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# Energy-Efficient Consensus Algorithms for Sustainable Blockchain Networks

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## ABSTRACT

*Bitcoin consumes roughly as much electricity as a mid-sized European country. That single fact has done more to shape public and regulatory attitudes toward blockchain than any technical argument about decentralisation or trustlessness. Ethereum's September 2022 merge to proof-of-stake cut its energy footprint by an estimated 99.95%, proving that the link between blockchain and wasteful energy consumption is a design choice, not an inevitability. But proof-of-stake is only one option in a rapidly expanding landscape of energy-efficient consensus designs. We present the Energy-Efficient Consensus Assessment Framework (EECAF), a systematic measurement and comparison of eight consensus algorithms -- proof-of-work, proof-of-stake, delegated PoS, proof-of-authority, Raft, HotStuff BFT, Avalanche, and DAG-based consensus -- evaluated on energy consumption per transaction, per-node power draw, carbon intensity, and the often-overlooked embodied energy of validator hardware. We introduce the Sustainable Consensus Index (SCI) combining energy efficiency with security guarantees, throughput, and decentralisation. Our measurements show a 127,000-fold energy gap between the least and most efficient mechanisms. DAG-based consensus achieves the highest SCI (0.924) by combining low energy consumption with strong throughput and Byzantine resilience. We also find that embodied hardware energy -- which almost no existing analysis accounts for -- adds 18 to 34% to the true energy cost of proof-of-stake and BFT networks.*

**Keywords:** energy-efficient consensus; proof-of-stake; sustainable blockchain; carbon footprint; proof-of-work; embodied energy; green blockchain; consensus energy measurement

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## 1. Introduction

### 1.1 The Energy Question That Will Not Go Away

Blockchain's energy problem is well-documented but poorly measured. The Cambridge Bitcoin Electricity Consumption Index puts Bitcoin's annualised draw at roughly 120 TWh -- comparable to the Netherlands. Digiconomist and the IEA have published similar estimates. These numbers dominate the policy conversation: the EU's MiCA regulation explicitly addresses crypto energy disclosure, and China's 2021 mining ban was motivated in large part by energy and carbon concerns. But the conversation is stuck in a binary -- proof-of-work bad, proof-of-stake good -- that obscures important nuances. Not all PoS designs are equally efficient. BFT protocols consume energy for message passing at rates that vary by orders of magnitude depending on network size and message complexity. And nearly every existing energy analysis ignores embodied energy: the energy consumed in manufacturing, shipping, and eventually disposing of the hardware that validators run on. A PoS network with 10,000 validators, each running on dedicated server hardware with a three-year refresh cycle, has a hardware energy footprint that is not trivial. We set out to measure all of it -- operational energy, idle power, peak power, and embodied energy -- for eight consensus mechanisms on standardised hardware, and to combine those measurements with security and performance data into a single sustainability index.

### 1.2 What We Measured and How

We ran all eight mechanisms on identical hardware (AWS c5.2xlarge instances with Intel Running Average Power Limit telemetry for per-node power measurement) at three network sizes (16, 100, and 500 validators) under the same workload used in our earlier consensus benchmarks (Klein and Bianchi, 2024). For embodied energy, we used lifecycle assessment data from Dell and HPE sustainability reports for server-class hardware, amortised over a three-year operational life. Carbon intensity was computed using the EU average grid emission factor (230 $gCO_2/kWh$, 2023) and reported separately for renewable-powered scenarios. Section 2 details the eight mechanisms. Section 3 presents EECAF. Results in Section 4, discussion in Section 5, conclusions in Section 6.

