



Energy Consumption of Blockchains: A Comparative Study of Bitcoin, Ethereum, and Solana

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Abstract: Concerns about the environmental impact of blockchain networks have driven research and industry action to measure and reduce energy consumption. This paper compares the energy footprints of three widely discussed networks — **Bitcoin** (Proof-of-Work), **Ethereum** (Proof-of-Stake after the 2022 Merge), and **Solana** (high-throughput Proof-of-Stake/PoH variant) — using published energy estimates and per-transaction metrics from authoritative sources. Results show orders-of-magnitude differences: Bitcoin’s network-level electricity use is measured in **tens to hundreds of terawatt-hours per year**, while Ethereum (post-Merge) and Solana report annual electricity use in the **single digit gigawatt-hour to low-megawatt-hour** ranges. This research paper consist of analyse of per-transaction energy, discuss methodological caveats (measurement model, accounting boundaries), and offer policy and technical recommendations for reducing blockchain carbon footprints. Key data sources and reproducible references are provided.

Keywords: Blockchain, energy consumption, Bitcoin, Ethereum, Solana, proof-of-work, proof-of-stake, sustainability.

1. INTRODUCTION

The rapid rise of blockchain technology over the past decade has transformed digital finance, decentralized applications, and distributed computing. As blockchain adoption accelerates, the environmental impact of these networks has become an increasingly critical concern among policymakers, researchers, and industry stakeholders. Energy consumption, in particular, has become a central point of debate, especially for large public blockchains like Bitcoin and Ethereum, whose global electricity footprints have been compared to those of small nations. Understanding the variation in energy usage across different blockchain architectures—especially between Proof-of-Work (PoW), Proof-of-Stake (PoS), and hybrid models—is essential for assessing the sustainability and long-term viability of decentralized ecosystems.

Bitcoin, the first and largest cryptocurrency, operates on a Proof-of-Work consensus mechanism that requires miners to perform computationally intensive hashing operations to secure the network. This process, commonly referred to as “mining,” is fundamentally energy-heavy because it incentivizes miners to use high-performance hardware such as ASIC (Application-Specific Integrated Circuit) machines. As a result, Bitcoin’s estimated electricity consumption has consistently reached hundreds of terawatt-hours per year, rivaling the energy usage of countries like Argentina and the Netherlands. Critics argue that the environmental footprint of Bitcoin undermines its long-term sustainability, while proponents contend that mining increasingly relies on renewable energy sources and contributes to grid stability by utilizing otherwise wasted power.

In contrast, Ethereum—the second-largest blockchain—underwent a transformative technological shift in September 2022 known as *The Merge*, transitioning from PoW to a Proof-of-Stake consensus mechanism. Under PoS, validators are selected to create new blocks based on the amount of cryptocurrency they “stake,” eliminating the need for energy-intensive mining hardware. This transition resulted in an unprecedented 99.95% reduction in Ethereum’s energy consumption, positioning it as one of the most energy-efficient large-scale blockchain networks in the world. Ethereum’s



post-Merge efficiency has set a benchmark for emerging networks and has reshaped discussions about blockchain sustainability.

Solana represents another approach to energy-efficient blockchain design, utilizing a hybrid combination of Proof-of-Stake and Proof-of-History (PoH). Proof-of-History enables extremely fast transaction ordering by using a cryptographic timestamping method, reducing the computational burden on validators and enabling throughput levels significantly higher than those of traditional PoW and PoS networks. Numerous independent analyses have shown that Solana consumes only a fraction of the energy used by Bitcoin and Ethereum, both on a per-transaction basis and in terms of annual network electricity usage. Solana's architecture demonstrates how innovative consensus and time-synchronization mechanisms can achieve high performance while maintaining low environmental impact.

Despite these advancements, there remains substantial debate surrounding the true sustainability of blockchain networks. Energy consumption can vary based on network activity, validator distribution, hardware efficiency, and electricity sources. Furthermore, operational energy represents only part of the ecological impact; lifecycle considerations—including hardware manufacturing, e-waste, and infrastructure emissions—contribute significantly to overall sustainability metrics. Therefore, a comprehensive analysis of blockchain energy consumption must consider both operational and embodied emissions.

This research paper provides a comparative, data-driven evaluation of three major blockchain ecosystems—Bitcoin, Ethereum, and Solana—to better understand their energy profiles. By examining annual electricity usage, energy per transaction, carbon emissions, and lifecycle factors, the paper offers insights into the environmental trade-offs associated with different consensus mechanisms. The findings aim to inform policymakers, developers, investors, and environmental researchers seeking to evaluate the sustainability of blockchain technologies and guide future innovation toward greener digital infrastructures.

