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Sustainability Metrics and Disclosure Alignment in Blockchain Networks

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Abstract: The rapid growth of blockchain networks has raised concerns about their environmental sustainability, yet existing assessments are fragmented and often rely on problematic metrics or unverifiable self-reported data. This article addresses these gaps by combining quantitative measures of annual energy consumption and carbon emissions with a qualitative assessment of sustainability initiatives. Using data from the Crypto Carbon Ratings Institute (CCRI) and corporate sustainability reports, we evaluate Bitcoin, Ethereum, Binance Chain, XRP, Cardano, Solana, Dogecoin, Polygon, and Polkadot, and benchmark their operational footprints against those of Visa and Mastercard as representatives of traditional payment systems. Results show wide variation in sustainability performance: Proof-of-Stake networks exhibit substantially lower energy use and carbon intensity than Proof-of-Work systems, while transparency and reporting practices differ significantly across projects. This research contributes to the sustainability discourse by providing one of the first systematic comparisons between blockchain networks and incumbent payment systems, identifying methodological challenges in sustainability accounting, and advancing policy recommendations for standardized reporting, third-party verification, and energy-efficient design.

Keywords: Blockchain sustainability, Eco-friendly cryptocurrencies, Proof of Stake (PoS), Energy consumption, Carbon footprint.

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1. Introduction

This research addresses the critical need to evaluate the environmental impact of leading blockchain networks that underpin widely adopted cryptocurrencies. By examining a curated selection of major blockchain platforms – chosen for their technological relevance, market influence, and diversity in consensus mechanisms – this study provides a comprehensive assessment of their ecological footprints, sustainability initiatives, and potential for environmental improvement. The findings offer valuable insights for developers, investors, policymakers, and users seeking to make informed decisions about sustainable blockchain adoption and development.

2. Literature Review

The environmental impact of blockchain technology, particularly regarding energy consumption, has been a subject of significant scholarly attention. Alshahrani et al. [1] conducted a systematic literature review on two major sustainability issues in blockchain: power consumption and scalability. Their research highlighted that the proof of work (PoW) consensus mechanism, used by Bitcoin and initially by Ethereum, requires intensive computational work resulting in high energy consumption. They noted that Bitcoin's annual energy usage exceeds 100 TWh, comparable to the electricity consumption of small nations. This finding aligns with data from the Cambridge Centre for Alternative Finance [2], which continues to track Bitcoin's substantial energy footprint through its Bitcoin Electricity Consumption Index.

Elsayed et al. [3] provide a comprehensive analysis of blockchain energy consumption challenges, emphasizing that, besides the technological benefits, significant concerns exist regarding the high energy consumption associated with blockchain operations. Their research explores alternative consensus techniques such as proof of stake (PoS) and delegated proof of stake (DPoS) as viable solutions to address the blockchain resource consumption challenge while maintaining the integrity and security of blockchain networks.

Previous comparative analyses, including early benchmark-based assessments of blockchain sustainability, have highlighted substantial disparities across consensus mechanisms and reporting practices [4].

2.1. Transition to More Sustainable Consensus Mechanisms

A significant development in blockchain sustainability has been Ethereum's transition to Proof of Stake (PoS) in 2022, which reduced its energy consumption by over 99 % [5]. This transition demonstrates the feasibility of achieving both scalability and sustainability in blockchain networks. Alshahrani et al. [1] emphasized that PoS-based networks like Cardano and Ethereum 2.0 validate transactions with minimal energy requirements, positioning them as significantly more sustainable alternatives to PoW systems.

2.2. Scalability Challenges and Solutions

Scalability represents another critical sustainability challenge for blockchain technology. Alshahrani et al. [1] identified that blockchain faces scalability problems when a large number of nodes and transactions are added to the network. Transaction throughput and transaction latency are the two major contentious performance metrics in blockchain systems, with most public blockchains yet to reach acceptable Quality of Service (QoS) standards.

