023/2413/EU) introduces binding requirements for renewable hydrogen production, demanding temporal and geographical correlation between generation and consumption on sub-annual timescales (European Parliament and Council, 2023). This regulatory convergence exposes a critical architectural mismatch: the current Guarantees of Origin (GoO) system, standardized under CEN-EN 16325:2023, operates at 1 MWh granularity with annual reconciliation windows, a macro-level approach designed for centralized utility-consumer relationships that proves structurally inadequate for decentralized, real-time compliance demands (Wimmers and Madlener, 2024; Association of Issuing Bodies, 2025).

The EN 16325 framework allows companies to purchase Guarantees of Origin from renewable generators and claim corresponding Scope 2 reductions without demonstrating temporal or geographic correlation between generation and consumption. Empirical research demonstrates that annual GoO matching obscures hourly consumption-generation mismatches: a manufacturing facility consuming electricity during evening peak hours may purchase annual-vintage renewable certificates from daytime-peak solar generation, creating a physical impossibility while satisfying traditional compliance frameworks (Bjørn, Gebara, and Brander, 2025; Riepin and Brown, 2024). Research by the International Energy Agency (2024) and the EnergyTag Initiative (2024) estimates that a substantial proportion of claimed renewable consumption in Europe lacks genuine temporal correlation, representing billions of euros in annually misallocated environmental credits. This greenwashing dynamic distorts capital allocation, regulatory signals, and competitive dynamics, penalizing first-movers genuinely implementing 24/7 renewable matching (Zioló, Bąk, and Spoz, 2024; Li et al., 2025).

RED III's Article 25 requirements for renewable hydrogen (RFNBO) certification introduce unprecedented technical rigor: renewable hydrogen requires proof of additionality, temporal correlation (monthly from 2025, hourly from 2030), and geographical correlation (same bidding zone or confirmed grid transmission capacity). The Delegated Acts 2023/1184 and 2023/1185 encode these criteria as

more than eighty technical validation points, currently audited through laborious manual document review requiring six to eight week cycles per producer (European Commission, 2023a; European Commission, 2023b; Talus, Pinto, and Gallegos, 2024). The hydrogen use case exposes the EN 16325 system's data poverty: traditional GoO certificates cannot store machine-readable proof of additionality, temporal matching windows, or geographic coordinates, functioning as bearer securities rather than verifiable claims and making automated RED III compliance structurally impossible.

This paper introduces Fractional Guarantees of Origin (FGoO)—a DLT-enabled paradigm enabling GoO issuance at kWh or Wh resolution, legally enabled by RED III Article 19, with immutable metadata sufficient for automated RED III and CSRD compliance verification. We validate FGoO through two complementary empirical cases: VoltVert, a deployed ISO 20022-native registry enabling tokenization of renewable energy across multiple EU jurisdictions with cryptographically validated temporal and geographic attributes; and H2Secure, a smart contract framework automating RED III compliance criteria for RFNBO hydrogen shipments. We further demonstrate sectoral replication across sustainable mobility and real estate, and integration with government infrastructure—specifically Romania's Central Virtual Resource (CVR, PNRR Target 415)—as a template for Compliance-as-a-Service architectures that automate Scope 2 and 3 reporting.

## 2. Literature review

### 2.1 Architectural constraints of traditional Guarantees of Origin

The Guarantees of Origin framework operates within three fundamental constraints rendering it incompatible with sub-annual compliance requirements. First, the system exhibits granularity rigidity: EN 16325 specifies 1 MWh as the minimum issuance unit, which prevents precise allocation to small economic units such as electric vehicle charging events (40 kWh), industrial process batches (100 kWh), or hydrogen molecules (Wimmers and Madlener, 2024; Holzapfel et al., 2024; Association of Issuing Bodies, 2025). Manual sub-allocation introduces reconciliation friction and creates audit vulnerabilities that undermine data integrity. Second, GoO certificates suffer from metadata poverty, storing only minimal descriptive information—renewable technology type, vintage year, and issuing country—while lacking machine-readable proof of additionality status, temporal production window, precise geographic location, or grid interconnection topology, all of which are mandatory for RED III compliance (European Commission,

2023a). Third, traditional GoO trading operates on T+2 or T+3 settlement cycles, creating data gaps for over 95% of consumption events when real-time temporal matching is required (Riepin, Jenkins, Swezey, and Brown, 2025; Paris, Hechelmann and Buchenau, 2024).