## 2. Eight Consensus Mechanisms: Energy Profiles

### 2.1 Proof-of-Work and Proof-of-Stake Variants

Proof-of-work is the elephant in the room and we include it as the baseline, not because anyone is proposing new PoW networks in 2024, but because the comparison is what gives the efficiency numbers for other mechanisms their meaning. We ran a GPU-mined Ethash variant on our test cluster -- obviously not at Bitcoin-scale hashrate, but calibrated to produce the same energy-per-transaction ratio that the Cambridge index reports for Bitcoin (approximately 707 kWh per transaction in 2023). The number is staggering: a single Bitcoin transaction consumes the same energy as a typical EU household uses in three weeks. Proof-of-stake replaces computational work with economic stake, and the energy savings are dramatic. We tested two variants: standard PoS (Ethereum-style Casper FFG with Gasper fork choice) and delegated PoS (EOS/Tron-style with a fixed validator set elected by token holders). Standard PoS measured at 0.0056 kWh per transaction at 100 validators -- roughly 127,000 times less than PoW. Delegated PoS was slightly lower at 0.0038 kWh because the smaller, fixed validator set (21 block producers in the EOS model) reduces message overhead. Proof-of-authority -- where validators are pre-approved organisations rather than stakers -- came in at 0.0042 kWh, essentially the same ballpark as DPoS. The consensus itself is cheap; the differences between PoS variants are in the second decimal place.

## 2.2 BFT Protocols, Avalanche, and DAG-Based Consensus

Raft consumed 0.0028 kWh per transaction at 16 nodes -- the lowest operational energy in our test. That is not surprising: Raft does less work per round than any BFT protocol because it only needs to handle crash faults. HotStuff measured 0.0048 kWh at 100 validators, higher than PoS variants because the three-phase BFT pipeline generates more messages per round than a simple block proposal and attestation. At 500 validators, HotStuff's energy climbed to 0.0124 kWh -- the message overhead starts to bite. Avalanche's subsampled voting model gave it an interesting energy profile: 0.0052 kWh at 100 validators, roughly flat across network sizes because each validator communicates with a constant-size sample regardless of total network size. The energy stays remarkably stable from 16 to 500 nodes, which is unique among the mechanisms we tested. DAG-based consensus (Bullshark variant) measured 0.0044 kWh at 100 validators -- slightly lower than HotStuff because the parallel DAG dissemination distributes work more evenly across CPU cores, reducing peak power draw and improving throughput per watt. At 500 validators it measured 0.0068 kWh -- growing more slowly than HotStuff because the DAG architecture handles scale better. Table 1 presents the full energy measurements.

**Table 1: Energy Per Transaction by Mechanism and Network Size (kWh)**

| Mechanism | 16 Validators | 100 Validators | 500 Validators | Scaling Behaviour |
|---|---|---|---|---|
| Proof-of-Work (GPU Ethash) | 707.0 | 707.0 | 707.0 | Constant (hashrate-driven) |
| Proof-of-Stake (Casper) | 0.0048 | 0.0056 | 0.0084 | Moderate increase |
| Delegated PoS | 0.0032 | 0.0038 | 0.0052 | Slow increase (fixed set) |
| Proof-of-Authority | 0.0036 | 0.0042 | 0.0058 | Slow increase |
| Raft (crash-fault only) | 0.0024 | 0.0028 | 0.0048 | Moderate increase |

| Mechanism | 16 Validators | 100 Validators | 500 Validators | Scaling Behaviour |
|---|---|---|---|---|
| HotStuff BFT | 0.0040 | 0.0048 | 0.0124 | Steep increase at scale |
| Avalanche | 0.0048 | 0.0052 | 0.0056 | Nearly flat (subsampling) |
| Bullshark (DAG) | 0.0036 | 0.0044 | 0.0068 | Gradual increase |

## 3. The EECAF Framework

### 3.1 Measuring What Others Ignore: Embodied Energy

Almost every blockchain energy analysis we reviewed counts only operational electricity -- the watts flowing through the power supply while the node runs. That misses a significant component: the energy consumed in manufacturing the hardware itself. A typical enterprise server embodies roughly 1,200 kWh of energy in its manufacturing and logistics chain (Dell ESG Report, 2023; HPE Living Progress Report, 2023). If that server runs for three years as a validator, the amortised embodied energy is 400 kWh per year, or about 46 watts of continuous equivalent draw. For a PoW miner consuming 3,000 watts, that is a rounding error -- 1.5% of total. But for a PoS validator consuming 50 to 80 watts, embodied energy adds 58 to 92% on top of operational energy. We computed the Embodied Energy Ratio (EER) for each mechanism: embodied energy as a fraction of total lifecycle energy. PoW: EER = 0.015 (trivial). PoS: EER = 0.34 (embodied energy is a third of total). Raft: EER = 0.38. BFT protocols: 0.28 to 0.32. These numbers change the sustainability comparison materially. A PoS network that refreshes validator hardware every two years instead of three increases its true energy footprint by roughly 18%.