Innovative approaches to address scalability include Layer 2 solutions, such as Ethereum's rollups and Polygon's scaling framework, which mitigate energy use through off-chain processing [1]. Additionally, Solana's combination of PoS with Proof of History (PoH) achieves high TPS with minimal energy use, demonstrating how architectural innovations can simultaneously address both scalability and sustainability concerns.

2.3. Critiques of 'Green' Claims and Offsets

A growing body of research cautions that headline claims of "carbon-neutral" or "renewable-powered" cryptocurrencies often rely on unverifiable surveys, renewable energy certificates (RECs), or carbon offsets, raising concerns of potential greenwashing. An MIT CEEPR analysis of publicly listed U.S. Bitcoin miners found that their carbon intensity broadly aligned with the U.S. grid average, contradicting industry survey claims of majority "sustainable" power and recommending dual-reporting under the GHG Protocol to avoid misuse of market-based instruments [8]. Similarly, the latest Cambridge Digital Mining Industry Report stresses the need for greater transparency in sustainability reporting and highlights persistent uncertainties in estimating the actual energy mix of PoW networks [10]. Beyond these power-mix debates, scholars emphasize that reliance on renewables, RECs, or offsets cannot resolve the structural energy intensity of Proof-of-Work systems and may obscure associated challenges such as electronic waste and rebound effects [9, 11]. Investigations into voluntary carbon credit markets – often used by blockchain projects to claim carbon neutrality – have also revealed widespread over-crediting and integrity concerns, underscoring the risks of greenwashing and the need for stronger standards [12].

2.4. Sustainability Disclosure, ESG Reporting, and Standardization Gaps

Despite the growing attention to the environmental impacts of blockchain systems, sustainability disclosure practices across cryptocurrency networks remain highly fragmented and inconsistent. Unlike traditional corporations, which increasingly operate under structured ESG reporting regimes, blockchain projects typically rely on voluntary disclosures issued by foundations, mining pools, or affiliated entities. These disclosures vary widely in scope, boundary definitions, and methodological assumptions, and are rarely subject to independent assurance. As a result, cross-chain comparisons are difficult and, in some cases, misleading, reinforcing information asymmetries for investors, regulators, and other stakeholders attempting to assess the environmental performance of blockchain networks [2, 5].

A central challenge underlying these disclosure inconsistencies is the accounting mismatch between operational energy use and reported sustainability claims. Many blockchain projects emphasize "carbon neutrality" through renewable energy certificates (RECs) or voluntary carbon offsets, yet such instruments do not necessarily correspond to reductions in actual energy consumption or network-level emissions. Prior research has shown that reliance on market-based instruments can obscure the structural energy intensity of Proof-of-Work systems, introduce risks of double counting, and weaken the credibility of sustainability claims when underlying emissions remain high [9, 11]. Empirical investigations into voluntary carbon markets have further raised concerns about over-crediting and limited environmental additionality, underscoring the risk of greenwashing when offsets are used without transparent and auditable reporting frameworks [12].

These limitations highlight the need for standardized sustainability reporting approaches that enable comparability across heterogeneous blockchain architectures. In corporate contexts, established frameworks such as the GHG Protocol emphasize consistent system boundaries, separation of gross emissions from offsetting activities, and the use of verifiable, decision-useful metrics. More recently, regulatory initiatives such as the European Union's Corporate Sustainability Reporting Directive (CSRD) and the IFRS International Sustainability Standards Board (ISSB) standards have reinforced the importance of harmonized disclosure and third-party assurance in sustainability reporting. Comparable, widely adopted standards have yet to emerge for blockchain systems, constraining both academic analysis and evidence-based policymaking in the digital infrastructure domain [5, 13].

In response to these disclosure and standardization gaps, this study adopts a comparative framework grounded in operational, gross energy consumption and carbon emissions metrics derived from a consistent third-party data source, complemented by a qualitative assessment of publicly disclosed sustainability initiatives. By excluding offset-based neutrality claims from the quantitative analysis and prioritizing annual network-level energy use and emissions, the approach emphasizes transparency and cross-chain comparability. This design directly addresses the reporting limitations identified in the literature and provides a more robust basis for evaluating the sustainability implications of different consensus mechanisms and network designs, thereby motivating the methodological choices detailed in the following section.

