



Article

Integrated Management of Air-Quality Monitoring Processes as a Framework for Disclosure Quality in Green Bond Markets

Venera-Stanca Nicolici ¹, Ahmed Adjal ¹, Ioana Ionel ^{1,*} and Eugenia Grecu ²

¹ Faculty of Mechanical Engineering, Politehnica University of Timisoara, 300006 Timisoara, Romania; venera-stanca.morar@student.upt.ro (V.-S.N.); ahmed.adjal@student.upt.ro (A.A.)

² Faculty of Management in Production and Transports, Politehnica University of Timisoara, 300006 Timisoara, Romania; eugenia.grecu@upt.ro

* Correspondence: ioana.ionel@upt.ro

Abstract

In the last 10 years, the global green bond market has reached an estimated value of USD 6.8 trillion. However, credibility concerns persist due to greenwashing risks and issues regarding the reporting system. The current measurement, reporting, and verification systems (MRV) have high uncertainty levels of 10–30%, and so they contribute to information asymmetries and fuel investor skepticism when allocating capital to green bond instruments. The scope of this study is to develop an integrated management approach that links air quality and greenhouse gas monitoring with financial incentives throughout the lifecycle of green bonds. The central contribution is a four-phase lifecycle model covering issuance, allocation, monitoring, and impact reporting, which systematically identifies where greenwashing risks and verification gaps arise across the investment cycle. Methodologically, the study combines qualitative content analysis, a novel Disclosure Quality Score (DQS) instrument, based on the Regulation (EU) 2023/2631, four documentary case studies, and an advanced verification framework. The content analysis shows that regulatory and market-performance studies dominate the literature, while integrated lifecycle verification frameworks remain less explored. The DQS uses eight indicators, applied to a matched sample of green bonds, in accordance with the European Green Bond Standard (EuGB) and the ICMA Green Bond Principles (GBP). The results demonstrate that bonds issued under the EuGB present higher disclosure quality (mean DQS = 15.4/16) compared to GBP-aligned bonds (mean DQS = 11.4/16). Case studies show strong issuance-stage disclosure, but weak post-issuance verification. The framework enables lifecycle-wide accountability by reducing information asymmetry. The proposed lifecycle framework and DQS instrument offer a replicable model for improving disclosure quality and ESG performance standards, with direct implications for sustainable investment screening and ESG fund selection. Overall, the findings show that improving green bond credibility requires moving beyond issuance-focused disclosure toward lifecycle-wide verification.



Academic Editor: Yongsheng Guo

Received: 21 April 2026

Revised: 31 May 2026

Accepted: 9 June 2026

Published: 2 July 2026

Copyright: © 2026 by the authors.

Licensee MDPI, Basel, Switzerland.

This article is an open access article distributed under the terms and conditions of the [Creative Commons Attribution \(CC BY\)](https://creativecommons.org/licenses/by/4.0/) license.

Keywords: sustainable finance; sustainable investment; green bonds; ESG funds; ESG performance; Disclosure Quality Score (DQS); lifecycle management

1. Introduction

Since the first climate-labelled bond was issued by the European Investment Bank in 2007, cumulative green bond issuance grew to exceed USD 6.8 trillion by the end of 2025. In recent years, annual issuance has remained above USD 1 trillion

(Climate Bonds Initiative, 2025; ICE, 2024; Earth5r, n.d.). This growth reflects the increasing role of capital markets in financing climate-mitigation and environmental projects.

Green bonds have become a key market-based instrument for financing environmental investments. They also support the transition toward a low-carbon economy and are a core element of sustainable finance (Bhutta et al., 2022; Flammer, 2021). For this reason, green bonds are increasingly used as policy instruments to promote sustainable transitions. Empirical and review studies show that green bonds channel capital toward renewable energy, energy efficiency, and environmental infrastructure. They also influence corporate financing conditions and investment decisions (Bhutta et al., 2022; Flammer, 2021).

From a management perspective, the effectiveness of green bonds depends not only on capital allocation at issuance. It also depends on how environmental performance is monitored throughout the bond lifecycle. Air-quality and greenhouse-gas monitoring are core operational components of MRV (measurement, reporting, and verification) systems. However, the integration of these components into financial disclosure and incentive structures remains limited.

This paper argues that the credibility of green bonds fundamentally depends on integrated management. Current approaches often treat disclosure, monitoring, and financial incentives as separate domains. Therefore, improvements introduced at the issuance stage are not always reflected in verified environmental performance at later stages. This paper addresses this gap by proposing an integrated lifecycle framework that links air-quality monitoring processes, disclosure quality, and financial outcomes.

Despite strong market growth, green bond credibility remains fragile. Environmental performance data are affected by high uncertainty and methodological inconsistency. Meanwhile, investors depend on disclosures provided by issuers (Rodrigues et al., 2018; Marlowe & Clarke, 2022). The literature on embodied carbon and product-level assessments demonstrates that uncertainty can be significant, particularly for complex assets (Marsh et al., 2021). These conditions create information asymmetries between issuers and investors.

Agency theory suggests that informational advantages held by issuers may lead to incentives for strategic misrepresentation when investors face limited access to relevant information (Jensen & Meckling, 1976). Signaling theory further suggests that labels and disclosures can be used to signal quality in the absence of complete verification (Pawlick et al., 2019). In the green bond market, this condition permits issuers with strong environmental performance and those with weak verification to be priced alike. This mechanism sustains pooling equilibria when information is asymmetric (Degen et al., 2017; Schmittmann & Gao, 2022).

MRV systems introduce a second weakness at structural level. Existing frameworks rely on modeling assumptions, boundary choices, and data proxies. These features generate systematic uncertainty (Rodrigues et al., 2018; Marlowe & Clarke, 2022; Marsh et al., 2021). Uncertainty persists across scales, from national carbon accounts to firm-level and asset-level reporting (Rodrigues et al., 2018; Marlowe & Clarke, 2022). As a result, disclosure regimes may fail to establish a reliable link between reported environmental performance and verified outcomes.

The literature reports mixed results on green bond effectiveness. While issuance generates measurable signaling benefits and lower financing costs (Flammer, 2021), post-issuance evidence shows no consistent reduction in greenhouse gas emissions (Bhagat & Yoon, 2023). Firm-level greenwashing studies attribute this pattern to weak post-issuance monitoring rather than issuer-specific failure (Li et al., 2025; Zhu et al., 2024; Lubl6y et al., 2024; Shi et al., 2023).

This divergence reflects a structural feature of current disclosure regimes. Across the green bond lifecycle, verification effort is unevenly distributed: front-loaded at issuance and progressively thinner in the monitoring and impact phases (ESMA, 2021; Zhu et al., 2024). Certification reduces greenwashing risks to a degree, but the gap between pre-issuance promises and post-issuance environmental realities persists.

The greenium literature adds another layer to this picture. Investors price environmental credibility into green bond spreads (Zerbib, 2019). Greenium stability, in turn, appears sensitive to the quality and verifiability of issuer disclosures (Dragotto et al., 2025). The link between pre-issuance disclosure quality and post-issuance environmental verification remains empirically underexplored.

Recent technology-oriented studies narrow this gap without closing it. Studies on blockchain-based fund traceability and digital twin monitoring suggest feasibility within current regulatory settings (Christodoulou et al., 2023; Siemens AG, 2024b). Work on quantum sensing applications establishes a physically bounded lower limit on measurement uncertainty that classical MRV systems do not achieve (Barry et al., 2020; Paudel et al., 2024). Yet no study published prior to 2023 appears to integrate these regulatory and technological dimensions within a single analytical framework. Greenwashing research ignores measurement technology; quantum sensing research does not engage with disclosure requirements, and regulatory studies address either. This fragmentation motivates the present study.

The problem can be illustrated by a city council issuing a green bond for the rehabilitation of a river. In the current model, the coupon is fixed (e.g., 4% per year) and the ecological impact is reported through a handwritten annual report, which cannot be independently verified. In the proposed model, quantum sensors placed in the river continuously measure water purity, oxygen levels and biodiversity indicators; a smart contract recalculates the coupon daily based on sensor data; if the river ecologically recovers faster than the initial projection, investors receive a carbon bonus. Due to the no-cloning principle in quantum mechanics, transmitted data is impossible to manipulate retroactively. However, the digital tools do not eliminate measurement uncertainty or data-manipulation risks on their own (Christodoulou et al., 2023; Ahmad et al., 2025).

Regulation (EU) 2023/2631 of the European Parliament and of the Council (Publications Office of the European Union, 2023) entered into force in December 2024, establishing the first mandatory disclosure framework for European green bonds. No replicable instrument existed at that point to measure compliance with quality systematically across issuers. The EuGB-certified segment was nascent but sufficiently developed for systematic comparison, generating a first cohort of comparable issuances against which disclosure quality could be assessed. The fragmentation documented above, combined with this regulatory shift and the absence of empirical measurement tools, left a precise and addressable gap in the literature.

This paper addresses these challenges through four contributions. First, it introduces a four-phase green bond lifecycle model: issuance, allocation, monitoring, and impact. This model identifies where greenwashing vulnerabilities arise. Second, it develops the Disclosure Quality Score (DQS), an eight-indicator instrument anchored in Regulation (EU) 2023/2631 (Publications Office of the European Union, 2023). The DQS enables systematic comparison of pre-issuance disclosure quality across certification regimes. Third, the paper reports a content analysis of 74 academic and regulatory references covering greenwashing, regulation, markets, and emerging technologies. Fourth, it proposes an advanced environmental monitoring and verification framework integrating quantum sensing, secure data transmission, and smart-contract-based incentives, with the goal of extending verification beyond disclosure toward lifecycle-wide accountability, contributing to the broader agenda of sustainable finance and sustainable investment in green capital markets.

Certification standard choice shapes what issuers disclose and what investors can verify. This study examines the extent to which the choice between EuGB and GBP ICMA determines disclosure quality at the issuance stage of the green bond lifecycle. It also investigates how an integrated lifecycle verification framework combining advanced sensing technologies and smart contract mechanisms reduces structural information asymmetries between issuers and investors. Four objectives are operationalized in this inquiry. The first maps the existing academic and regulatory literature across thematic dimensions relevant to green bond credibility. The second develops and empirically applies the Disclosure Quality Score (DQS) as a replicable instrument for measuring pre-issuance disclosure quality across certification regimes. The third illustrates the technological and institutional dimensions of lifecycle verification through documentary case studies. The fourth proposes an advanced verification framework integrating quantum sensing, secure quantum data transmission, and smart contract-based financial incentives, extending accountability beyond the issuance stage toward lifecycle-wide verification.