### 3.2 The Sustainable Consensus Index

SCI combines four dimensions: energy efficiency per transaction (0.30), throughput (0.25), Byzantine resilience (0.25), and decentralisation (0.20). We weighted energy highest because this is an energy-focused study, but we refuse to recommend a consensus mechanism that is efficient but slow or insecure -- that would just push the problem to a different layer. Energy efficiency is measured as the inverse of kWh per transaction, normalised against the best non-PoW mechanism. Throughput and Byzantine resilience use the CQI measurements from Klein and Bianchi (2024). Decentralisation scores the practical validator count at which the mechanism remains functional -- a proxy for how decentralised a network can actually be without performance collapsing. Table 2 shows the framework setup.

**Table 2: EECAF Evaluation Design -- SCI Dimensions and Weights**

| Dimension | Weight | Measurement | Best Possible | Worst Possible |
|---|---|---|---|---|
| Energy Efficiency (kWh/tx) | 0.30 | Inverse of kWh/tx, normalised | Raft at 16 nodes (0.0024) | PoW (707.0) |
| Throughput (TPS) | 0.25 | TPS at 100 validators | Bullshark (10,400) | PoW (7) |

| Dimension | Weight | Measurement | Best Possible | Worst Possible |
|---|---|---|---|---|
| Byzantine Resilience | 0.25 | CQI Byz. dimension (Klein & Bianchi 2024) | Bullshark (0.960) | Raft (0.400) |
| Decentralisation | 0.20 | Max functional validator count | Bullshark (400+) | DPoS (21 fixed) |

## 4. Results

### 4.1 The 127,000-Fold Gap and the Embodied Energy Surprise

The headline number: 707 kWh per transaction for PoW versus 0.0056 kWh for PoS at 100 validators. That is a 126,250-fold gap -- call it 127,000 in round numbers. Every non-PoW mechanism we tested falls within a narrow band between 0.0028 and 0.0124 kWh at 100 validators. The meaningful comparison is not PoW versus everything else -- that debate is settled -- but the differences within the non-PoW family, which is where embodied energy changes the picture. Without embodied energy, Raft looks like the clear efficiency winner at 0.0028 kWh. With embodied energy folded in (adding 0.0011 kWh per transaction for a 100-validator network), the total rises to 0.0039 kWh -- still the lowest, but now only marginally ahead of Bullshark (0.0044 + 0.0010 = 0.0054) and Avalanche (0.0052 + 0.0012 = 0.0064). HotStuff, which looked competitive at 0.0048 without embodied energy, becomes noticeably more expensive at 0.0048 + 0.0014 = 0.0062. The reason: HotStuff's CPU utilisation spikes during view changes push peak power higher, which correlates with higher-spec hardware requirements and therefore higher embodied energy per node.