## 2.2 Blockchain and DLT applications in energy markets

Distributed Ledger Technology has emerged as a transformative infrastructure for energy market design. Mollah et al. (2020) published one of the first surveys mapping blockchain use cases across smart grid systems—from decentralized energy trading and demand response coordination to renewable energy certificate management. The field has since matured rapidly: Rejeb et al. (2024) used co-word analysis of 390 journal articles to map the intellectual landscape of blockchain in renewable energy, surfacing thematic concentrations around peer-to-peer trading, prosumer engagement, transactive energy, and distributed energy resource integration. Vionis and Kotsilieris (2024) assessed blockchain and smart contract potentials specifically within the energy sector, concluding that DLT's immutability and transparency properties are well-suited to resolving trust deficits in renewable energy attribute tracking.

Peer-to-peer energy trading has received particular attention. Pradhan et al. (2022) developed a blockchain-based lightweight framework enabling high-throughput micro-transactions between prosumers, demonstrating settlement latencies below one second. Bhavana et al. (2024) applied blockchain to both peer-to-peer energy markets and green hydrogen supply chains, finding that cryptographic verification reduces counterparty risk by eliminating intermediary dependency. Abdin (2024) provided a comprehensive review of blockchain's transformative potential specifically for the hydrogen economy, concluding that DLT can address traceability, certification, and cross-border compliance challenges simultaneously. Wang et al. (2025), further advanced the consensus mechanism design for peer-to-peer electricity trading, proposing protocols that balance transaction throughput with energy efficiency—a critical consideration for sustainability-oriented platforms. Kirli et al. (2022) provided a systematic review of smart contract approaches in energy systems, cataloguing fundamental implementation patterns and identifying regulatory compliance automation as an underexplored but high-impact application domain.

### 2.3 Tokenization of renewable energy certificates

The tokenization of renewable energy certificates represents a natural application of DLT to overcome the limitations of traditional GoO systems. Zuo (2022) proposed an early blockchain approach for Renewable Energy Certificate issuance and trading, demonstrating that tokenization enables fractional ownership, automated verification, and transparent audit trails impossible under paper-based or centralized database systems. Fu, Tan, and Xu (2023) extended this concept to community-level trading, developing a blockchain-based framework for renewable energy certificate exchange among active energy agents in low-carbon communities. The OECD (2024) published a comprehensive policy paper on tokenization of assets and distributed ledger technologies in financial markets, providing institutional legitimacy to the application of these technologies in regulated energy markets. More recently, the International Organization of Securities Commissions (IOSCO, 2025) released a report on tokenization of financial assets that explicitly addresses energy certificate tokenization as a frontier application with significant regulatory implications. Schmid et al. (2024) advanced the design science methodology specifically for blockchain-based certification of green hydrogen in the EU market, proposing an architecture that reconciles RED III traceability mandates with cross-border interoperability requirements.

### 2.4 24/7 carbon-free energy and temporal granularity

The concept of 24/7 carbon-free energy (CFE) matching has gained substantial academic and policy traction. Riepin and Brown (2024) quantified the economic and grid-level consequences of shifting from annual to hourly carbon-free energy procurement, finding that temporal granularity fundamentally alters optimal technology portfolios and induces distinct investment signals for storage and flexible generation. Riepin et al. (2025) subsequently demonstrated that 24/7 carbon-free electricity matching accelerates adoption of advanced clean energy technologies, creating positive spillover effects for grid decarbonization beyond the procuring entity. The EnergyTag Initiative (2024) synthesized scientific consensus on the benefits of granular accounting, arguing that the GHG Protocol's Scope 2 guidance should incorporate temporal matching requirements. The International Energy Agency (2024) published a technical report on advancing decarbonization through clean electricity procurement, explicitly endorsing granular, time-stamped energy attribute tracking as essential for credible corporate renewable claims. Bjørn, Gebara, and Brander (2025) provided a critical analysis of deliverability, additionality, and double counting related to renewable energy certificates, proposing methodological improvements for Scope 2 emissions accounting that

align with temporal granularity principles. Most recently, Scholta and Blaschke (2025) furnished econometric evidence in *Nature Communications* that the carbon intensity ascribed to corporate electricity portfolios diverges markedly when calculated on an hourly rather than annual basis, reinforcing the case for making temporal matching a mandatory reporting principle rather than a voluntary enhancement.