The paper is organized to mirror the sequential logic of the research design. Section 2 details the materials and methods: the content analysis protocol, the DQS instrument, the documentary case study framework, and the advanced verification architecture. The empirical results emerge in Section 3, organized across the four methodological components. Section 4 discusses the findings in relation to the theoretical framework, with particular attention to the DQS–greenium relationship, the agency problem, and the implications for regulatory design and sustainable investment practice. Section 5 concludes the study and identifies directions for future research.

2. Materials and Methods

This study adopts a mixed-methods research design (Creswell & Creswell, 2023) combining qualitative content analysis, quantitative disclosure scoring, documentary case studies, and conceptual framework development, integrating four components executed sequentially:

1. systematic content analysis of academic and regulatory literature;
2. development and empirical application of the Disclosure Quality Score (DQS);
3. documentary case studies;
4. conceptual framework development.

The sequential mixed-methods design reflects the layered nature of the research problem. Market-level econometric tools measure greenium effects but cannot reach the physical layer of environmental verification. Qualitative analysis alone cannot produce comparable disclosure scores across certification regimes. The four components are therefore not interchangeable, but each addresses a gap the others leave open. Their sequence reflects the logic of building from theoretical mapping toward normative synthesis.

This design is appropriate for the research objectives because each component addresses a distinct analytical layer—theoretical mapping, empirical measurement, technological illustration, and normative synthesis—and is suited for research questions at the intersection of regulatory design, market behavior, and emerging verification technologies (Creswell & Creswell, 2023). The research gap identified in the literature concerns both the absence of empirical disclosure metrics and the lack of integrated lifecycle verification models. The theoretical framework of this study is grounded in agency theory (Jensen & Meckling, 1976) and signaling theory (Pawlick et al., 2019), which are widely applied in sustainable finance literature to explain information asymmetries between issuers and investors.

2.1. Content Analysis of the Reference Corpus

The content analysis covers 74 academic and regulatory references cited in this paper. Corporate and institutional reports are excluded, as they serve as empirical or documentary data sources rather than theoretical contributions. References span the period from 2017 to 2026. All references are publicly accessible through standard academic databases (Scopus, Web of Science) or official institutional websites (EUR-Lex, ESMA, ICMA). In addition to the primary corpus, supplementary data sources and second party opinions issued by market and supervisory actors were analyzed. These sources include reviews by ISS-Corporate, external assessments by Sustainable Fitch, and market-level reporting by the World Bank Treasury. They are used as documentary evidence for disclosure practices and allocation mechanisms rather than as theoretical contributions (ISS-Corporate, 2025a, 2025b, 2025c; Sustainable Fitch, 2025; World Bank Treasury, 2025).

Each reference was coded along four thematic dimensions:

- D1: greenwashing and information asymmetry;
- D2: regulatory and disclosure frameworks;
- D3: digital and quantum technologies;
- D4: portfolio performance and financial markets.

Each reference was assigned to a dimension when its title or abstract addressed the corresponding theme; in cases of uncertainty, the full text was consulted. D1 covers greenwashing, ecological fraud, information asymmetry between issuer and investor, divergence between reported and real environmental performance, or signaling and agency theory in the green bond context. D2 includes specific standards: EuGB, GBP ICMA, IFRS S1/S2 (IFRS, 2024a, 2024b), GHG Protocol, mandatory reporting or compliance requirements (ESMA, EU taxonomy), verification or certification instruments. D3 covers blockchain or distributed ledger technology, quantum computing, quantum sensing, quantum key distribution, post-quantum cryptography, AI/ML applied to ESG monitoring, or smart contract mechanisms. D4 includes green bond yields or spreads (greenium), portfolio diversification or hedging, market size or growth, or investor demand. A single reference could be assigned to more than one dimension.

To assess coding reliability, 20% of the corpus ($n = 15$ references, with allocation proportional to the six literature streams) was randomly selected and independently coded by a second coder. To assess inter-rater reliability, Cohen's κ was used as a standard indicator of categorical agreement in qualitative coding (Creswell & Creswell, 2023). Six disagreements were identified and resolved through structured discussion; following resolution, the D3 decision rule was refined: any reference employing a physically defined quantum variable (QBER, QFI, QCRB) is coded D3. The global pooled κ across all four dimensions and all 60 paired decisions was used as the primary reliability index, with a publication threshold of $\kappa \geq 0.70$. All reliability calculations were conducted with Microsoft Excel.

2.2. Disclosure Quality Score (DQS)

The Disclosure Quality Score (DQS) is an eight-indicator scoring instrument derived from Article 10 of Regulation (EU) 2023/2631 (Publications Office of the European Union, 2023). The DQS measures disclosure quality at the issuance stage (Phase 1) of the green bond lifecycle. Each indicator is scored on a three-point scale, where "0" means absent or unverifiable, "1" is partially disclosed, and "2" means fully disclosed and independently verifiable. The maximum total score is 16 points, with thresholds defined as: 0–5 = Weak; 6–10 = Moderate; 11–13 = Good; 14–16 = Excellent.

The eight indicators cover:

- (I1) EU taxonomy alignment;

- (I2) Allocation of proceeds;
- (I3) Quantified environmental KPIs;
- (I4) External review;
- (I5) Impact methodology;
- (I6) Baseline data;
- (I7) Monitoring and reporting plans;
- (I8) Do No Significant Harm (DNSH) compliance.

All these indicators are specified in Regulation (EU) 2023/2631 ([Publications Office of the European Union, 2023](#)).

The study uses secondary data consisting of publicly available issuer documents. All data sources are accessible without restriction through issuer websites, official regulatory repositories, and ESMA's external reviewer register ([ESMA, n.d.](#)). The sample covers ten green bond issuances from 2025 from the European market. The sample is divided into two matched groups of five bonds each: Group A includes bonds certified under the European Green Bond Standard (EuGB), identified using issuer-published European Green Bond factsheets; Group B comprises bonds aligned with the ICMA Green Bond Principles (GBP ICMA), identified using issuer green bond frameworks and impact reports ([ICMA, 2025](#); [EFDData, n.d.](#)).

Group A (EuGB) includes: A2A S.p.A. ([A2A S.p.A., 2025](#)), Eurogrid GmbH ([Eurogrid GmbH, 2025a, 2025b](#)), ABN AMRO Bank N.V. ([ABN AMRO Bank N.V., 2025](#)), Iberdrola Finanzas S.A.U. ([Iberdrola Finanzas, S.A.U., 2025](#)), and Terna S.p.A. ([Terna S.p.A., 2025](#)). Group B (GBP ICMA) includes: EDF (Électricité de France) ([EDF, 2025a, 2025b](#)), ENGIE S.A. ([ENGIE, 2025, 2026](#)), BBVA S.A. ([BBVA CIB, 2025](#)), Ørsted A/S ([Ørsted, 2025a, 2025b](#)), and SSE plc ([SSE plc, 2025](#)).

Bonds were matched by sector (utilities, energy, or financial institutions), investment-grade credit rating, issuance year (2025), issuance size ($\pm 50\%$ tolerance), and maturity (± 3 years tolerance). The $\pm 50\%$ tolerance for issuance size was necessitated by the structural heterogeneity of the emerging EuGB-certified market segment in 2025, where the simultaneous application of sector, maturity, and credit rating constraints reduced the set of eligible matching candidates. Where a criterion cannot be fully satisfied, the deviation is reported in the limitations section. The matching pairs are: P1 (A2A—ENGIE), P2 (Eurogrid—EDF), P3 (ABN AMRO—BBVA), P4 (Iberdrola—Ørsted), P5 (Terna—SSE plc).

Scoring was performed independently by two coders (the first and the second authors of the study). Each coder assigned scores to all eight indicators for all ten bonds without prior discussion. Disagreements were resolved through consensus review after initial independent scoring. Inter-rater reliability for the DQS instrument was assessed using Cohen's κ for each indicator across all ten bonds ($n = 10$ paired scores per indicator, 80 paired decisions in total), using a linear-weighted scheme. The resulting Cohen's κ values are reported in Section 3: Results.

Group differences were tested using the Mann–Whitney U test, appropriate for small samples with ordinal data ([Creswell & Creswell, 2023](#)). Effect size was calculated as the standardized mean difference between the two groups with pooled standard deviation (Cohen's d). All statistical analyses were conducted with Microsoft Excel for the web (Microsoft 365).

2.3. Documentary Case Studies

Four documentary case studies were selected using theoretical sampling, with the objective of maximizing conceptual variation across lifecycle phases rather than achieving statistical representativeness ([Creswell & Creswell, 2023](#)). The cases are:

1. Siemens Energy: green bond issuance and industrial decarbonization, covering Phase 1 (Siemens Energy, 2023);
2. Siemens AG: blockchain-based digital bond and digital-twin monitoring, covering Phases 2–3 (Siemens AG, 2024a, 2024b; CoinDesk, 2024);
3. HSBC: green bond issuance and allocation reporting, covering Phases 1–2 (HSBC Holdings plc, 2024, 2025; HSBC Holdings plc & Sustainable Digital Finance Alliance, 2020; PricewaterhouseCoopers LLP, 2026);
4. HSBC and IBM Quantum: quantum computing applied to bond trading, covering Phase 4 (Herman et al., 2023; HSBC Holdings plc & Sustainable Digital Finance Alliance, 2020).

All assessments rely exclusively on publicly available documentation. Each case was evaluated using a four-dimension grid: D1 (technological maturity: pilot, prototype, or commercial); D2 (lifecycle phases covered); D3 (compatibility with EuGB disclosure requirements); and D4 (scaling barriers: regulatory, technical, financial, or institutional).

2.4. Advanced Verification Framework

The advanced verification framework was developed using a conceptual-integrative methodology that integrates quantum metrology, quantum-secure communication, and financial contract theory. At the physical layer, nitrogen-vacancy (NV) diamond sensors are proposed for measuring greenhouse-gas fluxes (CH₄ and CO₂), with measurement precision bounded by the quantum Cramér–Rao bound (QCRB) (Barry et al., 2020, 2024; Degen et al., 2017; Q. Liu et al., 2024; Paudel et al., 2024). At the cyber-physical layer, secure data transmission is achieved by quantum key distribution (QKD), ensuring that any unauthorized alteration is physically detectable (Pawlick et al., 2019; Reddy et al., 2025; Dutta & Pathak, 2024). At the financial layer, smart contracts link bond cash flows to verified environmental performance, reducing information asymmetry (Jensen & Meckling, 1976; Pawlick et al., 2019).