2. Literature Review

2.1 Measuring blockchain energy use

Estimating blockchain energy consumption is non-trivial: studies vary by approach (top-down economic/income models vs bottom-up hashing-hardware inventories), assumptions about miner profitability and electricity price, and inclusion/exclusion of ancillary systems (cooling, data center overhead). The **Cambridge Bitcoin Electricity Consumption Index (CBECI)** and analytical efforts in peer-reviewed journals provide ongoing best-effort estimates for Bitcoin using economic and hash rate data. Digiconomist maintains energy indices (Bitcoin and Ethereum) that have been widely cited for high-level comparisons, while national agencies (e.g., U.S. EIA) publish broader contextual analyses of crypto mining's share of grid electricity. These works emphasize transparency about methods and the sensitivity of estimates to key assumptions.

2.2 PoW vs PoS and energy implications

Multiple studies and industry reports document the large energy reductions achieved when a chain moves from PoW to PoS: Ethereum's Merge (September 2022) replaced mining with staking and is repeatedly reported to reduce network energy consumption by **orders of magnitude** (figures frequently quoted as >99% reduction relative to PoW baselines). This transition illustrates how protocol-level design choices affect sustainability. Vendor and independent reports for PoS chains like Solana provide bottom-up network energy dashboards that enable per-transaction and annualized estimates, though verification and standardization remain important.

2.3 Recent comparative studies and concerns

Recent literature and reviews (2023–2025) examine not only absolute energy but also **carbon intensity** (energy source mix), network utility (transactions/sec), and trade-offs such as decentralization vs efficiency. The European Commission and research groups have called for improved transparency, standardized reporting, and lifecycle analyses to capture



embodied emissions (mining hardware production and e-waste). This paper builds on that literature by assembling comparable metrics for Bitcoin, Ethereum (post-Merge), and Solana and explaining measurement caveats.

3. Methods

3.1 Data sources and selection

I rely on authoritative and publicly available sources: the Cambridge Centre for Alternative Finance (CBECE) (Bitcoin estimates), Digiconomist energy indices (Bitcoin and Ethereum historic/upper-bound estimates), and the Solana Foundation’s energy-impact report and public dashboard (Solana). Where vendor reporting exists (Solana), I use their dashboard numbers; where independent index estimates exist (Bitcoin, Ethereum), National energy statistics (U.S. EIA) and peer-reviewed articles are used for context. All sources are cited inline and listed in the references.

3.2 Metrics computed

- **Annual network electricity consumption (TWh/year)** — primary network-level metric.
- **Energy per transaction (kWh/tx)** — network energy divided by observed annual transactions (approximate; note that transaction counts and energy use may not scale linearly).
- **Carbon footprint (MtCO₂/year)** — where available, using carbon intensity estimates from cited sources.

3.3 Limitations of method

- **Accounting boundaries:** Some reports (vendor dashboards) measure direct validator/validator-server energy only; other estimates attempt to include miner economics, power usage effectiveness (PUE) and cooling. Results must be compared carefully.
- **Time sensitivity:** Hash rate, network utilization, and energy mixes vary; numbers are snapshots or annualized projections from 2023–2025 reporting windows. We clearly label which figures are measured vs target/estimated.

4. Data Analysis

4.1 Key reported figures (synthesized)

Table 1 —Energy Consumption of Major Blockchains

Network	Annual Energy Consumption (TWh/year)	Energy per Transaction (kWh/Tx)	Carbon Emissions (MtCO ₂ /year)
Bitcoin (PoW)	~204.4 TWh/year <i>(Uses energy similar to a medium-sized country)</i>	~1301 kWh per transaction <i>(One Tx = energy of a household’s monthly use)</i>	~114 MtCO ₂ <i>(Very high emissions due to mining)</i>
Ethereum (PoS, post-Merge)	0.0026–0.01 TWh/year <i>(99.95% less energy than PoW)</i>	~0.02 kWh per Tx <i>(Like running an LED bulb for 1–2 minutes)</i>	~0.01 MtCO ₂ <i>(Almost negligible)</i>



Network	Annual Energy Consumption (TWh/year)	Energy per Transaction (kWh/Tx)	Carbon Emissions (MtCO ₂ /year)
Solana (PoS + PoH)	~0.00848 TWh/year <i>(Extremely low compared to Bitcoin)</i>	0.00000412 kWh per Tx <i>(Equal to a LED bulb running for ~0.001 sec)</i>	~0.00267 MtCO ₂ <i>(≈ 2.67 ktCO₂/year, very low)</i>

Source: Digiconomist Bitcoin Energy Index (2025), Digiconomist, CCRI Reports (2024), Solana Foundation Energy Impact Report (2024)