3. Methodology

This study employs a mixed-methods approach to evaluate the sustainability of blockchain networks underlying a selection of widely adopted and technologically diverse cryptocurrencies. The research combines quantitative analysis of energy consumption and carbon emissions data with qualitative assessment of sustainability initiatives and technological innovations. This comprehensive approach enables a holistic evaluation of blockchain sustainability that goes beyond mere energy metrics.

3.1. Data Collection Methods

Data for this study were collected from multiple sources to ensure accuracy and comprehensiveness:

1. Academic Literature: Peer-reviewed research on blockchain sustainability, energy consumption, and environmental impact;
2. Industry Reports: Reports from specialized blockchain analytics firms, environmental organizations, and sustainability consultancies;
3. Public Disclosures: Sustainability reports, carbon footprint disclosures, and environmental initiatives announced by blockchain foundations and development teams;
4. Energy Consumption Indices: Data from established tracking platforms such as the Cambridge Bitcoin Electricity Consumption Index [2].

While multiple sources were reviewed to ensure comprehensiveness, the quantitative dataset is standardized on the CCRI 2025 indices [14] to maintain methodological consistency across blockchains. Other sources, including Digiconomist [6] and CBECI [2], were used only for triangulation and context; their published estimates (e.g., Bitcoin's annual electricity use ranging from ~120–190 TWh) fall within the same order of magnitude as CCRI [14], reinforcing confidence in the dataset.

3.2. Evaluation Framework (Selected Metrics)

Consensus Mechanism: The consensus mechanism is a critical determinant of blockchain sustainability, influencing both energy efficiency and decentralization. This study categorizes blockchains based on Proof of Work (PoW), Proof of Stake (PoS), Delegated Proof of Stake (DPoS), and hybrid models. PoW blockchains, such as Bitcoin, require intensive computational work, resulting in high energy consumption and carbon emissions. In contrast, PoS-based networks, such as Ethereum 2.0, Cardano, and Solana, validate transactions with minimal energy requirements.

Energy consumption: Energy use is a direct measure of a blockchain's environmental impact. PoW blockchains, particularly Bitcoin, consume exponentially more electricity than PoS or hybrid models [2]. Bitcoin's annual energy usage exceeds 100 TWh, comparable to the electricity consumption of small nations. Ethereum's transition to PoS in 2022 reduced its energy consumption by over 99 %. Post-Merge estimates vary by method; this article adopts CCRI's bottom-up value (≈0.0046 TWh/year)

[14], while acknowledging higher top-down figures reported elsewhere [5]. This discrepancy underscores the need for standardized methodologies in blockchain energy-use measurement, an issue increasingly emphasized in European blockchain policy discussions [7].

Carbon Footprint: We assess carbon impact using gross annual CO_2 emissions derived from energy consumption and grid-intensity factors. PoW networks tend to have higher emissions due to their dependence on energy-intensive mining operations, while PoS-based networks, like Cardano and Tezos, show substantially lower footprints due to their energy-efficient validation processes. In line with our methodology, we exclude per-transaction metrics (energy or CO_2) and do not net out offsetting claims. Reported neutrality programs (e.g., by the Cardano Foundation and Polygon Labs) are therefore excluded from the quantitative dataset to ensure comparability; instead, such sustainability initiatives (e.g., renewable procurement, offset programs) are reviewed qualitatively in Section 2.3.