## 2.5 CSRD, ESG reporting, and the EU Taxonomy

The Corporate Sustainability Reporting Directive creates unprecedented demand for verified, granular sustainability data. Hummel and Jobst (2024) traced the regulatory arc from voluntary disclosure to audit-grade sustainability reporting across the four principal EU legislative instruments—CSRD, Taxonomy Regulation, SFDR, and Pillar 3 disclosures—demonstrating the increasing convergence of financial and non-financial reporting standards. Garcia-Torea, Luque-Vilchez, and Rodriguez-Gutierrez (2024) analyzed how the EU Taxonomy, sustainability reporting, and financial institutions interact, identifying regulatory uncertainty as a significant implementation barrier. Tonnarello et al. (2025) empirically demonstrated that EU Taxonomy alignment affects European utilities' financial performance, establishing a material link between sustainability reporting quality and market valuation. Seow (2025) conducted a systematic literature review of machine learning applications in ESG analytics, finding that digital tools substantially improve reporting accuracy but face challenges in standardization and auditability—precisely the gap that blockchain-based systems address. The greenwashing literature provides additional motivation: Ziolo, Bał, and Spoz (2024) systematically reviewed greenwashing research, concluding that the absence of verifiable, granular environmental claims is the primary enabler of misleading corporate sustainability communications.

## 2.6 Organizational design for sustainability transformation

The organizational design literature underscores that technology adoption alone is insufficient for sustainability transformation. Building on Jabbour et al. (2020), who examined stakeholder pressures, barriers, and organizational factors enabling circular economy adoption in emerging economies, the present study operationalizes five organizational design dimensions critical for compliance-by-design sustainability systems: awareness, formalization, measurement, governance, and resource allocation. This framework, synthesized from the broader circular economy literature (Jabbour et al., 2020; Seles et al., 2022; Hussain and Malik, 2020), applies directly to compliance-by-design models where sustainability is embedded

into operational transactions rather than treated as post-factum reporting. De Sousa Jabbour et al. (2023) extended this line of inquiry to demonstrate that circular business models enhance organizational resilience when Industry 4.0 technologies and customer integration are present—a finding directly applicable to DLT-enabled sustainability platforms. Seles et al. (2022) explored the role of resources and capabilities as enablers for circular economy transition, identifying digital infrastructure as a necessary but not sufficient condition. Hussain and Malik (2020) empirically validated organizational enablers for circular economy in the context of sustainable supply chain management, finding that governance structures and measurement systems mediate the relationship between technology adoption and environmental outcomes.

Digital transformation intersects sustainability management in complex ways. Research demonstrates that digital transformation enables corporate sustainability through internal and external efficiency improvements (multiple studies, 2022–2024), but the mechanisms through which DLT specifically facilitates compliance-by-design remain underexplored. Heldt and Pikuleva (2025) provided a process study of blockchain adoption for sustainability in supply chains, finding that upstream suppliers can drive traceability when appropriate incentive structures exist—a finding relevant to the energy certificate value chain where generators, traders, and consumers must coordinate. The RegTech literature, while nascent in the sustainability domain, suggests that regulatory technology can transform compliance from a cost center to a competitive advantage when integrated into core organizational processes (Jayavarma et al., 2025).

### 3. Methodology

This study employs a qualitative case study methodology (Yin, 2018) combining technical validation with regulatory conformance analysis. The research design encompasses two complementary components. The first is a qualitative case validation with two units of analysis: the VoltVert platform (L1–L7 infrastructure) and the H2Secure smart contract protocol. Data sources include technical documentation (ISO 20022 specifications, Delegated Act codification), semi-structured interviews with platform architects (n=4) and regulatory liaison officers (n=3), source code audit of Solidity smart contracts, and API specification review. The analytical method applies replication logic (Eisenhardt, 1989) to examine whether FGoO architectural principles transfer across energy consumption modalities from electricity to transport to real estate.

The second component involves quantitative testing of regulatory criterion implementation. The testing matrix maps RED III Article 19, Delegated Acts 2023/1184 and 2023/1185, and CSRD Annex S requirements against implementation verification including blockchain transaction validation, temporal window tolerance, and geographic zone adjacency. The sample universe comprises fifty pilot companies across manufacturing, logistics, and real estate (2024–2025). Metrics include double-counting risk reduction, compliance cost differential, settlement latency improvement, and audit trail immutability measured through cryptographic validation pass rates.

The literature search followed a systematic approach across peer-reviewed databases (Scopus, Web of Science, Google Scholar) applying filters for publication date from January 2020, with keywords including distributed ledger technology energy, tokenization renewable, temporal matching electricity, CSRD automation, RED III compliance, and origin guarantees DLT. The search identified forty-seven academic papers, twenty-three technical reports from international organizations (OECD, IEA, IOSCO, European Commission), eight technical white papers, and twelve regulatory guidance documents. Data triangulation was achieved through cross-validation of platform-reported metrics against independent auditor assessments.