2.5. Use of Generative Artificial Intelligence

The authors disclose that generative AI tools (Microsoft 365 Copilot version 2.20260602.20.0; Claude Sonnet 4.6; and Writefull for Word version 2025.59.0) were used during the preparation of this manuscript to assist in study design and structural reorganization of text sections, and to support grammatical revision and improvement of academic tone. The authors have reviewed and edited the output and taken full responsibility for the content of this publication.

3. Results

Results are presented across three components: the DQS analysis and lifecycle model, the four documentary case studies, and the Quantum-Verified Green Bond (QVGB) architecture as an integrated framework.

Figure 1 maps the four-phase green bond lifecycle: Issuance (P1), Allocation (P2), Monitoring (P3), and Impact (P4), across three intervention layers: greenwashing vulnerabilities, disclosure-based remediation mechanisms, and advanced verification technologies. This figure illustrates how structural credibility gaps persist and where targeted interventions can be applied at each phase.

3.1. Content Analysis

The content analysis is based on 74 academic and regulatory references. Each reference was coded along four thematic dimensions: greenwashing and information asymmetry (D1), regulatory and disclosure frameworks (D2), quantum and digital technologies (D3),

and portfolio performance and markets (D4). A reference could be assigned to more than one dimension.

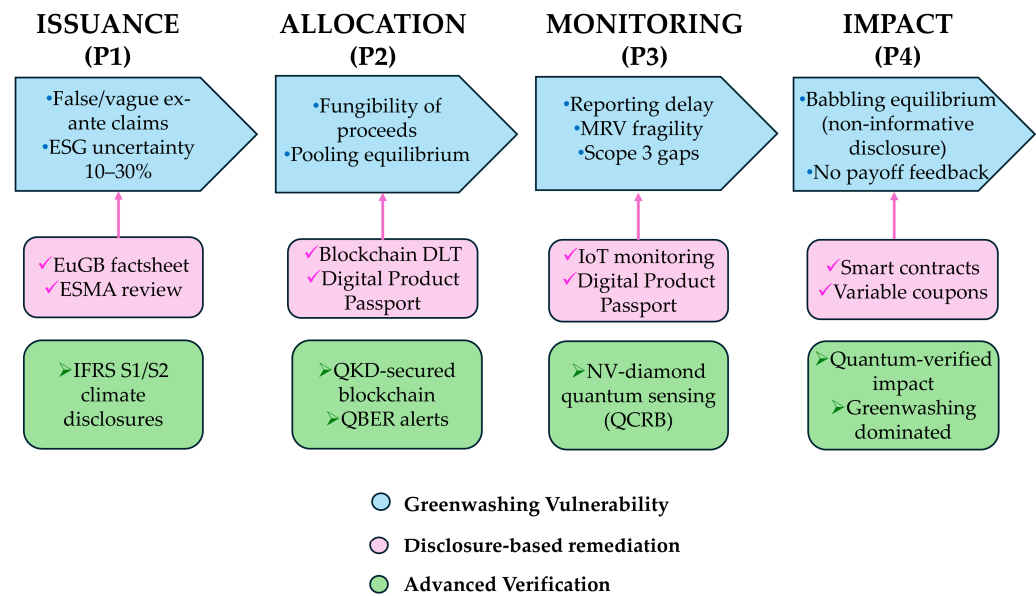


Figure 1. Lifecycle-based verification framework for green bonds: greenwashing vulnerabilities, disclosure-based remediation, and advanced verification mechanisms across the four lifecycle phases.

3.1.1. Dimensional Frequencies

Table 1 presents the dimension of frequencies across the 74-reference corpus. Portfolio performance and market studies (D4) form the largest dimension, with 38 references (51.4%), reflecting the maturity of empirical work on greenium, diversification, and market efficiency. Regulatory and disclosure frameworks (D2) cover 25 references (33.8%), driven by the adoption of Regulation (EU) 2023/2631 and related standards. Greenwashing and information asymmetry (D1) appear in 22 references (29.7%), including recent systematic reviews and firm-level studies. Quantum and digital technologies (D3) remain the smallest dimension with 16 references (21.6%) but show the fastest growth trajectory after 2023.

Table 1. Content analysis: thematic dimension of frequencies across the reference corpus ($n = 74$ academic and regulatory references).

Dimension	<i>n</i>	% of Corpus	Primary Role in the Article
D1: Greenwashing and information asymmetry	22	29.7%	Motivates DQS instrument; lifecycle model phases 1–4; agency theory
D2: Regulatory and disclosure frameworks	25	33.8%	Regulatory basis for DQS (Regulation (EU) 2023/2631); EuGB vs. GBP ICMA comparison
D3: Quantum and digital technology	16	21.6%	Most rapidly expanding cluster; basis for advanced verification framework
D4: Portfolio performance and markets	38	51.4%	Diversification, greenium dynamics, DQS–greenium link

Multiple coding was common; 26 references (35.1%) were coded under two or more dimensions. The intersection of D1 and D2 includes research examining certification effectiveness and the distinction between signaling and greenwashing. The overlap between D2 and D3 appears in only four references, all published starting with 2023.

3.1.2. Temporal Distribution

Table 2 presents the temporal distribution across four periods. The 2023–2024 period shows the highest publication activity ($n = 32$), reflecting the convergence of EuGB regulatory development, post-pandemic ESG research, and early quantum-finance applications. Quantum and digital studies (D3) appear as a significant dimension in this period (10 references), including quantum portfolio optimization (Catalano et al., 2024), quantum sensing for carbon measurement (Paudel et al., 2024), and QKD-secured data provenance (Reddy et al., 2025; Dutta & Pathak, 2024). The 2025–2026 period ($n = 21$) sustains D2 and D4 growth but shows a D3 slowdown.

Table 2. Content analysis: temporal distribution of references by thematic dimension and period ($n = 74$).

Period	<i>n</i>	D1	D2	D3	D4	Main Pattern
Pre-2020	6	3	1	2	2	Foundational work; D3 present in physics only
2020–2022	14	6	4	1	9	D4 expands; D3 near-absent; EU taxonomy debate in D2
2023–2024	32	8	10	10	14	Turning point: D3 jumps to 10; D2 accelerates prior to EuGB (December 2024)
2025–2026	21	5	10	3	13	D2 and D4 lead; D3 slows

3.1.3. Literature Streams

Literature streams were identified by grouping the analyzed references according to their primary thematic contribution, as determined during the coding process. Six streams emerged from the data: origins and market growth, greenium, greenwashing, portfolio diversification and market performance, technology and regulation, and quantum computing and sensing. Two references cited exclusively for theoretical and methodological grounding (Jensen & Meckling, 1976; Creswell & Creswell, 2023) were classified separately. Stream assignment was recorded in the coding spreadsheet alongside the D1–D4 dimension scores and used to structure the cross-dimensional analysis reported in Table 3.

Table 3. Content analysis: literature stream distribution and cross-dimension coding ($n = 74$).

Literature Stream	<i>n</i>	D1	D2	D3	D4	Thematic Intersections
Stream 1: Origins and market growth	8	0	4	0	8	D4-heavy; D2 in policy-oriented papers
Stream 2: Greenium	6	1	1	0	6	D4 dominant; greenium magnitude and stability
Stream 3: Greenwashing	14	14	6	0	5	D1 almost exclusive; D2 intersection in certification papers
Stream 4: Portfolio diversification	11	0	0	0	11	Pure D4; connectedness, hedging, efficiency
Stream 5: Technology and regulation	15	1	13	6	1	D2 dominant; DLT/blockchain bridge to D3
Stream 6: Quantum computing and sensing	10	1	0	10	2	D3 almost exclusive; no D2 overlap until 2025
General theory (Jensen & Meckling, 1976; Creswell & Creswell, 2023)	2	1	0	0	0	Cited for theoretical/methodological grounding only

Stream 1 (origins and market growth) has 8 references and is dominated by the D4 code, with 4 papers also carrying a D2 code, reflecting policy-oriented discussions of issuance drivers. None of the studies in this stream engage with verification of quality or MRV uncertainty, indicating that early literature treats instrument credibility as an implicit assumption rather than an explicit research problem (Flaherty et al., 2017; Tolliver et al., 2020; Tu et al., 2020; Horn et al., 2025).

Stream 2 (greenium) consists of 6 references, also concentrated in D4, with only marginal overlap with D1 and D2. The absence of D3-coded references indicates that technology-based verification mechanisms have not yet been incorporated into green bond pricing models (Gronwald & Wadud, 2023; L. Liu & Hu, 2025).

Stream 3 (greenwashing) comprises 14 references, all carrying a D1 code, and none a D3 code. The complete absence of quantum or physics-based verification methods in this stream indicates that greenwashing research remains detached from advances in measurement technology.

Stream 4 (portfolio diversification and market performance) contains 11 references, all coded D4 and do not cover regulatory design or verification technologies (Adekoya et al., 2021; Arouri et al., 2024; Ben Ameer et al., 2024; Dong et al., 2023; Hammoudeh et al., 2022; Karim et al., 2024; Naeem et al., 2021a, 2021b; Papavassiliou et al., 2025; Rehman et al., 2023; Silva et al., 2024).

Stream 5 (technology and regulation) includes 15 references acting as the primary bridge between D2 and D3. None of these studies integrate digital or quantum technologies to meet the disclosure requirements specified in Regulation (EU) 2023/2631 (Publications Office of the European Union, 2023).

Stream 6 (quantum computing and sensing) contains 10 references, exclusively coded D3. No reference in this stream carries a D2 code prior to 2025.

3.1.4. Inter-Rater Reliability

Inter-rater reliability was assessed on a stratified subsample of 15 references (20.3% of corpus, seed = 42). Table 4 reports Cohen's κ values for each dimension. The global pooled $\kappa = 0.786$ (based on 60 paired decisions) exceeds the publication threshold of 0.70, confirming acceptable overall reliability.

Table 4. Inter-rater reliability: Cohen's kappa by thematic dimension ($n = 15$ references, 20.3% of corpus).