Visa's 2023 Corporate Responsibility & Sustainability Report documents an annual energy consumption of 841000 gigajoules (GJ) in fiscal year 2023, equivalent to 0.234 TWh using the conversion factor (1 TWh = 3.6×10^6 GJ) [15]. The same report records 10600 metric tons of CO_2 equivalent (tCO_2e) in combined Scope 1 and Scope 2 emissions, corresponding to 0.011 $MtCO_2e$ when expressed in megatons [15]. In addition, Visa's 2023 CDP Climate Change Response (Section C6.5) provides a category-level disclosure of Scope 3 emissions, including 369200 tCO_2e from purchased goods and services. When all categories are summed, Visa's Scope 3 footprint totals approximately 409500 tCO_2e (≈ 0.410 $MtCO_2e$) [16]. To ensure methodological consistency with blockchain data – which typically covers only direct energy-related Scope 1 and 2 emissions – our quantitative comparison tables use Visa's Scope 1+2 total (0.011 $MtCO_2e$), while the substantially larger Scope 3 emissions are discussed qualitatively.

Mastercard's 2024 Impact Report (covering calendar year 2023) discloses a total electricity consumption of 107023 megawatt-hours (MWh) [17]. Applying the conversion factor 1 MWh = 3.6 gigajoules (GJ), this equals 385283 GJ, which in turn corresponds to 0.107 TWh using the standard relationship 1 TWh = 3.6×10^6 GJ. The same report records 52054 metric tons of CO_2 equivalent (tCO_2e) in combined Scope 1 and Scope 2 emissions, which equals 0.052 $MtCO_2e$ when expressed in megatons [16]. Mastercard additionally provides Scope 3 data in its disclosures, with values that substantially exceed Scope 1+2 emissions. However, for comparability with blockchain networks – whose reported carbon footprints reflect only operational and electricity-related emissions – our quantitative tables include only Mastercard's Scope 1+2 total (0.052 $MtCO_2e$). The broader implications of Mastercard's Scope 3 footprint are addressed in the discussion section.

A key limitation of this study is the partial reliance on industry self-reports and disclosures from blockchain foundations, mining firms, and sustainability consortia. While these sources provide valuable data and insights, they are often voluntary, unaudited, and potentially influenced by reputational or market incentives. Prior critiques of sustainability claims in blockchain highlight risks of selective reporting, inconsistent methodologies, and even greenwashing [8, 10, 12]. To mitigate this, we cross-referenced self-reported data with independent indices and academic studies whenever possible, but acknowledge that industry disclosures may not always reflect full lifecycle impacts or provide standardized metrics.

For cross-chain comparability, annual energy and carbon figures are taken from the Crypto Carbon Ratings Institute (CCRI) indices (2025) using a consistent bottom-up methodology. Alternative estimates (e.g., Digiconomist; EU Blockchain Observatory summaries) may differ due to methodological assumptions; this study standardizes on CCRI for consistency.

4. Comparative Results

To enable fair comparison across blockchains of different sizes and transaction volumes, raw annual energy consumption (TWh) and annual carbon emissions (Mt CO_2) from CCRI [14] were used directly as inputs to the scoring framework.

The comprehensive analysis of selected leading cryptocurrencies reveals several key findings regarding blockchain sustainability:

1. Consensus Mechanism Dominance: Consensus mechanism emerges as the primary determinant of blockchain sustainability, with PoS and its variants demonstrating dramatically lower environmental impact than PoW systems;
2. Scalability-Sustainability Correlation: Higher transaction throughput generally correlates with better aggregate energy utilization at the network level;
3. Sustainability Initiative Effectiveness: Formal sustainability programs, particularly carbon offset initiatives, significantly improve overall environmental profiles, even for already efficient blockchains;
4. Transition Feasibility: Ethereum's successful transition from PoW to PoS demonstrates that even established blockchains can implement fundamental sustainability improvements without compromising security or decentralization;
5. Transparency Variations: Significant disparities exist in sustainability reporting and transparency across blockchain networks, with newer, purpose-built networks generally providing more comprehensive environmental disclosures.

Table 1. Annual energy consumption (TWh) and carbon emissions ($MtCO_2e$) of major blockchain networks and traditional payment systems.