## **4. Results and discussion**

### **4.1 Technical validation: VoltVert architecture**

VoltVert's ISO 20022-native registry enables tokenization of renewable energy at 1 Wh resolution, compliant with RED III Article 19, with sub-ten-millisecond settlement validation. Testing across the pilot deployment confirms a mean settlement time of 8.3 milliseconds (compared to two to three business days for traditional GoO), temporal matching precision within a fifteen-minute window (compared to monthly or annual for traditional GoO), automated geographic validation through GPS coordinates and MRID bidding zone verification, and storage of forty-five discrete metadata points per kWh token (compared to approximately five for traditional GoO certificates). This represents a reduction of compliance latency by several orders of magnitude, functionally transforming Scope 2 accounting from post-factum annual estimation to near-real-time hourly verification. These findings align with the theoretical predictions of Riepin and Brown (2024) regarding the system-level impacts of granular energy tracking, while extending their framework from procurement to compliance automation.

Each kWh token issued by VoltVert carries immutable W3C Verifiable Credential proof using EdDSA 2020 signature standard. Testing across fifty pilot companies measured double-counting incidents: the traditional GoO baseline showed eighteen companies flagged for potential double-counting upon external audit (a 36% risk rate), while FGoO implementation reduced this to zero companies flagged, yielding a 100% audit pass rate with immutable evidence chain. This validates the theoretical basis articulated by Bjørn, Gebara, and Brander (2025): when each kWh carries cryptographic binding to a specific consumption event rather than relying on portfolio averaging, double-counting becomes geometrically impossible.

#### 4.2 RED III compliance: H2Secure smart contract automation

H2Secure implements Delegated Acts 2023/1184 and 2023/1185 criteria as Solidity smart contracts, validated through 120 RFNBO hydrogen shipments during the pilot period. Table 1 presents the comparative validation performance.

**Table 1. Comparative validation performance: manual audit vs. smart contract**

Criterion	Manual audit cycle	Smart contract	Improvement factor
Additionality (generator online date)	5–7 days	< 1 second	~500,000x
Temporal correlation	10–14 days	< 1 second	~1,000,000x
Geographical adjacency	8–10 days	< 1 second	~1,000,000x
GHG savings (ISO 14067)	8–12 days	< 2 seconds	~400,000x
<b>Total validation cycle</b>	<b>~42 days</b>	<b>~2 seconds</b>	<b>~1,800,000x</b>

*Source: Author's compilation based on H2Secure pilot data (2025)*

All 120 test shipments were validated successfully with zero regulatory rejection post-implementation, compared to a 23% rejection rate during the pre-automation manual pilot in 2024. These results corroborate the findings of Kirli et al. (2022), who identified regulatory compliance automation as a high-impact but underexplored smart contract application, and are consistent with the design principles proposed by Schmid et al. (2024) for EU hydrogen market certification and the technical validation framework of Alshehhi et al. (2024) for blockchain-based hydrogen traceability. Collectively, these findings extend the empirical evidence base from theoretical feasibility to demonstrated operational performance at scale.

### 4.3 Scope 2 calculation transformation

Testing across twenty-five mid-market manufacturing firms implementing FGoO with CVR integration demonstrates a fundamental evolution in Scope 2 calculation methodology. Under the traditional approach, Scope 2 emissions are calculated as a single annual product of total consumption and grid average emission factor, producing a result subject to approximately 15% measurement uncertainty with a twelve-month reporting lag. Under the FGoO compliance-by-design approach, Scope 2 emissions are calculated as the hourly sum of consumed kilowatt-hours multiplied by their matched emission factor, where temporally matched renewable kWh carry a zero emission factor and unmatched consumption carries the grid factor. This approach achieves measurement uncertainty below 1%, monthly reporting updates with real-time dashboard visibility, and continuous compliance risk assessment with predictive alerts. The GHG Protocol's current Scope 2 guidance (WRI and WBCSD, 2015) permits both location-based and market-based calculations; our findings align with the recommendations of Bjørn, Gebara, and Brander (2025) that market-based claims should incorporate temporal verification to prevent greenwashing.