Dimension	n Pairs	Cohen's κ	Disagreement Resolution
D1: Greenwashing	15	0.727	2 disagreements resolved after discussion
D2: Regulation	15	0.727	2 disagreements resolved after discussion
D3: Quantum/digital	15	0.634	1 disagreement; criterion clarified post-hoc
D4: Portfolio/markets	15	0.865	1 disagreement resolved
Global κ (pooled, 60 pairs)	60	0.786	¹

¹ Global κ exceeds the 0.70 publication threshold; 54 out of 60 paired decisions reached agreement (90.0%).

3.2. DQS Analysis: Structural Projections for P1

Within the lifecycle framework, the DQS measures disclosure quality exclusively at Phase 1 (Issuance). The results test Proposition P1 and provide the empirical foundation for the lifecycle and verification analyses that follow.

The analysis compares five EuGB-certified bonds with five GBP ICMA-aligned bonds. EuGB bonds achieve a mean DQS of 15.4 out of 16, while GBP ICMA bonds reach 11.4 out of 16, resulting in a gap of 4 points (Table 5).

Table 5. Disclosure Quality Scores (DQS) by issuer and certification standard: EuGB vs. GBP ICMA-aligned bonds ($n = 10$, issuance year 2025).

Standard	Issuer of Green Bond	DQS Score (Max = 16)	Mean
EuGB	A2A S.p.A.	15	15.4
	Eurogrid GmbH	16	
	ABN AMRO Bank N.V.	14	
	Iberdrola S.A.	16	
	Terna S.p.A.	16	
GBP ICMA	EDF (Électricité de France)	11	11.4
	ENGIE S.A.	11	
	BBVA S.A.	9	
	Ørsted A/S	13	
	SSE plc	13	

A Mann–Whitney U test confirms statistical significance ($U = 25$, $z = 2.611$, $p = 0.009$), and the effect size is large (Cohen’s $d = 3.320$, well above the $d \geq 0.80$ threshold). $U = 25$ represents the maximum possible value for samples of $n_1 = n_2 = 5$, indicating that every EuGB bond outsourced every GBP ICMA bond across all 25 pairwise comparisons, indicating a pattern of complete separation between the two groups.

Indicator-level analysis shows a differentiated pattern across the eight DQS dimensions (Table 6). The largest gaps occur in DNSH compliance (I8, $\Delta = 1.2$), EU taxonomy alignment (I1, $\Delta = 1$), and ESMA-registered external review (I4, $\Delta = 1$), which are mandatory requirements under Regulation (EU) 2023/2631 that are absent or voluntary under the ICMA Green Bond Principles (ICMA, 2025; Publications Office of the European Union, 2023). The moderate gaps in impact methodology (I5, $\Delta = 0.4$) and baseline data (I6, $\Delta = 0.4$) reflect voluntary adoption of best practices by advanced GBP ICMA issuers. Convergence is obtained about allocation of proceeds (I2), quantified KPIs (I3), and monitoring and reporting plans (I7). These results confirm that the total DQS gap of 4.0 points is determined by the mandatory dimensions of Regulation (EU) 2023/2631, rather than by issuer capacity or sector characteristics.

Table 6. Mean DQS scores by indicator: comparison between EuGB-certified and GBP ICMA-aligned bonds.

Indicator	Mean EuGB (A)	Mean GBP ICMA (B)	Mean Difference (A – B)
I1: EU taxonomy alignment	2.0	1.0	1.0
I2: Allocation of use-of-proceeds	2.0	2.0	0.0
I3: Quantified environmental KPIs	1.8	1.8	0.0
I4: External review/ESMA-registered verifier	2.0	1.0	1.0
I5: Impact calculation methodology	1.8	1.4	0.4
I6: Baseline environmental data	1.8	1.4	0.4
I7: Monitoring and reporting plan	2.0	2.0	0.0
I8: DNSH compliance	2.0	0.8	1.2

3.3. Documentary Case Studies

3.3.1. Siemens Energy: Industrial Decarbonization via Green Bond (Phase 1)

Siemens Energy issued a EUR 1.5 billion green bond in 2023 to finance the decarbonization of gas turbine manufacturing and wind energy activities (Siemens Energy, 2023). The Green Bond Framework commits to EU taxonomy alignment and third-party external review. The estimated DQS ranges between 12 and 14 out of 16 (Good to Excellent). This case demonstrates that large industrial issuers can achieve high disclosure quality at Phase 1 under existing frameworks, while MRV uncertainty at Phase 3 remains unresolved.

3.3.2. Siemens AG: Blockchain Bond and Digital Twin Monitoring (Phases 2–3)

In September 2024, Siemens AG issued a EUR 300 million digital bond on the private SWIAT blockchain (Siemens AG, 2024b; CoinDesk, 2024). The Bundesbank trigger solution, implemented within the ECB distributed ledger pilot (European Central Bank, 2025), reduced settlement duration from two days to a few minutes. At the same time, Siemens introduced digital twin systems compliant with EU Digital Product Passport requirements, facilitating near real-time tracking of asset-level data (European Commission, 2026; Siemens AG, 2024a). This case confirms that blockchain-based fund traceability and digital monitoring are feasible within the current EU regulatory setting.

3.3.3. HSBC: Green Bond Issuance and Allocation Reporting (Phases 1–2)

HSBC has issued multiple green bonds under its Green Financing Framework (HSBC Holdings plc, 2024, 2025; HSBC Holdings plc & Sustainable Digital Finance Alliance, 2020). Annual impact reports present information on the allocation of proceeds, project categories, and quantified environmental KPIs, supported by external assurance from PricewaterhouseCoopers (PricewaterhouseCoopers LLP, 2026). Public disclosures indicate high quality for I2 and I3, whereas coverage of DNSH compliance (I8) remains limited, consistent with the structural gap identified under Proposition P1 between GBP ICMA-aligned and EuGB-certified bonds. Impact reporting continues to be characterized by MRV uncertainty of 10–30% (HSBC Holdings plc, 2024, 2025; HSBC Holdings plc & Sustainable Digital Finance Alliance, 2020).

3.3.4. HSBC and IBM Quantum: Quantum Computing in Bond Trading (Phase 4)

In September 2025, HSBC and IBM reported a 34% increase in bond trading precision achieved with the IBM Heron quantum processor. This result marks the first commercially validated quantum advantage in fixed income trading. By enabling dynamic-coupon smart-contract designs, quantum computing facilitates the simultaneous optimization of investor returns and environmental incentives across large portfolios. Such simultaneous optimization is not feasible under classical Markowitz optimization. A comprehensive overview of quantum computing applications in finance is provided by Herman et al. (2023).

3.4. Advanced Verification Framework Architecture

The advanced verification framework integrates all four lifecycle phases into a three-layer architecture. At the physical layer, Gen 1 systems rely on classical IoT sensors; Gen 2 systems use NV diamond quantum sensors to measure CH₄ and CO₂ fluxes, with precision bounded by the quantum Cramér–Rao bound (Barry et al., 2020, 2024; Degen et al., 2017; Q. Liu et al., 2024; Paudel et al., 2024). This defines a stable precision threshold, in contrast to the flexible uncertainty ranges characteristic of classical MRV systems (HSBC Holdings plc, 2024, 2025; HSBC Holdings plc & Sustainable Digital Finance Alliance, 2020). At the cyber-physical layer, QKD secures data transmission, making unauthorized interference physically detectable (Reddy et al., 2025; Dutta & Pathak, 2024). At the financial layer,

smart contracts link bond coupons to quantum verified impact data, allowing automatic adjustment based on verified environmental performance and directly addressing the Jensen–Meckling agency problem (Jensen & Meckling, 1976; Pawlick et al., 2019). Figure 2 illustrates the transition from Monte Carlo-based estimation to a deterministic, quantum-verified data pipeline, and the resulting shift from pooling to separating equilibria under QBER-based monitoring (Pawlick et al., 2019; Dutta & Pathak, 2024).

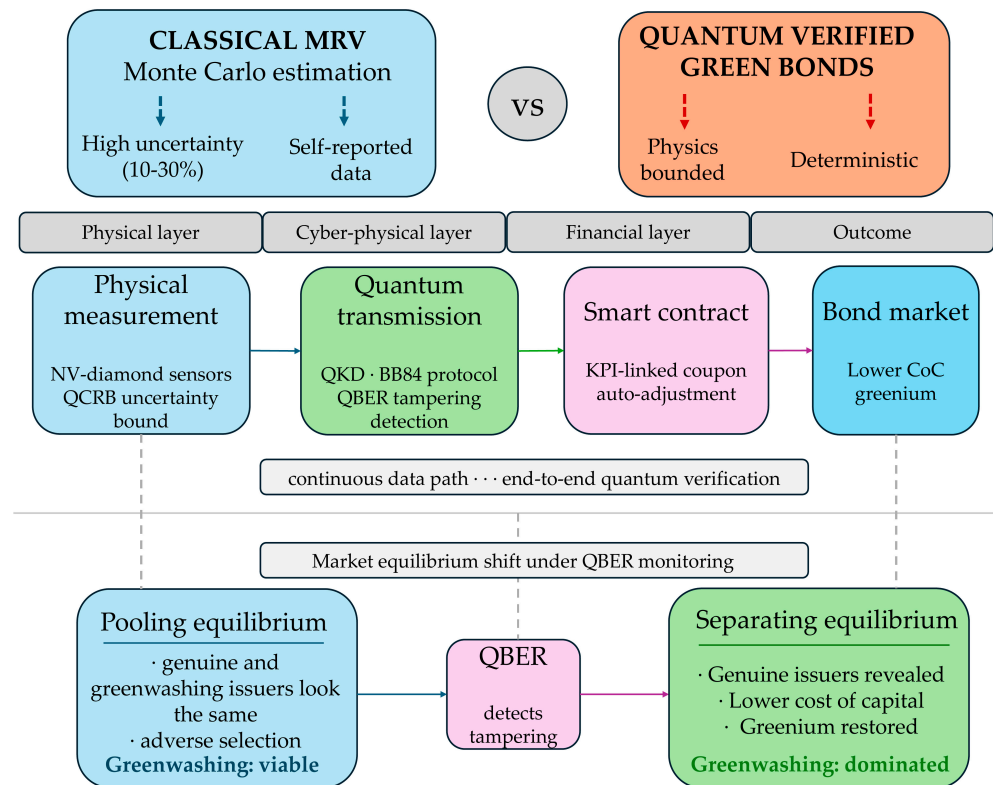


Figure 2. Advanced verification framework: physical, cyber-physical and financial layer architecture for quantum-verified green bonds and market equilibrium transition under QBER monitoring.