Cryptocurrency/Payment System	Annual Energy Consumption (TWh)	Annual Carbon Emissions (Mt CO_2)
Bitcoin (BTC)	169.5	69.0
Ethereum (ETH)	0.0046	0.0014
XRP (XRP)	0.00049	0.00020
BNB Chain (BNB)	0.00021	0.00007
Solana (SOL)	0.018	0.0057
Cardano (ADA)	0.00048	0.00016
Polygon (MATIC)	0.00021	0.00005
Polkadot (DOT)	0.00103	0.00031
Dogecoin (DOGE)	9.0	3.7
Visa (2023)	0.234	0.011
Mastercard (2023)	0.107	0.052

Source: Blockchain data from CCRI (2025) [14]. Visa and Mastercard data from corporate sustainability reports [15-17].

Visa and Mastercard are included as non-blockchain benchmarks for energy and carbon comparison. They are not scored in Table 2 since consensus and scalability metrics are not applicable to centralized payment networks.

The overall sustainability ranking in Table 2 was derived using a weighted scoring framework. We assigned weights to five sustainability metrics based on their relative environmental importance: Consensus mechanism = 30 %; Energy consumption = 25 %; Carbon footprint = 20 %; Scalability = 15 %; and Sustainability efforts = 10 %. Each blockchain was given a score from 1 (worst) to 10 (best) for every metric. The bands were defined a priori: Consensus mechanism: PoW (1–2), hybrid (5–6), PoS (7–8), optimized PoS (9–10); Energy: >100 TWh/year = 1–2; ≤0.02 TWh/year = 9–10. Carbon: > 50 Mt CO_2/year = 1–2; ≤0.006 Mt CO_2/year = 9–10; Scalability: <10 TPS = 1–2, >10000 TPS = 9–10; Sustainability efforts: no initiatives = 1–2, carbon-negative verified = 9–10. Within each broad band (e.g., 9–10), the exact score was assigned by relative ranking across chains.

The overall score for each blockchain was computed as:

$$\begin{gathered} Overall\ Score = \\ = (Consensus \times 0.30) + \\ + (Energy \times 0.25) + (Carbon \times 0.20) + \\ + (Scalability \times 0.15) + \\ + (Sustainability\ Efforts \times 0.10) \end{gathered} \tag{1}$$

For example, Solana (PoS/PoH) scored: Consensus = 9, Energy = 10, Carbon = 9, Scalability = 10, Sustainability Efforts = 8. Therefore, Solana (PoS/PoH) yields: $(9 \times 0.30) + (10 \times 0.25) + (9 \times 0.20) + (10 \times 0.15) + (8 \times 0.10) = 9.30$.

This computation was repeated for each blockchain. The resulting weighted scores produced the ranking in Table 2.

As shown in Table 2, blockchains adopting energy-efficient consensus mechanisms and proactive sustainability strategies (e.g., Solana, Polygon, Cardano) achieve higher overall sustainability scores compared to Proof-of-Work networks with limited environmental measures (e.g., Bitcoin, Dogecoin) [14].

Table 2. Overall Sustainability Ranking of Top Cryptocurrencies (2025).

Cryptocurrency	Weighted Score	Rank
Solana (SOL)	9.30	1
Polygon (MATIC)	9.00	2
Cardano (ADA)	8.60	3
Polkadot (DOT)	8.10	4
XRP (XRP)	8.00	5
Ethereum (ETH)	7.90	6
Binance (BNB)	6.55	7
Dogecoin (DOGE)	3.65	8
Bitcoin (BTC)	1.25	9

Source: Calculated by authors using weighted score formula integrating all five-sustainability metrics.

Although Dogecoin is derived from Bitcoin's original codebase and employs a Proof-of-Work consensus mechanism, its sustainability ranking differs from Bitcoin's due to material differences in network scale and operational footprint. In particular, Dogecoin operates at a substantially lower aggregate hash rate and benefits from auxiliary merged mining with Litecoin, allowing portions of its security to be obtained without proportional increases in energy consumption. As a result, Dogecoin's annual electricity use and carbon emissions remain significantly lower than those of Bitcoin, despite sharing a similar consensus design. Empirical evidence shows that Bitcoin alone accounts for roughly two-thirds of the total energy consumed by mineable cryptocurrencies, with the remaining networks (including Dogecoin) representing a smaller share of overall consumption [18]. The ranking framework used in this study evaluates sustainability based on absolute operational impacts rather than protocol ancestry, and therefore distinguishes between Proof-of-Work networks according to their realized energy and emissions profiles. This explains why

Dogecoin, while still ranking poorly overall, scores marginally higher than Bitcoin in Table 2.