### 4.4 Organizational design validation: the Jabbour framework

Comparative analysis of thirty firms implementing FGoO technology alone versus twenty firms implementing FGoO with concurrent organizational redesign (2024-2025) reveals substantial performance differentials. Table 2 presents the results across Jabbour's five dimensions.

**Table 2. Organizational design dimensions and environmental performance**

Jabbour dimension	Tech-only (n=30)	Tech + org. redesign (n=20)	Performance delta
Awareness	35% staff understand matching	92% staff understand profile	+57 pp
Formalization	40% contracts include GoO specs	95% include temporal matching	+55 pp
Measurement	Quarterly; 6-week audit lag	Real-time; 2-hour audit lag	>10x velocity
Governance	0 firms created new roles	18/20 reassigned or hired staff	Structural shift
Resource allocation	€50–100k capex	€500k–1M capex	+700%
<b>ESG outcome (Scope 2)</b>	<b>+12% reduction (YoY)</b>	<b>+48% reduction (YoY)</b>	<b>4x improvement</b>

*Source: Author's compilation based on pilot deployment data (2024–2025)*

Organizations addressing all five Jabbour dimensions achieved approximately four times higher environmental performance compared to technology-focused implementations. This finding validates the organizational design framework operationalized from Jabbour et al. (2020) in a novel domain and confirms the observation of Seles et al. (2022) that digital infrastructure constitutes a necessary but insufficient condition for sustainability transition. The governance dimension proved particularly instructive: firms that created dedicated Energy Intelligence roles or cross-functional sustainability teams achieved systematically better outcomes, suggesting that compliance-by-design requires not merely technological capability but organizational architecture that embeds sustainability oversight into routine decision-making processes.

#### 4.5 Sectoral replication: green kilometers and decarbonized square meters

FGoO principles extend beyond electricity to sustainable mobility through standardized WLTP efficiency metrics. An electric vehicle with WLTP efficiency of 15 kWh per 100 km consuming 40 kWh during a charging event backed by temporally matched kWh tokens may certify 267 green kilometers with a cryptographic audit trail. The European Commission's mandate that 1% of transport fuels consist of advanced biofuels or electrofuels by 2030 (Article 25, RED III) creates demand for Green Kilometer Certificates as NFT-based vouchers representing certified sustainable mobility distance.

Similarly, FGoO replicates to building-level energy accounting through nZEB (Nearly Zero Energy Building) standards. Construction phase allocation requires approximately 85 kWh per square meter; operational phase approximately 1.2 kWh per square meter per month. Each square meter receives renewable energy allocation corresponding to standardized consumption profiles, generating Green Square Meter Certificates. The conceptual alignment with the EU Digital Product Passport framework, as analysed by Rizos and Urban (2024) for the battery sector, suggests that FGoO architecture can serve as a template for sector-specific traceability systems wherever regulatory verification of environmental attributes is mandated. Table 3 summarizes the sectoral replication matrix.

**Table 3. Sectoral replication matrix for Fractional Guarantees of Origin**

Sector	Economic unit	Conversion factor	Standard	Certificate type
Energy / Industrial	1 kWh	1 kWh renewable	EN 16325 + RED III	kWh-NFT
Hydrogen	1 kg H <sub>2</sub>	55 kWh @ 70% GHG savings	ISO 14067 + DA 2023/1184	H <sub>2</sub> -NFT

Sector	Economic unit	Conversion factor	Standard	Certificate type
Transport	1 km (Green Km)	0.15 kWh per WLTP	WLTP standard	VKM-NFT
Real estate	1 m <sup>2</sup> (Green m <sup>2</sup> )	0.85 kWh/m <sup>2</sup> (capex); 1.2 kWh/m <sup>2</sup> /mo (opex)	nZEB / LEED / BREEAM	m <sup>2</sup> -NFT

*Source: Author's compilation*

#### 4.6 CVR integration: Compliance-as-a-Service infrastructure

Romania's Central Virtual Resource (CVR, PNRR Target 415) represents a template for integrating FGoO and smart contracts into government compliance infrastructure. The architecture comprises five layers: data ingestion (VoltVert L3 API to CVR via secure feeds), mapping and transformation (local indicators to EU standards including ESRS, GRI, and CSRD taxonomy), automated calculation (Scope 2 formula application with XBRL GL output generation), quality assurance (algorithmic anomaly detection with cryptographic validation), and reporting (monthly draft, quarterly audited, annual final submission to ESAP). EU-wide implementation of CVR-equivalent infrastructure could eliminate approximately 50,000 person-hours annually of redundant ESG data re-entry, representing a collective efficiency gain in the order of EUR 2.5 billion. Furthermore, a standardized data layer enables downstream applications: bank ESG risk assessment, investor portfolio screening, and regulatory stress-testing—all fed from a single verified source (Romanian Ministry of Environment, 2025).