4. Discussion

Each component of this study produces a finding that sharpens the one before it. First, EuGB-certified bonds demonstrate systematically higher disclosure quality than GBP ICMA-aligned bonds, with a mean DQS gap of 4.0 points driven by mandatory regulatory requirements rather than issuer capacity or sector characteristics. Second, the lifecycle model suggests that this disclosure gap is not an isolated measurement outcome and reflects a structural asymmetry between verification intensity at issuance and the comparatively weaker scrutiny applied at the monitoring and impact stages. Third, the documentary case studies show that high disclosure quality at issuance is achievable under current frameworks, while allocation traceability and post-issuance monitoring remain fragmented or limited to pilot implementations. Fourth, the advanced verification framework proposes an architecture through which integrating physically bounded sensing, quantum-secure transmission, and smart contract mechanisms into the bond lifecycle could shift the market equilibrium from pooling toward separation.

These findings address a fragmentation that runs through literature: greenwashing research, regulatory studies, and technology-oriented work have developed in isolation. This study integrates all three within a single analytical framework.

4.1. The Flammer–Bhagat Tension

Green bond research reports conflicting results because it measures conflicting phases. Signaling effects dominate where verification is mandatory and concentrated, at issuance. Emission reductions fail to materialize where verification is voluntary and dispersed, at monitoring and impact. Flammer documents the first (Flammer, 2020, 2021). Bhagat and Yoon document the second (Bhagat & Yoon, 2023). The lifecycle model explains both. The content analysis maps a literature concentrated on regulatory design and market pricing. Post-issuance verification receives comparatively little attention. This emphasis reflects a wider trend identified in recent systematic reviews, showing that research on green bonds is still largely concentrated on issuance-stage impacts, while lifecycle accountability remains underexplored empirically (Lublóy et al., 2024; Sneideriene & Legenzova, 2024; Flöttmann et al., 2025). The lifecycle framework proposed here is designed specifically to address this gap.

Empirical findings suggest that the issuance of green bonds does not automatically lead to proportional or timely reductions in emissions (Chen et al., 2024; Aswani & Rajgopal, 2025). The content analysis further reveals that no study published prior to 2023 integrates regulatory frameworks (D2) and quantum digital technologies (D3) within a single analytical model. The four references coded under both D2 and D3 are all published from 2023 onward and address digital or quantum technologies at a general governance level, without explicitly linking these tools to EuGB disclosure requirements or the eight indicator DQS framework. This pattern is consistent with the predictions of signaling theory: credible signals dominate at issuance, where verification costs are lowest, while the absence of post-issuance monitoring mechanisms leaves the signal unanchored in verified environmental reality (Pawlick et al., 2019).

4.2. The Epistemic Transformation of ESG Data

At this stage of development, the advanced verification framework makes a conceptual rather than an empirical claim. Classical MRV uncertainty of 10–30%, documented in the HSBC case study and consistent with broader evidence (Rodrigues et al., 2018; Marlowe & Clarke, 2022; Marsh et al., 2021), cannot be resolved by refining the reporting layer that produces it. The framework proposes replacing that layer with physically bounded measurement. Whether this replacement delivers the theoretical precision gains suggested by the quantum Cramér–Rao bound remains an empirical question for future research.

The advanced verification framework shifts the epistemic status of ESG data. Existing MRV frameworks are based on organizational processes, modeling assumptions, and reporting conventions, which introduce persistent uncertainty (HSBC Holdings plc, 2024, 2025). Agency theory explains how such asymmetries sustain pooling equilibria (Jensen & Meckling, 1976; Pawlick et al., 2019). By defining a physical lower limit on measurement uncertainty independent of reporting choices, the quantum Cramér–Rao bound (Barry et al., 2020, 2024; Degen et al., 2017; Q. Liu et al., 2024; Paudel et al., 2024) transforms ESG data from institutionally constructed signals into physics-verified quantities. Pooling equilibria persists because investors cannot verify what issuers report (Jensen & Meckling, 1976). Physically bounded ESG measurements change this: the informational advantage that makes misrepresentation rational disappears when data integrity is guaranteed at the physical layer.

4.3. Disclosure Quality, Greenium, and Lifecycle

The DQS results draw a precise boundary between what regulation mandates and what it leaves voluntary. EuGB-certified bonds score higher on EU taxonomy alignment, ESMA-registered external review, and DNSH compliance, all mandatory under Regulation

(EU) 2023/2631. On allocation of proceeds, quantified KPIs, and monitoring plans, where both standards converge, the two groups score identically. The 4.0-point gap tracks the regulatory boundary perfectly. Variation in disclosure quality between EuGB-certified and GBP ICMA-aligned bonds directly affects greenium formation. Previous research shows that information asymmetry gives rise to greenium, as investors incorporate environmental credibility and verification risk into prices (Zerbib, 2019; Dragotto et al., 2025; Aroui et al., 2024; Pietsch & Salakhova, 2025; Hao & Zhou, 2025). The results from the DQS show that EuGB bonds perform better than GBP ICMA bonds on disclosure dimensions linked to credibility (Flammer, 2021; Zhu et al., 2024). Thus, the DQS analysis results confirm Proposition P1 ($p < 0.05$). The DQS gap is mainly explained by regulatory design, not by issuer type or sector, aligning with earlier findings that associate stronger disclosure and verification with greater credibility and pricing benefits (Zhu et al., 2024; Publications Office of the European Union, 2023; ICMA, 2025; Zerbib, 2019). However, the DQS covers Phase 1 only, meaning that even a perfect score fails to reflect MRV uncertainty in Phases 3 and 4, where uncertainty levels of 10–30% persist (Rodrigues et al., 2018; Marlowe & Clarke, 2022; Marsh et al., 2021).

Disclosure quality reaches further than pricing. It shapes sustainable investment decisions, ESG performance assessments, and capital allocation efficiency (Rodrigues Loiola et al., 2025; C. Liu & Wu, 2023). The EuGB framework imposes more stringent requirements at the issuance stage but does not yet address verification gaps in later phases (Flammer, 2021; Y. Liu et al., 2025). Practitioner evidence indicates that EuGB-certified bonds are associated with more stable greeniums and lower volatility (ABN AMRO, 2025a, 2025b, 2025c).

These findings align with signaling theory's prediction that credible, verifiable signals command a pricing premium and extend it by showing that the premium is determined by mandatory regulatory design rather than by voluntary issuer behavior (Pawlick et al., 2019; Jensen & Meckling, 1976). This distinction has direct implications for how disclosure regimes should be designed.

4.4. Policy Implications for the Carbon Economy

Carbon pricing mechanisms and green bonds are complementary instruments (Hafner et al., 2020). Evidence on environmental outcomes remains mixed; although some studies document reductions in carbon emission intensity linked to green bond financing, the effects are heterogeneous (Chen et al., 2024; Aswani & Rajgopal, 2025). Mandatory disclosure standards improve green bond market effectiveness by mitigating information asymmetry (Publications Office of the European Union, 2023; Flammer, 2020). Within the banking sector, mandatory reporting and EuGB adoption offer a route for greening banking practices and aligning lending portfolios with climate targets. Accountability in later lifecycle phases can only be strengthened by integrating digital and verification infrastructures into regulatory frameworks, including DLT-based traceability and Digital Product Passport mechanisms (Christodoulou et al., 2023; European Commission, 2026). Mandatory disclosure standards and digital verification infrastructures function as institutional mechanisms that reduce the informational advantage issuers hold over investors (Jensen & Meckling, 1976). The equilibrium shifts from pooling toward separation, without requiring individual investors to bear the cost of verification. The case studies confirm that the technologies needed for post-issuance verification exist: blockchain traceability, digital twin monitoring, and quantum sensing are all at pilot or prototype stage. The gap is not technological. It is institutional and regulatory.

4.5. Practical Implications

For regulatory authorities, the DQS enhances the binary EuGB compliance check under Regulation (EU) 2023/2631 by offering a more structured assessment ([Publications Office of the European Union, 2023](#)). For issuers, early adoption of Digital Product Passport infrastructure and digital twin systems can enhance disclosure consistency and lower compliance costs ([Siemens AG, 2024a](#); [European Commission, 2026](#)). Institutional investors managing ESG funds benefit from EuGB-certified portfolios with ESMA-accredited reviewers, which practitioner evidence links to more stable greeniums and lower volatility ([ABN AMRO, 2025a, 2025c](#)). This stability premium is not merely a function of label adoption but of the mandatory verification architecture that the EuGB framework imposes, a distinction that earlier research on greenium dynamics could not establish in the absence of an instrument capable of decomposing disclosure quality at the indicator level. The structural asymmetry between issuance-stage verification and post-issuance monitoring identified in this study suggests that EuGB certification should be treated as a necessary but not sufficient condition for lifecycle-wide accountability, and that ESG fund selection criteria should reflect verification quality across all lifecycle phases, not only at issuance. For retail investors, market access is facilitated through sustainability-linked bonds and indirect exposure channels based on advanced analytics ([Catalano et al., 2024](#); [HSBC Holdings plc & Sustainable Digital Finance Alliance, 2020](#)). The advanced verification framework points toward next-generation instruments in which coupon adjustments are linked to quantum-verified environmental data rather than to self-reported metrics, a development that could make the credibility premium transparent and accessible to retail investors without requiring specialized ESG analytical capacity. Prospective analyses point to rising interest in next-generation sustainable finance instruments combining regulatory disclosure with digital infrastructure and advanced analytics ([Natixis CIB, 2026](#); [TodayESG, 2026](#)).

For academic researchers, this study opens several theoretical and empirical pathways. The DQS instrument is replicable by design: its eight indicators are anchored in a publicly available regulatory text. Its scoring protocol is transparent, and its inter-rater reliability has been formally assessed. Researchers working on greenium dynamics gain an instrument capable of decomposing the credibility premium at the indicator level, a granularity that aggregate disclosure indices do not provide. The lifecycle model offers a theoretical lens for reconciling conflicting findings in the green bond literature. Studies reporting strong issuance-stage effects and studies finding weak post-issuance outcomes are not contradicting each other. They are measuring distinct phases of the same instrument. For researchers at the intersection of sustainable finance and measurement science, the advanced verification framework identifies a precise empirical agenda: testing whether quantum sensing delivers the precision gains suggested by the quantum Cramér–Rao bound under field conditions and whether QBER-based monitoring produces the separating equilibrium predicted by signaling theory. Both propositions are empirically testable, which means the framework generates a concrete research agenda rather than remaining at the level of theoretical speculation.