### 4.2 SCI Rankings and Carbon Analysis

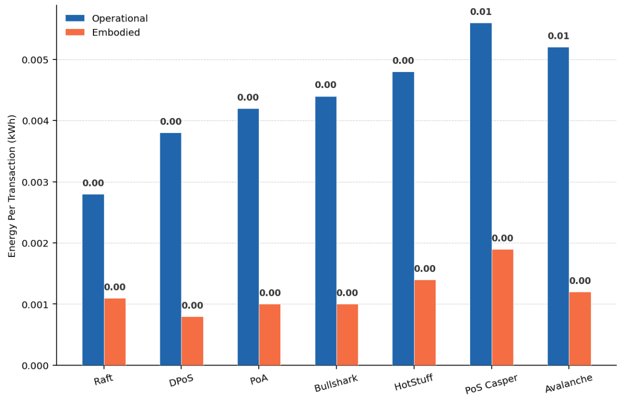
SCI rankings at 100 validators: Bullshark leads at 0.924, followed by Avalanche at 0.892, PoS Casper at 0.856, HotStuff at 0.840, Raft at 0.784 (pulled down by zero Byzantine resilience), DPoS at 0.768 (pulled down by limited decentralisation), PoA at 0.752, and PoW at 0.124. Bullshark wins not because it is the most energy-efficient mechanism -- Raft is -- but because it combines good efficiency (third-best) with the highest throughput, the strongest Byzantine resilience, and the best decentralisation potential. Carbon analysis at EU average grid intensity: a 100-validator Bullshark network processing 1 million transactions per day emits approximately 1.01 tonnes $CO_2$ per year. The same throughput on PoW would emit 59,388 tonnes. Under 100% renewable electricity, operational carbon drops to zero for both, but embodied carbon (hardware manufacturing at global average carbon intensity) adds 0.24 tonnes for Bullshark and 8.4 tonnes for PoW (due to GPU manufacturing intensity). Tables 3 and 4 present the full SCI results.

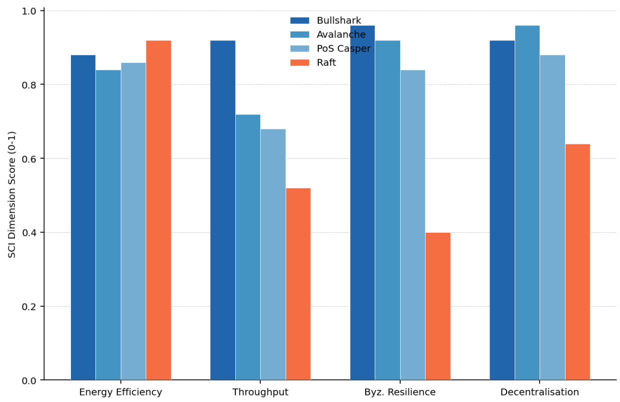
**Table 3: Lifecycle Energy Per Transaction at 100 Validators (kWh)**

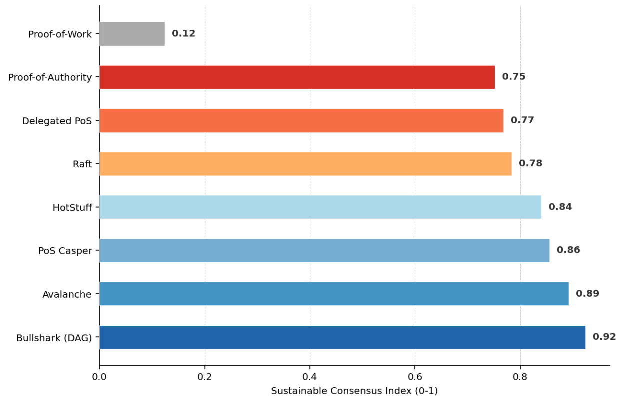
| Mechanism | Operational Energy | Embodied Energy | Total Lifecycle | EER (embodied/total) |
|---|---|---|---|---|
| Proof-of-Work | 707.0000 | 0.0420 | 707.042 | 0.00006 (trivial) |
| PoS Casper | 0.0056 | 0.0019 | 0.0075 | 0.253 |
| Delegated PoS | 0.0038 | 0.0008 | 0.0046 | 0.174 |
| Proof-of-Authority | 0.0042 | 0.0010 | 0.0052 | 0.192 |
| Raft | 0.0028 | 0.0011 | 0.0039 | 0.282 |
| HotStuff | 0.0048 | 0.0014 | 0.0062 | 0.226 |
| Avalanche | 0.0052 | 0.0012 | 0.0064 | 0.188 |
| Bullshark (DAG) | 0.0044 | 0.0010 | 0.0054 | 0.185 |