5. Discussion

Fig. 1 illustrates the magnitude of structural differences in energy consumption across blockchain networks and payment systems, reinforcing that sustainability outcomes are dominated by consensus design rather than incremental operational adjustments.

The findings of this research highlight the complex interplay between technological design choices, operational practices, and environmental outcomes in blockchain networks. The study found that decision-makers and practitioners often struggle to understand the underlying mechanisms of blockchain and its sustainability outcomes, creating barriers to adoption for **sustainability purposes.**

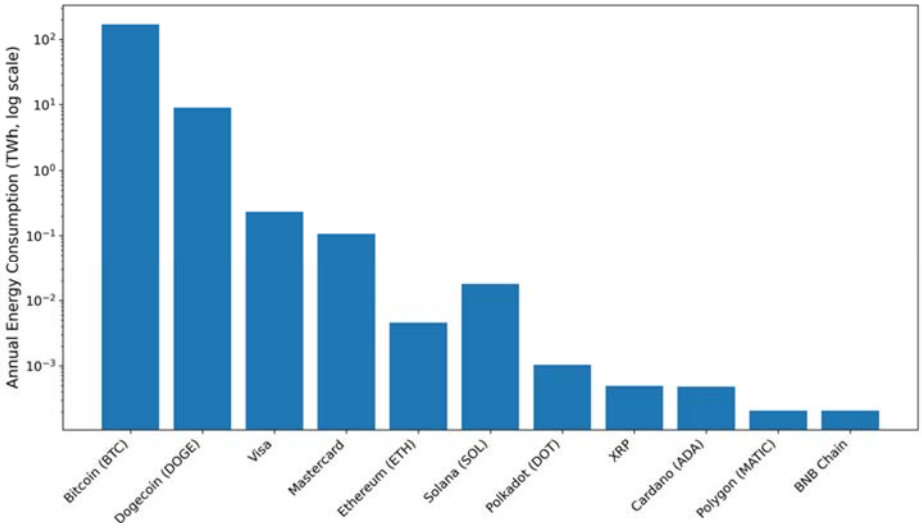

Fig. 1. Annual energy consumption of blockchain networks and traditional payment systems (log scale).

Visa and Mastercard were included in Table 1 as non-blockchain benchmarks to contextualize the relative scale of blockchain energy use and emissions. Their values provide a point of comparison with incumbent global payment systems but are not integrated into the composite sustainability ranking (Table 2), since blockchain-specific metrics such as consensus mechanism and scalability are not applicable to centralized networks.

5.1. Implications for Sustainability Disclosure and Regulatory Reporting (Signaling and Information Asymmetry)

The results indicate that sustainability performance across blockchain networks is primarily driven by structural design choices, most notably the underlying consensus mechanism, rather than by discretionary sustainability initiatives or offset-based commitments. Networks operating under Proof-of-Stake architectures consistently exhibit substantially lower operational energy consumption and carbon emissions than Proof-of-Work systems, regardless of scale or market capitalization. This pattern suggests that protocol-level design decisions exert a dominant influence on environmental outcomes, while post hoc mitigation strategies play a secondary role. Consequently, observed differences in sustainability performance reflect inherent architectural characteristics rather than short-term managerial or reputational interventions.

While sustainability disclosures are increasingly used by blockchain projects to signal environmental responsibility, the extent to which such disclosures align with observed operational environmental impacts remains unclear. To illustrate this alignment–misalignment dynamic, Table 3 juxtaposes publicly communicated sustainability claims with independently estimated operational energy use and emissions derived from third-party data sources. This comparison highlights how differences in disclosure practices, boundary definitions, and the treatment of offsets affect the credibility and comparability of sustainability signals across networks.