5. Conclusions

The central finding of this study is that improving green bond credibility requires moving beyond issuance focused disclosure toward lifecycle wide verification. While stronger regulation can raise minimum disclosure standards, the decisive constraint on credibility lies in unresolved verification gaps at the monitoring and impact stages, which can only be addressed through the integration of digital and physical verification infrastructures into the core architecture of green bond markets.

This paper offers an integrated analysis of green bonds that combines lifecycle theory, disclosure assessment, and emerging verification technologies to explain why credibility challenges persist despite rapid market growth. The four phase lifecycle model clarifies why strong signaling effects at issuance coexist with weak post issuance environmental outcomes, demonstrating that this pattern arises from a structural gap between disclosure and verification, with implications for sustainable investment allocation.

The DQS offers a simple and replicable instrument for assessing disclosure quality at the issuance stage. EuGB-certified bonds demonstrate higher disclosure quality than GBP ICMA-aligned bonds and this gap is driven by mandatory requirements related to EU taxonomy alignment, ESMA-registered external review, and compliance with the Do No Significant Harm principle. These findings have direct implications for sustainable investment screening and ESG fund selection.

The content analysis confirms that no study published prior to 2023 integrates regulatory compliance requirements with advanced verification mechanisms within a single analytical framework. Recent systematic reviews corroborate this fragmentation in the literature. This gap directly motivates the advanced lifecycle verification framework proposed in this paper.

The documentary case studies demonstrate that high disclosure quality at the issuance stage is achievable under current frameworks, while allocation traceability, ongoing monitoring, and impact linked financial feedback mechanisms remain fragmented or limited to a pilot stage.

The advanced verification framework demonstrates how physical sensing, secure data transmission, and smart-contract-based incentives can be integrated across the full bond lifecycle, shifting green bond verification from narrative disclosure toward lifecycle-wide accountability. By reducing information asymmetry at its source, this architecture addresses the core agency problem.

Several limitations should be acknowledged. The DQS analysis is based on a small sample and should be extended to larger cohorts of EuGB issuances. A second methodological limitation concerns the divergence in matched pair P2 (Eurogrid GmbH—EDF), exceeding the 3-year matching tolerance. This reflects the absence of comparable GBP ICMA issuances for TSO issuers in the 2025 European market following the entry into force of Regulation (EU) 2023/2631; therefore, the P2 comparison should be interpreted with caution. Further, documentary case studies rely on publicly available sources, which may not capture all implementation details. In addition, advanced verification architecture remains at the pilot stage, and their broader deployment depends on continued progress in quantum hardware and sensing technologies.

Four research directions follow directly from the limitations and findings of this study:

1. Large-scale testing of the relationship between the DQS and greenium using expanded EuGB datasets. The sample analyzed here captures a single issuance year in a nascent market segment. Panel data designs applied to expanding EuGB cohorts would test whether the DQS–greenium relationship holds across issuance cycles and whether it strengthens as the EuGB framework matures, and market participants become more familiar with its requirements. Testing the instrument in non-European markets would establish whether the disclosure dimensions that drive the gap under Regulation (EU) 2023/2631 carry equivalent weight in other regulatory environments. Hedonic pricing models offer the methodological precision needed to move from aggregate DQS scores to indicator-level estimates of greenium contribution.
2. Empirical comparisons between quantum and classical portfolio optimization methods applied to green bond portfolios. The 34% precision gain reported in bond trading establishes that quantum advantage in fixed income markets is no longer purely theo-

retical. What remains missing is a controlled comparison, one in which quantum and classical optimization methods are applied to identical green bond portfolios under standardized conditions. Designing such experiments around DQS-weighted ESG objectives, rather than just financial metrics, would test whether quantum optimization delivers superior outcomes precisely where environmental performance and investor returns need to be balanced simultaneously. Infrastructure for such comparisons is increasingly accessible, with multiple quantum computing platforms now available to academic researchers without requiring proprietary hardware investment.

3. Regulatory sandbox experimentation that links verified environmental data to dynamic coupon bond designs under supervisory oversight. Existing sandbox frameworks, like the ones in the United Kingdom, Singapore, and the European Union, provide structured environments for testing QBER-linked coupon adjustment mechanisms under supervisory oversight. A sandbox experiment could systematically compare investor behavior and greenium formation under static and dynamic coupon designs, generating the first empirical evidence on whether financial incentives linked to verified environmental performance alter issuer monitoring behavior. Such an experiment would directly test the separating equilibrium prediction of the advanced verification framework.
4. Extension of the DQS instrument beyond the issuance stage. The current instrument measures disclosure quality exclusively at Phase 1, leaving the allocation, monitoring, and impact phases without a comparable scoring tool. Developing Phase 2–4 equivalents, anchored in the allocation reporting, monitoring plan execution, and impact measurement requirements of Regulation (EU) 2023/2631, would enable lifecycle-wide disclosure quality assessment and allow researchers to test empirically whether issuance-stage DQS scores predict post-issuance verification quality. For regulators, a lifecycle-wide DQS would shift oversight from a one-time issuance check toward ongoing monitoring of disclosure quality at each phase of the instrument's life.

Author Contributions: Conceptualization, V.-S.N. and E.G.; methodology, V.-S.N.; software, V.-S.N.; validation, E.G. and I.I.; formal analysis, V.-S.N. and A.A.; investigation, V.-S.N. and A.A.; resources, E.G. and I.I.; data curation, E.G. and I.I.; writing—original draft preparation, V.-S.N.; writing—review and editing, E.G.; visualization, V.-S.N.; supervision, E.G. and I.I.; project administration, E.G. and I.I.; funding acquisition, E.G. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: The DQS scoring data, content analysis raw coding data, coding spreadsheets, and inter-rater reliability calculations underlying the results reported in this study are available from the corresponding author upon reasonable request. All summary statistics and processed values used in the tables are contained in the article.

Acknowledgments: This work was carried out within a grant of the Ministry of Research, Innovation and Digitization, CNCS—UEFISCDI, project number PN-IV-P1-PCE-2023-0679, within PNCDI IV. During the preparation of this manuscript, the authors used Microsoft 365 Copilot (version 2.20260602.20.0), Claude Sonnet 4.6, and Writefull for Word (version 2025.59.0) for the purposes of assisting for study design and structural reorganization of text sections, and to support grammatical revision and improvement of academic tone. The authors have reviewed and edited the output and take full responsibility for the content of this publication.

Conflicts of Interest: The authors declare that they have no conflicts of interest.

Abbreviations

The following abbreviations are used in this manuscript:

CBI	Climate Bonds Initiative
CH ₄	Methane
CO ₂	Carbon Dioxide
D1–D4	Thematic coding dimensions (content analysis)
DLT	Distributed Ledger Technology
DNSH	Do No Significant Harm
DQS	Disclosure Quality Score
ECB	European Central Bank
ESG	Environmental, Social, and Governance
ESMA	European Securities and Markets Authority
EuGB	European Green Bond (Standard)
GBP	Green Bond Principles (ICMA)
GHG	Greenhouse Gas
ICMA	International Capital Market Association
IFRS	International Financial Reporting Standards
IoT	Internet of Things
KPI	Key Performance Indicator
ML	Machine Learning
MRV	Measurement, Reporting, and Verification
NV	Nitrogen-Vacancy (Diamond Sensor)
QAQA	Quantum Approximate Optimization Algorithm
QBER	Quantum Bit Error Rate
QCRB	Quantum Cramér–Rao Bound
QFI	Quantum Fisher Information
QKD	Quantum Key Distribution
QVGB	Quantum-Verified Green Bond
SPO	Second Party Opinion
SWIAT	Shared Wholesale Infrastructure & Access Technology (blockchain platform)
TSO	Transmission System Operator
USD	United States Dollar
VQE	Variational Quantum Eigensolver

References

- A2A S.p.A. (2025, November 20). *Pre-issuance EU green bond review—European green bond factsheet* (External reviewer: Sustainable fitch). Available online: <https://content.gruppoa2a.it/sites/default/files/2025-11/pre-issuance-eu-gb-review.pdf> (accessed on 7 April 2026).
- ABN AMRO. (2025a, March 27). *ESG strategist: Green bonds exhibit lower volatility and higher liquidity* (Financial Markets & Sustainability Research). Available online: <https://www.abnamro.com/research/> (accessed on 7 April 2026).
- ABN AMRO. (2025b, October 16). *ESG strategist: Investigating commonly-cited factors of the greenium* (Financial Markets & Sustainability Research). Available online: <https://www.abnamro.com/research/> (accessed on 7 April 2026).
- ABN AMRO. (2025c, November 26). *ESG strategist: EuGBs outperform regular green bonds* (Research Note). Available online: <https://www.abnamro.com/research/> (accessed on 7 April 2026).
- ABN AMRO Bank N.V. (2025, February 14). *European green bond factsheet*. Available online: https://assets.ctfassets.net/1u811bvgvthc/2mKUOfOk6jp1eSYbm9qj0P/cd6973465c36bfbb3124e6d25673e445/250214_Green_Bond_Factsheet_-vF.pdf (accessed on 7 April 2026).
- Adekoya, O. B., Oliyide, J. A., Ghaemi Asl, M., & Jalalifar, S. (2021). Financing the green projects: Market efficiency and volatility persistence of green versus conventional bonds, and the comparative effects of health and financial crises. *International Review of Financial Analysis*, 78, 101954. [CrossRef]
- Ahmad, F., Boumaiza, A., Sanfilippo, A., & Al-Fagih, L. (2025). A detailed comprehensive role of digital technologies in green finance initiative for net-zero energy transition. *Advanced Energy and Sustainability Research*, 6(1), 2500066. [CrossRef]