#### 5. Conclusions

The transition from macro-level (MWh, annual) to micro-level (Wh, hourly) Guarantees of Origin management constitutes a paradigm shift in organizational accountability for sustainability. This research validates three core propositions. First, at the technical level, Fractional Guarantees of Origin enabled by DLT and RED III Article 19 legal foundations eliminate structural barriers to sub-hourly compliance verification: VoltVert demonstrates operability at pilot scale across multiple EU jurisdictions, while H2Secure demonstrates automated RED III verification orders of magnitude faster than manual audit. Second, at the accounting level, Scope 2 emissions accounting transitions from static portfolio-based estimation to dynamic transaction-level verification, reducing measurement uncertainty from approximately 15% to below 1% and reporting latency from twelve months to one month. Third, at the organizational level, technology adoption is necessary but insufficient: organizations implementing compliance-by-

design achieve approximately four times higher ESG performance when all five Jabbour dimensions—awareness, formalization, measurement, governance, and resource allocation—are addressed concurrently.

The policy implications extend across multiple stakeholder categories. For EU regulators, we recommend mandating real-time GoO allocation for CSRD-scope companies (phased by company size, 2027–2030), funding CVR-equivalent interoperable infrastructure across member states, and harmonizing RFNBO certification via DLT-based smart contract registries to replace competing voluntary schemes. For corporate leaders, initiating compliance-by-design pilot programs immediately offers an eighteen-to-twenty-four-month first-mover data advantage; investing in Energy Intelligence organizational capability and integrating suppliers into real-time renewable matching through contractual redesign are critical enabling actions. For technology providers, developing sector-specific Compliance-as-a-Service solutions and building APIs integrating DLT platforms with CVR and ESAP infrastructure represent substantial market opportunities.

This study carries limitations that define avenues for future research. The validation of FGoO at mid-scale requires further testing at the petabyte-scale EU energy system; smart contract auditing methodologies remain nascent; and sectoral replication rests on preliminary modeling that large-scale implementation will inevitably challenge. Future research should investigate the behavioral economics of dynamic green premiums, explore FGoO extension to Scope 3 supply chain emissions across heavy industry verticals, and examine mechanisms for synchronizing CSRD annual reporting cycles with RED III sub-annual reconciliation requirements.

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### **References**

- Abdin, Z. (2024) Empowering the hydrogen economy: the transformative potential of blockchain technology, *Renewable and Sustainable Energy Reviews*, 200, 114572.
- Alshehhi, S., Musamih, A., Salah, K., Mayyas, A. and Jayaraman, R. (2024) *Blockchain-based sustainability, traceability, and certification of hydrogen production*, in Proceedings of the 2024 Annual Computer Security Applications Conference Workshops (ACSAC). Honolulu: IEEE, pp. 146-155.

- Association of Issuing Bodies (2025) *Renewable Energy Guarantees of Origin System Documentation and Standards*. Available at: <https://www.aib-net.org/certification>.
- Bhavana, G.B., Anand, R., Ramprabhakar, J., Meena, V.P., Jadoun, V.K. and Benedetto, F. (2024) *Applications of blockchain technology in peer-to-peer energy markets and green hydrogen supply chains: a topical review*, *Scientific Reports*, 14, 21954.
- Bjørn, A., Gebara, C.H. and Brander, M. (2025) *Untangling deliverability, additionality and double counting related to renewable energy certificates for improved scope 2 emissions accounting*, *Environmental Research Letters*, 20(5), 051006.
- CEN (2023) EN 16325:2023 – *Technical Specifications for Electricity Origin Guarantees*. Brussels: European Committee for Standardization.
- De Sousa Jabbour, A.B.L., Latan, H., Jabbour, C.J.C. and Seles, B.M.R.P. (2023) *Does applying a circular business model lead to organizational resilience? Mediating effects of industry 4.0 and customers integration*, *Technological Forecasting and Social Change*, 181, 122013.
- EFRAG (2025) *CSRD Frequently Asked Questions: Scope 2 Compliance and Temporal Matching*. Draft guidance document, version 2.1.
- Eisenhardt, K.M. (1989) *Building theories from case study research*, *Academy of Management Review*, 14(4), pp. 532-550.
- EnergyTag Initiative (2024) *GHG Protocol Part 3: Impact – Scientific Consensus on the Benefits of Granular Accounting*. Available at: <https://energytag.org/>.
- European Commission (2022) *Directive (EU) 2022/2464 of the European Parliament and of the Council as regards corporate sustainability reporting (CSRD)*. *Official Journal of the European Union*, L 322/15.
- European Commission (2023a) Commission Delegated Regulation (EU) 2023/1184 on criteria for determining when hydrogen is considered RFNBO. *Official Journal of the European Union*, L 152/1.
- European Commission (2023b) Commission Delegated Regulation (EU) 2023/1185 establishing minimum threshold for GHG emissions savings of recycled carbon fuels. *Official Journal of the European Union*, L 152/7.
- European Parliament and Council (2023) Directive (EU) 2023/2413 (RED III) amending Directive (EU) 2018/2001. *Official Journal of the European Union*, L 2023/2413.
- European Parliament and Council (2023) Regulation (EU) 2023/1804 on the deployment of alternative fuels infrastructure, and repealing Directive 2014/94/EU (AFIR). *Official Journal of the European Union*, L 234/1.
- Fu, S., Tan, Y. and Xu, Z. (2023) *Blockchain-based renewable energy certificate trade for low-carbon community of active energy agents*, *Sustainability*, 15(23), 16300.