Table 3 reveals substantial heterogeneity in the alignment between sustainability disclosures and observed environmental impacts across blockchain networks. Projects with low operational footprints but fragmented or narrative-driven disclosures exhibit moderate alignment, whereas networks with high absolute energy consumption and limited standardized reporting display pronounced disclosure gaps. Conversely, platforms that explicitly communicate operational reductions – particularly following structural changes such as consensus mechanism transitions – show higher directional alignment, even when absolute impacts remain non-negligible. These patterns reinforce the argument that disclosure credibility depends not only on performance outcomes but also on the standardization, transparency, and auditability of reported sustainability information.

Table 3. Alignment between blockchain sustainability disclosures and observed operational environmental impacts.

Network	Project sustainability disclosure (what they claim)	Observed operational impact (CCRI via MiCA disclosure)	Alignment
Bitcoin (BTC)	No protocol-level standardized sustainability disclosure is provided by the network itself (typical info is ecosystem- or miner-driven rather than a single issuer disclosure) [19].	Energy consumption: **165002667937 kWh/yr**; Scope 2 emissions: **67597922605 tCO2e/yr [19].**	**Low alignment / disclosure gap:** very large observed footprint + no unified project disclosure.
Dogecoin (DOGE)	No unified foundation-level sustainability disclosure appears as a standard reporting artifact comparable to ESG/CSRD/ISSB-style reporting [20].	Energy consumption: **8562992922 kWh/yr**; Scope 2 emissions: **3626830.160 tCO2e/yr [20, 18].**	**Low alignment / disclosure gap:** PoW footprint is material; limited standardized disclosure.
Ethereum (ETH)	Publicly states PoS transition reduced energy use by **~99.95 %** (Merge) and provides an energy consumption page (PoS-era) [2829].	Energy consumption: **4177274.115 kWh/yr**; Scope 2 emissions: **1293.391 tCO2e/yr [21]**.	**High alignment (directionally):** disclosure emphasizes sharp reduction; observed estimates are orders of magnitude below PoW systems.
Polygon (PoS chain / "Polygon")	Announces a plan to become **carbon negative** (via offset/credits strategy + funding commitments) [31].	Energy consumption (MiCA): **183582.888 kWh/yr**. Independent CCRI update estimates Polygon post-Merge total annualized emissions **~55 tCO2e/yr [25, 32].**	**Partial alignment:** observed operational impacts are low, but the "carbon negative" claim relies on offset framing; comparability depends on separating gross emissions vs offsets.
Solana (SOL)	Publishes "Energy Impact / Energy Use" reports and discusses offset instruments (carbon credits, biodiversity credits) [30].	MiCA disclosure indicates renewable share and Scope 2 emissions (example snapshot): Scope 2 emissions: **4856.208 tCO2e/yr** (and renewable share reported) [26].	**Mixed/partial alignment:** disclosure is active and detailed, but the inclusion of offsets can confuse "impact" vs "net claims" unless reported separately.
Cardano (ADA)	No single, universally-used sustainability reporting artifact comparable to corporate ESG standards is consistently used across the ecosystem (disclosures tend to be scattered across entities) [22].	Energy consumption: **497956.700 kWh/yr**; Scope 2 emissions: **172.337 tCO2e/yr [22].**	**Moderate alignment:** observed footprint is low; the main issue is **standardization/assurance** rather than performance.
Polkadot (DOT)	Project-facing claims often emphasize efficiency, but formal standardized sustainability disclosure is not always presented in the same way across venues [23].	Energy consumption: **1028091.344 kWh/yr**; Scope 2 emissions: **311.963 tCO2e/yr [23].**	**Moderate alignment:** observed footprint is low; the remaining gap is disclosure consistency and auditability.
XRPL (XRP Ledger)	Sustainability statements are typically communicated through Ripple/corporate sustainability positioning and goals, not always a protocol-level standardized reporting package [24].	Energy consumption: **476747.129 kWh/yr**; Scope 2 emissions: **189.302 tCO2e/yr [24].**	**Moderate alignment:** low footprint, but disclosure is more "narrative + targets" than standardized operational reporting.
BNB Chain (BNB)	Often referenced via exchange/corporate sustainability communications; protocol-level standardized disclosures are inconsistent across channels [27].	Energy consumption: **269175.594 kWh/yr [27].**	**Moderate alignment (limited):** operational estimate is low, but disclosure standardization is thin (and emissions fields may not be consistently published in the same format).