- Arouri, M., Mhadhbi, M., & Shahrour, M. H. (2024). Dynamic connectedness and hedging effectiveness between green bonds, ESG indices, and traditional assets. *European Financial Management*, 31(5), 1704–1719. [CrossRef]
- Aswani, J., & Rajgopal, S. (2025). Rethinking the value and emission implications of green bonds. *Management Science*, 72(6), 4569–5489. [CrossRef]
- Barry, J. F., Schloss, J. M., Bauch, E., Turner, M. J., Har, C. A., Pham, L. M., & Walsworth, R. L. (2020). Sensitivity optimization for NV-diamond magnetometry. *Reviews of Modern Physics*, 92, 015004. [CrossRef]
- Barry, J. F., Steinecker, M. H., Alsid, S. T., Majumder, J., Pham, L. M., O’Keeffe, M. F., & Braje, D. A. (2024). Sensitive AC and DC magnetometry with nitrogen-vacancy-center ensembles in diamond. *Physical Review Applied*, 22, 044069. [CrossRef]
- BBVA Corporate & Investment Banking. (2025). *Green and social bond bulletin—September 2025*. Available online: <https://www.bbvacib.com/wp-content/uploads/2025/09/BBVA-Green-and-Social-Bond-Bulletin-September-2025.pdf> (accessed on 7 April 2026).
- Ben Ameur, H., Ftiti, Z., Louhichi, W., & Yousfi, M. (2024). Do green investments improve portfolio diversification? Evidence from mean conditional value-at-risk optimization. *International Review of Financial Analysis*, 94, 103255. [CrossRef]
- Bhagat, S., & Yoon, A. (2023). *Do green bonds actually lead to rosy returns?* Kellogg Insight. Available online: <https://insight.kellogg.northwestern.edu/article/do-green-bonds-actually-lead-to-rosy-returns> (accessed on 7 April 2026).
- Bhutta, U. S., Tariq, A., Farrukh, M., Raza, A., & Iqbal, M. K. (2022). Green bonds for sustainable development: Review of literature on development and impact of green bonds. *Technological Forecasting and Social Change*, 175, 121378. [CrossRef]
- Catalano, F., Nasello, L., & Guterding, D. (2024). Quantum computing approach to realistic ESG-friendly stock portfolios. *Risks*, 12, 66. [CrossRef]
- Chen, T., Yang, G., & Xu, T. (2024). The promoting effect of green bonds on reducing carbon emission intensity through energy structure transition. *Sustainability*, 16, 9318. [CrossRef]
- Christodoulou, P., Psillaki, M., Sklias, G., & Chatzichristofis, S. A. (2023). A blockchain-based framework for effective monitoring of EU green bonds. *Finance Research Letters*, 58, 104397. [CrossRef]
- Climate Bonds Initiative. (2025). *Global state of the green bond market 2025*. Available online: <https://www.climatebonds.net> (accessed on 7 April 2026).
- CoinDesk. (2024). *Siemens issues EUR 330M digital bond on private blockchain*. Available online: <https://www.coindesk.com/business/2024/09/04/siemens-issues-330m-digital-bond-on-private-blockchain-with-major-german-banks-including-deutsche-bank> (accessed on 7 April 2026).
- Creswell, J. W., & Creswell, J. D. (2023). *Research design: Qualitative, quantitative, and mixed methods approaches* (5th ed.). Sage.
- Degen, C. L., Reinhard, F., & Cappellaro, P. (2017). Quantum sensing. *Reviews of Modern Physics*, 89, 035002. [CrossRef]
- Dong, X., Xiong, Y., Nie, S., & Yoon, S.-M. (2023). Can bonds hedge stock market risks? Green bonds vs. conventional bonds. *Finance Research Letters*, 52, 103367. [CrossRef]
- Dragotto, M., Dufour, A., & Varotto, S. (2025). Greenium fluctuations and climate awareness in the corporate bond market. *International Review of Financial Analysis*, 105, 104281. [CrossRef]
- Dutta, A., & Pathak, A. (2024). Use of Nash equilibrium in finding game theoretic robust security bound on quantum bit error rate. *Physica Scripta*, 99, 095106. [CrossRef]
- Earth5r. (n.d.). *Green finance trends: Sustainable bonds and climate funds*. Available online: <https://earth5r.org/green-finance-trends-sustainable-bonds-climate-funds/> (accessed on 7 April 2026).
- EDF (Électricité de France). (2025a, April). *Green financing framework*. Available online: <https://www.edf.fr/sites/groupe/files/2025-05/2025-05-12-edf-green-bond-framework-2025-final.pdf> (accessed on 18 April 2026).
- EDF (Électricité de France). (2025b, April 30). *Senior green bond—EUR 2.25 billion multi-tranche issuance*. Press Release. Available online: <https://www.edf.fr/en/the-edf-group/dedicated-sections/journalists/all-press-releases/edf-announces-the-success-of-its-senior-green-multi-tranche-bond-issue-for-a-nominal-amount-of-225-billion-euros> (accessed on 18 April 2026).
- EFDData. (n.d.). *Environmental finance data—GSS+ bond market data*. Available online: <https://efdata.org/> (accessed on 7 April 2026).
- ENGIE S.A. (2025, September 9). *Final terms—Issue of €700,000,000 3.875% senior green notes due 11 September 2037 (Euro Medium Term Note Programme)*. Available online: <https://www.engie.com/en/finance/credit/green-finance> (accessed on 7 April 2026).
- ENGIE S.A. (2026, March). *Green financing framework*. Available online: <https://www.engie.com/en/finance/credit/green-finance> (accessed on 7 April 2026).
- ESMA. (n.d.). *External reviewers of European green bonds*. Available online: <https://www.esma.europa.eu/esmas-activities/investors-and-issuers/external-reviewers-european-green-bonds> (accessed on 7 April 2026).
- ESMA. (2021). *ESMA report on trends, risks and vulnerabilities No. 2, 2021 (ESMA50-165-1842)*. European Securities and Markets Authority. Available online: <https://www.esma.europa.eu/> (accessed on 7 April 2026).
- Eurogrid GmbH. (2025a). *Green bond reporting 2025*. Available online: <https://www.eurogrid.com/cdn/files/551a298e-f5ce-4b4a-23d1-08de9ed77c54/eurogrid%20greenbond%20report%202025.pdf> (accessed on 7 April 2026).

- Eurogrid GmbH. (2025b, September). *Green financing framework*. Available online: <https://www.eurogrid.com/en-us/Investor-Relations/Green-Financing> (accessed on 7 April 2026).
- European Central Bank. (2025, June). *Bridging innovation and stability: The Eurosystem's exploratory work on new technologies for wholesale central bank money settlement*. ECB Report. Available online: <https://www.ecb.europa.eu/press/pubbydate/2025/html/ecb.exploratoryworknewtechnologies202506.en.html> (accessed on 7 April 2026).
- European Commission. (2026). *Implementing the ecodesign for sustainable products regulation*. Available online: https://green-forum.ec.europa.eu/implementing-ecodesign-sustainable-products-regulation_en (accessed on 7 April 2026).
- Flaherty, M., Gevorkyan, A., Radpour, S., & Semmler, W. (2017). Financing climate policies through climate bonds—A three-stage model and empirics. *Research in International Business and Finance*, 42, 468–479. [CrossRef]
- Flammer, C. (2020). Green bonds: Effectiveness and implications for public policy. *Environmental and Energy Policy and the Economy*, 1, 95–128. [CrossRef]
- Flammer, C. (2021). Corporate green bonds. *Journal of Financial Economics*, 142, 499–516. [CrossRef]
- Flöttmann, C., Köchling, G., Neukirchen, D., & Posch, P. (2025). Green debt: A systematic literature review and future research agenda. *Management Review Quarterly*. [CrossRef]
- Gronwald, M., & Wadud, S. (2023). “My name is bond. Green bond.” Informational efficiency of climate finance markets. *Journal of Environmental Management*, 344, 118451. [CrossRef]
- Hafner, S., Jones, A., Anger-Kraavi, A., & Pohl, J. (2020). Closing the green finance gap—A systems perspective. *Environmental Innovation and Societal Transitions*, 34, 26–60. [CrossRef]
- Hammoudeh, S., Ajmi, A. N., & Mokni, K. (2022). Relationship between green bonds and financial and environmental variables: A novel time-varying causality. *Energy Economics*, 108, 105842. [CrossRef]
- Hao, Y., & Zhou, Y. (2025). Green bond issuance premium effect and investor incentive effect. *Finance Research Letters*, 85, 108042. [CrossRef]
- Herman, D., Googin, C., Liu, X., Sun, Y., Galda, A., Safro, I., & Pistoia, M. (2023). Quantum computing for finance. *Nature Reviews Physics*, 5, 450–465. [CrossRef]
- Horn, M., Dabbous, A., Oehler, A., & Göbel, F. (2025). Determinants and effects of green bond issuance: Environmental awareness, ecological budget, biodiversity, oil and lithium. *Ecological Economics*, 227, 108753. [CrossRef]
- HSBC Holdings plc. (2024). *Green financing framework 2024*. Available online: <https://www.hsbc.com/investors/fixed-income-investors/green-financing-framework> (accessed on 7 April 2026).
- HSBC Holdings plc. (2025, December). *Green bonds report 2025*. Available online: <https://www.hsbc.com/investors/fixed-income-investors/green-financing-framework> (accessed on 7 April 2026).
- HSBC Holdings plc & Sustainable Digital Finance Alliance. (2020). *Blockchain: Gateway for sustainability-linked bonds*. Available online: <https://www.greenfinanceplatform.org/research/blockchain-gateway-sustainability-linked-bonds> (accessed on 7 April 2026).
- Iberdrola Finanzas, S.A.U. (2025, May 16). *Bond-specific european green bond factsheet*. Available online: <https://www.iberdrola.com/documents/20125/42169/iberdrola-eu-gbs-bond-specific-factsheet.pdf> (accessed on 7 April 2026).
- ICE. (2024). *Sustainable bond report 2024*. Available online: <https://www.ice.com/insights/sustainable-bond-report-2024> (accessed on 7 April 2026).
- ICMA (International Capital Market Association). (2025, June). *Green bond principles: Voluntary process guidelines for issuing green bonds*. Available online: <https://www.icmagroup.org/sustainable-finance/the-principles-guidelines-and-handbooks/green-bond-principles-gbp/> (accessed on 7 April 2026).
- IFRS. (2024a). *IFRS S1 general requirements for disclosure of sustainability-related financial information*. Available online: <https://www.ifrs.org/issued-standards/ifrs-sustainability-standards-navigator/ifrs-s1-general-requirements/> (accessed on 7 April 2026).
- IFRS. (2024b). *IFRS S2 climate-related disclosures*. Available online: <https://www.ifrs.org/issued-standards/ifrs-sustainability-standards-navigator/ifrs-s2-climate-related-disclosures/> (accessed on 7 April 2026).
- ISS-Corporate. (2025a). *ISS-corporate leads reviews as EU GBS gains traction*. Available online: <https://www.iss-corporate.com/resources/blog/iss-corporate-leads-reviews-as-eu-gbs-gains-traction/> (accessed on 7 April 2026).
- ISS-Corporate. (2025b). *Sustainability quality of the issuer and European green bond factsheet: ABN AMRO bank N.V. pre-issuance review*. Available online: <https://spowidget.iss-corporate.com/icsspoapp/file/documents/spo/pre-issuance%20review-20250214-ABNAmro.pdf> (accessed on 7 April 2026).
- ISS-Corporate. (2025c). *Sustainability quality of the issuer's European green bond factsheet: Elia transmission Belgium (Pre-Issuance Review)*. Available online: <https://investor.eliagroup.eu/-/media/project/elia/shared/documents/elia-group/financial-position/european-green-bonds/iss-pre-issuance-review.pdf> (accessed on 7 April 2026).
- Jensen, M. C., & Meckling, W. H. (1976). Theory of the firm: Managerial behavior, agency costs and ownership structure. *Journal of Financial Economics*, 3, 305–360. [CrossRef]