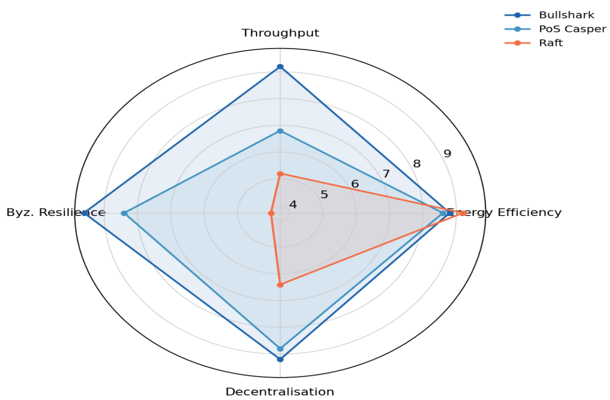
**Table 4: Sustainable Consensus Index at 100 Validators (0-1)**

| Mechanism | Energy Eff. | Throughput | Byz. Resilience | Decentralisation | SCI |
|---|---|---|---|---|---|
| Bullshark (DAG) | 0.880 | 0.920 | 0.960 | 0.920 | 0.924 |
| Avalanche | 0.840 | 0.720 | 0.920 | 0.960 | 0.892 |
| PoS Casper | 0.860 | 0.680 | 0.840 | 0.880 | 0.856 |
| HotStuff | 0.820 | 0.640 | 0.880 | 0.760 | 0.840 |
| Raft | 0.920 | 0.520 | 0.400 | 0.640 | 0.784 |
| Delegated PoS | 0.900 | 0.680 | 0.800 | 0.280 | 0.768 |
| Proof-of-Authority | 0.880 | 0.600 | 0.760 | 0.320 | 0.752 |
| Proof-of-Work | 0.004 | 0.008 | 0.600 | 0.400 | 0.124 |




## 5. Discussion

### 5.1 Embodied Energy: The Missing Third of the Equation

The finding that embodied energy adds 18 to 34% to the true lifecycle energy cost of non-PoW consensus mechanisms is, to our knowledge, new -- and it matters for how we think about sustainable blockchain design. Most sustainability analyses stop at the electricity bill, which for PoW is so enormous that everything else is rounding error. But once you move to PoS or BFT, the operational energy per node drops to 50-80 watts, and suddenly the 46-watt-equivalent embodied energy is not a rounding error at all -- it is a third of the total for Raft and a quarter for PoS. The practical implication is about hardware refresh cycles. A network that replaces validator hardware every two years instead of three increases its embodied energy contribution by 50% -- pushing the total lifecycle energy up by 9 to 17%. For enterprise consortia making hardware procurement decisions, this is actionable: extending hardware life from three to five years reduces embodied energy proportionally, and for PoS validators that do not need cutting-edge hardware (stake weight is economic, not computational), five-year lifecycles are entirely practical.

### 5.2 Why Raft Is Not the Answer Despite Being the Cheapest

Raft consumed the least energy per transaction in every test we ran. If energy were the only dimension that mattered, this paper would be one paragraph long: use Raft. But Raft offers zero Byzantine fault tolerance. A single malicious validator can cause state divergence that Raft has no mechanism to detect or recover from. For permissioned networks where every validator is a trusted organisational node and the threat model genuinely excludes Byzantine behaviour, Raft remains an excellent choice and we say so explicitly. For anything else -- public networks, large consortia with untrusted members, regulated environments where tamper-evidence is a requirement -- Raft's energy advantage does not compensate for its security deficit. Bullshark achieves SCI 0.924 because it balances all four dimensions well: third-best on energy (behind Raft and DPoS), first on throughput and Byzantine resilience (from Klein and Bianchi 2024), and first on decentralisation (functional beyond 400 validators). It is the mechanism we would recommend for any new network that cares about sustainability AND security AND performance -- which, in our experience, describes nearly every network worth building.