Source: Markets in Crypto-Assets Regulation (MiCA) sustainability disclosures issued by Coinbase Luxembourg S.A. [19-27]; Ethereum Foundation disclosures [28, 29]; Solana Foundation energy report [30]; Polygon sustainability disclosures and CCRI assessment [31, 32]; comparative energy context from Gallersdörfer et al. [18].

These findings carry direct implications for regulatory and policy design. A minimum sustainability disclosure baseline for public blockchain networks should require reporting of: (i) annual network electricity consumption (TWh) and estimation methodology; (ii) annual gross carbon emissions

($MtCO_2e$) and underlying grid-intensity assumptions; (iii) clear system boundary definitions and treatment of uncertainty; (iv) energy mix claims supported by auditable evidence; (v) offsets and renewable energy certificates disclosed separately from gross emissions (gross versus net reporting); (vi) governance responsibility for sustainability reporting, including reporting frequency and accountability; and (vii) independent third-party assurance of key metrics. Such requirements directly address greenwashing risks identified in the literature and would improve transparency and comparability across networks, enabling regulators and market participants to evaluate sustainability performance using decision-useful information [10, 12].

Looking forward, the convergence of sustainability reporting standards in corporate contexts suggests a plausible trajectory toward analogous disclosure expectations for blockchain infrastructure, particularly as crypto-assets increasingly intersect with regulated financial markets. As institutional investors, exchanges, and custodians integrate sustainability considerations into screening and risk management processes, standardized and assured disclosure may become a prerequisite for market access and legitimacy. In this context, the development of harmonized blockchain sustainability reporting frameworks – aligned with emerging international disclosure standards – would enable longitudinal monitoring of technological transitions and their environmental effects, while supporting evidence-based policymaking and future research on sustainable digital infrastructure.

6. Conclusion

This comparative analysis of blockchain sustainability across selected leading cryptocurrency networks reveals significant disparities in environmental impact, with the consensus mechanism emerging as the primary determinant of overall sustainability. By prioritizing sustainability in both technical design and operational practices, the blockchain industry can minimize its environmental footprint while continuing to deliver transformative benefits across numerous sectors. The best practices identified in this research provide a roadmap for achieving this balance between innovation and environmental responsibility.

Future research should explore emerging consensus mechanisms and their environmental implications, standardized approaches to blockchain sustainability measurement, and the potential integration of blockchain with complementary technologies such as renewable energy systems and carbon markets. Additionally, longitudinal studies tracking the evolution of blockchain sustainability over time would provide valuable insights into the effectiveness of various improvement strategies.

This study provides an initial benchmark by comparing blockchain networks with the operational footprints of major global payment systems (Visa and Mastercard), included in Table 1. Future research should extend these comparisons to cover the full lifecycle energy costs of credit card transactions, debit card transactions, and physical fiat transactions, thereby providing a more comprehensive benchmark for evaluating blockchain systems against traditional payment methods. Based on these findings, regulators and industry stakeholders should prioritize the development of standardized sustainability reporting frameworks for blockchain projects, aligned with established initiatives such as the GHG Protocol and emerging EU analyses [7, 8]. Independent third-party verification of energy use and carbon offset claims is essential to mitigate greenwashing risks [10, 12]. In parallel, policymakers should incentivize transitions toward energy-efficient consensus mechanisms (e.g., PoS) and encourage adoption of credible renewable energy procurement. Establishing minimum disclosure requirements – covering energy consumption, carbon footprint, governance, and sustainability initiatives – would enhance transparency, comparability, and trust across blockchain networks, thereby supporting responsible investment and long-term industry legitimacy.

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