- Karim, S., Lucey, B. M., Naeem, M. A., & Yarovaya, L. (2024). Extreme risk dependence between green bonds and financial markets. *European Financial Management*, 30, 935–960. [CrossRef]
- Li, Y., Yang, Z., & Dong, X. (2025). Green bond and greenwashing: New insights from Chinese firms. *Finance Research Letters*, 85, 107847. [CrossRef]
- Liu, C., & Wu, S. S. (2023). Green finance, sustainability disclosure and economic implications. *Fulbright Review of Economics and Policy*, 3, 1–24. [CrossRef]
- Liu, L., & Hu, Y. (2025). Green bond pricing: A comprehensive review of the empirical literature. *Journal of Risk and Financial Management*, 18, 689. [CrossRef]
- Liu, Q., Hu, Z., Yuan, H., & Yang, Y. (2024). Fully-optimized quantum metrology: Framework, tools, and applications. *Advanced Quantum Technologies*, 7, 2400094. [CrossRef]
- Liu, Y., Fu, S., Liu, G., & Huang, X. (2025). Green bond issuance and corporate environmental disclosure: Signaling or greenwashing? *Journal of Business Ethics*, 204, 825–854. [CrossRef]
- Lublóy, A., Keresztúri, J. L., & Berlinger, E. (2024). Quantifying firm level greenwashing: A systematic literature review. *Journal of Cleaner Production*, 469, 143053. [CrossRef]
- Marlowe, J., & Clarke, A. (2022). Carbon accounting: A systematic literature review and directions for future research. *Green Finance*, 4, 71–87. [CrossRef]
- Marsh, E., Orr, J., & Ibell, T. (2021). Quantification of uncertainty in product stage embodied carbon calculations for buildings. *Energy and Buildings*, 251, 111340. [CrossRef]
- Naeem, M. A., Farid, S., Ferrer, R., & Shahzad, S. J. H. (2021a). Comparative efficiency of green and conventional bonds pre- and during COVID 19: An asymmetric multifractal detrended fluctuation analysis. *Energy Policy*, 153, 112285. [CrossRef]
- Naeem, M. A., Nguyen, T. T. H., Nepal, R., Ngo, Q. T., & Taghizadeh Hesary, F. (2021b). Asymmetric relationship between green bonds and commodities: Evidence from extreme quantile approach. *Finance Research Letters*, 43, 101983. [CrossRef]
- Natixis CIB. (2026). 2026 sustainability outlook. Available online: <https://home.cib.natixis.com/articles/2026-sustainability-outlook> (accessed on 7 April 2026).
- Ørsted. (2025a). *Green finance impact report 2025*. Available online: <https://orsted.com/en/investors/debt/green-financing> (accessed on 7 April 2026).
- Ørsted. (2025b, May). *Green finance framework*. Available online: <https://orsted.com/en/investors/debt/green-financing> (accessed on 7 April 2026).
- Papavassiliou, E., Topaloglou, N., & Zenios, S. A. (2025). Do green bonds provide diversification benefits? The need for tax incentives. *Annals of Operations Research*. [CrossRef]
- Paudel, H. P., Lander, G. R., Crawford, S. E., & Duan, Y. (2024). Sensing at the nanoscale using nitrogen vacancy centers in diamond. *Nanomaterials*, 14, 675. [CrossRef]
- Pawlick, J., Colbert, E., & Zhu, Q. (2019). Modeling and analysis of leaky deception using signaling games with evidence. *IEEE Transactions on Information Forensics and Security*, 14, 1871–1886. [CrossRef]
- Pietsch, A., & Salakhova, D. (2025). Pricing of green bonds: Greenium dynamics and the role of retail investors. *Journal of International Financial Markets, Institutions and Money*, 104, 102211. [CrossRef]
- PricewaterhouseCoopers LLP. (2026). *Independent assurance report on HSBC green bond report 2025*. Available online: <https://www.hsbc.com> (accessed on 7 April 2026).
- Publications Office of the European Union. (2023). *Regulation (EU) 2023/2631 of the European Parliament and of the Council of 22 November 2023 on European Green Bonds and optional disclosures for bonds marketed as environmentally sustainable and for sustainability-linked bonds*. Publications Office of the European Union. Available online: <http://data.europa.eu/eli/reg/2023/2631/oj> (accessed on 7 April 2026).
- Reddy, N. R., Suryadevara, S., Reddy, K. G. R., Umamaheswari, R., Guttula, R., & Kotoju, R. (2025). Quantum secured blockchain framework for enhancing post quantum data security. *Scientific Reports*, 15, 31048. [CrossRef]
- Rehman, M. U., Zeitun, R., Vo, X. V., Ahmad, N., & Al Faryan, M. A. S. (2023). Green bonds' connectedness with hedging and conditional diversification performance. *Journal of International Financial Markets, Institutions and Money*, 86, 101802. [CrossRef]
- Rodrigues, J. F. D., Moran, D., Wood, R., & Behrens, P. (2018). Uncertainty of consumption-based carbon accounts. *Environmental Science & Technology*, 52, 7577–7586. [CrossRef]
- Rodrigues Loiola, R., Kimura, H., & Melo Souza, L. d. (2025). Sustainable finance, green bonds and financial performance—A literature review. *International Journal of Financial Studies*, 13, 233. [CrossRef]
- Schmittmann, J. M., & Gao, Y. (2022). Green bond pricing and greenwashing under asymmetric information. *MF Working Papers*, 2022(246), 1–40. [CrossRef]
- Shi, X., Ma, J., Jiang, A., Wei, S., & Yue, L. (2023). Green bonds: Green investments or greenwashing? *International Review of Financial Analysis*, 90, 102850. [CrossRef]

- Siemens AG. (2024a). *Sustainability report 2024*. Available online: <https://static.sw.cdn.siemens.com/siemens-disw-assets/public/1kCbvHXz8cNZx0PEuyFEbI/en-US/sustainability-report.pdf> (accessed on 7 April 2026).
- Siemens AG. (2024b, September). *Siemens remains a pioneer—Another digital bond successfully issued on blockchain*. Press Release. Available online: <https://press.siemens.com/global/en/pressrelease/siemens-remains-pioneer-another-digital-bond-successfully-issued-blockchain> (accessed on 7 April 2026).
- Siemens Energy. (2023). *Siemens energy successfully places EUR 1.5 billion green bond*. Press Release. Available online: <https://www.siemens-energy.com/us/en/home/press-releases/siemens-energy-successfully-places-eur-1-5-billion-green-bond.html> (accessed on 7 April 2026).
- Silva, F., Ferreira, A., & Cortez, M. C. (2024). The performance of green bond portfolios under climate uncertainty. *Research in International Business and Finance*, 70, 102354. [CrossRef]
- Sneideriene, A., & Legenzova, R. (2024). Greenwashing prevention in environmental, social, and governance (ESG) disclosures: A bibliometric analysis. *Journal of Cleaner Production*, 469, 143218. [CrossRef]
- SSE plc. (2025, December 10). *Sustainability financing framework*. Available online: <https://www.sse.com/media/fndlvccy/sses-sustainability-financing-framework-dec-2025-website-version.pdf> (accessed on 7 April 2026).
- Sustainable Fitch. (2025, November 20). *A2A S.p.A. pre-issuance review—European green bond assessment*. Available online: <https://www.gruppoa2a.it/en/investors/debt/sustainable-financing#factsheet> (accessed on 7 April 2026).
- Terna S.p.A. (2025). *European green bond factsheet 2025*. Available online: https://download.terna.it/terna/EuGB_Factsheet_Terna_8ddc30fc4902636.pdf (accessed on 7 April 2026).
- TodayESG. (2026). *CBI releases 2026 sustainable finance trends*. Available online: <https://www.todayesg.com/cbi-releases-2026-sustainable-finance-trends/> (accessed on 7 April 2026).
- Tolliver, C., Keeley, A. R., & Managi, S. (2020). Drivers of green bond market growth: The importance of nationally determined contributions to the Paris Agreement and implications for sustainability. *Journal of Cleaner Production*, 244, 118643. [CrossRef]
- Tu, C. A., Rasoulinezhad, E., & Sarker, T. (2020). Investigating solutions for the development of a green bond market: Evidence from analytic hierarchy process. *Finance Research Letters*, 34, 101457. [CrossRef]
- World Bank Treasury. (2025, February). *Labeled sustainable bonds market update—Issue No. 10*. Available online: <https://thedocs.worldbank.org/en/doc/cd82b4033281dab2cb1a1c71eeb691e4-0340012025/original/Labeled-Bond-Quarterly-Newsletter-Issue-No-10.pdf> (accessed on 7 April 2026).
- Zerbib, O. D. (2019). The effect of pro environmental preferences on bond prices: Evidence from green bonds. *Journal of Banking & Finance*, 98, 39–60. [CrossRef]
- Zhu, Q., Zhao, X., & Wu, M. (2024). Third-party certification: How to effectively prevent greenwash in green bond market? *Environment, Development and Sustainability*, 26, 16173–16199. [CrossRef]

Disclaimer/Publisher’s Note: The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.