- Garcia-Torea, N., Luque-Vilchez, M. and Rodriguez-Gutierrez, P. (2024) *The EU Taxonomy, sustainability reporting and financial institutions: understanding the elements driving regulatory uncertainty*, *Accounting Forum*, 48(3), pp. 427-454.
- H2Secure Project (2025) *RFNBO Compliance Validation Protocol: 120-Transaction Pilot Summary*. HORIZON Europe.
- Heldt, L. and Pikuleva, E. (2025) When upstream suppliers drive traceability: a process study on blockchain adoption for sustainability, *International Journal of Physical Distribution and Logistics Management*, 55(3), pp. 196-222.
- Holzapfel, P.K.R., Bánk, J., Bach, V. and Finkbeiner, M. (2024) Relevance of guarantees of origin for Europe's renewable energy targets, *Renewable and Sustainable Energy Reviews*, 205, 114850.
- Hummel, K. and Jobst, D. (2024) *An overview of corporate sustainability reporting legislation in the European Union*, *Accounting in Europe*, 21(3), pp. 320-355.
- Hussain, M. and Malik, M. (2020) Organizational enablers for circular economy in the context of sustainable supply chain management, *Journal of Cleaner Production*, 256, 120375.
- International Energy Agency (2024) *Advancing Decarbonisation through Clean Electricity Procurement*. Paris: IEA Publications.
- IOSCO (2025) *Tokenization of Financial Assets*. FR/17/2025. Available at: <https://www.iosco.org/library/pubdocs/pdf/IOSCOPD809.pdf>.
- Jabbour, C.J.C., Seuring, S., de Sousa Jabbour, A.B.L., Jugend, D., De Camargo Fiorini, P., Latan, H. and Izeppi, W.C. (2020) Stakeholders, innovative business models for the circular economy and sustainable performance of firms in an emerging economy facing institutional voids, *Journal of Environmental Management*, 264, 110416.
- Jayavarma, A., Parakkat, P., Panikker, K. and Nair, M.G. (2025) *Revolutionizing the energy sector: exploring diversified blockchain platforms for a sustainable future*, *Frontiers in Blockchain*, 8, 1544770.
- Kirli, D., Couraud, B., Robu, V., Salgado-Bravo, M., Norbu, S., Andoni, M., Antonopoulos, I., Negrete-Pincetic, M., Flynn, D. and Kiprakis, A. (2022) Smart contracts in energy systems: a systematic review of fundamental approaches and implementations, *Renewable and Sustainable Energy Reviews*, 158, 112013.
- Li, Y., Qi, T., Li, Q., Tan, W. and Huang, Y. (2025) *The motivation of corporate greenwashing: evidence from energy consumption intensity*, *Sustainable Development*, 33(4), pp. 5234-5250.
- Mollah, M.B., Zhao, J., Niyato, D., Lam, K.Y., Zhang, X., Ghias, A.M., Koh, L.H. and Yang, L. (2020) Blockchain for future smart grid: a comprehensive survey, *IEEE Internet of Things Journal*, 8(1), pp. 4201-4238.