Meaning of terms used in table 1

Term	Full Form	Meaning (Easy Explanation)
Tx	Transaction	One completed action on a blockchain (e.g., sending coins, minting NFT).
kWh	Kilowatt-hour	Amount of energy used by a 1000-watt (1 kW) device running for 1 hour.
Wh	Watt-hour	1/1000 of a kWh.
TWh	Terawatt-hour	Very large energy unit: 1 TWh = 1 trillion (1,000,000,000,000) watt-hours . Used for national electricity consumption.
MtCO ₂	Million tonnes of CO ₂	1 MtCO ₂ = 1,000,000 tonnes of carbon emitted.
PoW	Proof of Work	Mining-based consensus — very energy-heavy.
PoS	Proof of Stake	Validator-based — very energy efficient.
PoH	Proof of History	Solana’s time-based cryptographic system that reduces energy overhead.

4.2 Interpretation and normalized comparisons

- **Huge difference in energy use:** Bitcoin uses a lot more energy because its Proof-of-Work system requires thousands of mining machines to run non-stop. These machines solve complex puzzles, which consumes huge power. Also, Bitcoin only processes a limited number of transactions every 10 minutes, so the large energy cost is divided across fewer transactions, making the energy per transaction extremely high. Proof-of-Stake networks, like Ethereum and Solana, do not use mining. They verify transactions using lightweight validators, which need very little electricity. They also process far more transactions in the same amount of energy, making them much more efficient
- **Per-transaction energy numbers can be confusing:** Energy used “per transaction” is helpful for basic comparison, but different transactions do different things:
 - A simple coin transfer uses very little computation
 - 2A smart-contract execution or NFT minting uses more
 - Some work also happens off-chain (e.g., Layer-2 networks)



So comparing all transactions as equal isn't perfect. Still, per-transaction energy is a good general indicator of how energy-efficient a blockchain is.

- **Carbon emissions depend on where the energy comes from:** The environmental impact is not only about how much energy a network uses, but also **what type of energy** it uses. If miners or validators use electricity made from coal, emissions are high. If they use renewable energy (solar, wind, hydro), emissions are low. For example, after China banned Bitcoin mining in 2021, many miners moved to places with different energy sources, which changed the network's carbon footprint. After the mix of energy sources in each region has a big effect on total CO₂ emissions.

5. Discussion

5.1 Policy and technical implications

- **Protocol choice matters:** Consensus design (PoW vs PoS) is the dominant factor in network energy profile; migrating to PoS or similarly efficient mechanisms dramatically reduces network energy (Ethereum example). Policymakers can encourage or mandate energy-efficient consensus for new public blockchains.
- **Transparency & standardization:** Vendor dashboards (e.g., Solana) and independent indices (CBECI, Digiconomist) are useful but use different methodologies. There is a need for standardized reporting protocols (similar to energy disclosure frameworks for data centers) so stakeholders can compare networks fairly.
- **Beyond operational energy:** Full lifecycle assessments should include embodied emissions (hardware manufacture, shipping, e-waste). For PoW hardware, high turnover and specialized ASIC production contribute additional carbon and material impacts.

5.2 Practical recommendations

1. **Favor energy-efficient consensus** in public procurement and regulation for new blockchain projects.
2. **Require transparent, auditable energy dashboards** and third-party verification for public claims.
3. **Incentivize renewables and regional green energy mix** for validator/miner operations to reduce carbon intensity.
4. **Adopt layer-2 scaling** (for networks where appropriate) to increase useful transactions per unit energy.

6. Limitations

- **Estimate variance:** Different estimation models yield widely divergent figures (e.g., Digiconomist vs CBECI). Readers should interpret absolute numbers cautiously and focus on order-of-magnitude comparisons and trends.
- **Temporal changes:** Network energy and throughput evolve rapidly (hash rate changes, protocol upgrades); the figures used are snapshots (2023–2025 windows) and should be updated for future analyses.
- **Accounting boundaries:** Some vendor reports exclude certain overheads (e.g., office/administration energy), while others attempt to estimate full system costs.

7. CONCLUSION

This comparative analysis shows that **consensus choice and architecture** dominate blockchain energy footprints. Bitcoin (PoW) remains extremely energy-intensive at the network level; Ethereum's shift to PoS resulted in a reduction by multiple orders of magnitude in reported operational energy; Solana's high throughput and PoS/PoH design yield a much lower per-transaction energy footprint as reported by its foundation. For sustainable blockchain growth, technical pathways (efficient consensus, layer-2 scaling), operational practices (renewable sourcing), and regulatory transparency are essential.



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