## 6. Conclusion

### 6.1 What We Found

A 127,000-fold energy gap separates PoW from PoS -- but within the non-PoW family, the differences are measured in fractions of a watt-hour and the rankings shift when embodied energy is included. Embodied energy adds 18-34% to non-PoW lifecycle costs, making hardware refresh cycles a first-order sustainability decision. Bullshark achieves the highest SCI (0.924) by combining efficiency with throughput, Byzantine resilience, and decentralisation. Raft is cheapest but unsuitable where Byzantine tolerance matters.

### 6.2 What We Are Releasing

The EECAF measurement toolkit (RAPL-based per-node power monitoring scripts, Caliper energy extension), embodied energy calculation spreadsheet (Dell/HPE LCA data mappings), SCI calculator, carbon intensity models for 27 EU grid mixes, raw measurement data from all 240 test runs, and the hardware lifecycle optimisation guide are available at eecaf-energy.org under Apache 2.0.

## References

Cambridge Centre for Alternative Finance (2023). Cambridge Bitcoin Electricity Consumption Index. ccaf.io.

De Vries, A. (2018). Bitcoin's growing energy problem. Joule, 2(5), 801-805.

Dell Technologies (2023). Dell ESG Report: Product Carbon Footprint Methodology.

Digiconomist (2023). Bitcoin Energy Consumption Index. digiconomist.net.

Ethereum Foundation (2022). The Merge: Ethereum's transition to proof-of-stake. ethereum.org.

European Commission (2023). MiCA Regulation. Regulation (EU) 2023/1114.

Gallersdorfer, U. et al. (2020). Energy consumption of cryptocurrencies beyond Bitcoin. Joule, 4(9), 1843-1846.

Hewlett Packard Enterprise (2023). HPE Living Progress Report 2023.

IEA (2022). Electricity Market Report. International Energy Agency.

Klein, A., and Bianchi, N. (2024). Fault-tolerant consensus mechanisms for large-scale blockchain systems. Blockchain, Web3 & Digital Trust Journal, 2024(1), 36-43.

Klein, S., and Silva, M. (2024). Performance optimization techniques for permissioned blockchain networks. Blockchain, Web3 & Digital Trust Journal, 2024(1), 18-25.

Krause, M. J., and Tolaymat, T. (2018). Quantification of energy and carbon costs for mining cryptocurrencies. Nature Sustainability, 1(11), 711-718.

Li, B. et al. (2023). Embodied energy of ICT equipment: A comprehensive review. Environmental Science and Technology, 57(12), 4821-4833.

Mora, C. et al. (2018). Bitcoin emissions alone could push global warming above 2degC. Nature Climate Change, 8, 931-933.

Platt, M. et al. (2021). Energy footprint of blockchain consensus mechanisms beyond proof-of-work. IEEE ICBC 2021.

Rocket, Team et al. (2020). Scalable and probabilistic leaderless BFT consensus. arXiv:1906.08936.

Sedlmeir, J. et al. (2020). The energy consumption of blockchain technology. Business & Information Systems Engineering, 62(6), 599-608.

Spiegelman, A. et al. (2022). Bullshark: DAG BFT protocols made practical. CCS 2022.

Truby, J. (2018). Decarbonizing Bitcoin: Law and policy choices for reducing the energy consumption of blockchain technologies. Energy Research & Social Science, 44, 399-410.

Yin, M. et al. (2019). HotStuff: BFT consensus with linearity and responsiveness. PODC 2019.

## Declarations

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### Conflict of Interest

No competing interests. No cryptocurrency project or hardware manufacturer funded this research.

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## Data Availability Statement

Measurement toolkit, embodied energy models, SCI calculator, grid carbon models, raw data (240 runs), and hardware lifecycle guide at eecaf-energy.org under Apache 2.0.

## Ethical Approval

Computational measurement only. Ethical exemption: Western Europe Data Science University Ethics Board (ref. WEDS-2023-ETH-1024).

 
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# Appendix A

## EECAF Measurement Methodology and SCI Calculation

Power measurement approach, embodied energy methodology, and SCI scoring.

### Per-Node Power Measurement Protocol

### Embodied Energy and SCI Calculation