- OECD (2024) *Tokenisation of Assets and Distributed Ledger Technologies in Financial Markets*. Paris: OECD Publishing.
- Paris, A., Hechelmann, R.-H. and Buchenau, N. (2024) Exploring the effect of Guarantees of Origin on the decarbonization of corporate electricity procurement: a case study of Germany and Norway, *Journal of Industrial Ecology*, 28(6), pp. 1657-1669.
- Pradhan, N.R., Singh, A.P., Verma, S. et al. (2022) *A blockchain based lightweight peer-to-peer energy trading framework for secured high throughput micro-transactions*, *Scientific Reports*, 12, 14523.
- Rejeb, A., Rejeb, K., Zrelli, I., Süle, E. and Iranmanesh, M. (2024) *Blockchain technology in the renewable energy sector: a co-word analysis of academic discourse*, *Heliyon*, 10(8), e29600.
- Riepin, I. and Brown, T. (2024) On the means, costs, and system-level impacts of 24/7 carbon-free energy procurement, *Energy Strategy Reviews*, 54, 101488.
- Riepin, I., Jenkins, J.D., Swezey, D. and Brown, T. (2025) '24/7 carbon-free electricity matching accelerates adoption of advanced clean energy technologies', *Joule*, 9(1), 101808.
- Rizos, V. and Urban, P. (2024) *Implementing the EU Digital Battery Passport: Opportunities and Challenges for Battery Circularity*. CEPS In-Depth Analysis, IDA-2024-05. Brussels: Centre for European Policy Studies.
- Romanian Ministry of Environment (2025) *Central Virtual Resource (CVR) – Target 415 PNRR: Technical Specifications and Integration Roadmap*. Bucharest: Government Publication.
- Schmid, J., Ubacht, J., van Engelenburg, S., van Oudheusden, J. and Chappin, E. (2024) *Is it green? Designing a blockchain-based certification system for the EU hydrogen market*, *Frontiers in Blockchain*, 7, 1408743.
- Scholta, H.F. and Blaschke, M.J. (2025) *Temporal matching as an accounting principle for green electricity claims*, *Nature Communications*, 16, 9280.
- Seles, B.M.R.P., Mascarenhas, J., de Sousa Jabbour, A.B.L. and Trevisan, A.H. (2022) *Smoothing the circular economy transition: the role of resources and capabilities enablers*, *Business Strategy and the Environment*, 31(4), pp. 1814-1837.
- Seow, R.Y.C. (2025) *Transforming ESG analytics with machine learning: a systematic literature review using TCCM framework*, *Corporate Social Responsibility and Environmental Management*, 32(6), pp. 7358-7389.
- Talus, K., Pinto, J. and Gallegos, F. (2024) Realism at the end of the rainbow? An argument towards diversifying hydrogen in EU regulation, *Journal of World Energy Law and Business*, 17(4), pp. 217-233.
- Tonnarello, F., Vermiglio, C., Migliardo, C. and Naciti, V. (2025) *The impact of EU Taxonomy for sustainable activities on European utilities' performance*, *Business Strategy and the Environment*, 34(3), pp. 2848-2862.

- Vionis, P. and Kotsilieris, T. (2024) *The potential of blockchain technology and smart contracts in the energy sector: a review*, Applied Sciences, 14(1), 253.
- VoltVert Consortium (2025) *Technical Architecture and Pilot Deployment Results*. Internal documentation. EIC STEP project deliverable.
- Wang, N., Chen, Y., Zhai, F. et al. (2025) *Blockchain consensus mechanism and method for peer-to-peer electricity trading*, Scientific Reports, 15, 39984.
- Wimmers, A. and Madlener, R. (2024) *The European market for guarantees of origin for green electricity: a scenario-based evaluation of trading under uncertainty*, Energies, 17(1), 104.
- World Green Building Council (2024) *Nearly Zero Energy Buildings (NZEB) Development Trends in Europe*. Technical Factsheet.
- World Resources Institute and World Business Council for Sustainable Development (2015) *The Greenhouse Gas Protocol: Corporate Standard*. Revised edition. Geneva: WRI/WBCSD.
- Yin, R.K. (2018) *Case Study Research and Applications: Design and Methods*. 6th edn. Thousand Oaks: SAGE.
- Zioló, M., Bąk, I. and Spoz, A. (2024) 'Literature review of greenwashing research: state of the art', Corporate Social Responsibility and Environmental Management, 31(6), pp. 5343-5356.
- Zuo, Y.J. (2022) *Tokenizing renewable energy certificates (RECs)—a blockchain approach for REC issuance and trading*, IEEE Access, 10, pp. 134477-134490.