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Commentary

We need a broader debate on the sustainability of blockchain

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Cryptocurrencies are often criticized not only for their enormous energy consumption and e-waste but also for their carbon emissions, impact on local air quality, and detrimental health effects for humans and animals.[1,2] Criticism ignites especially around the proof of work (PoW) consensus mechanism that, for instance, Bitcoin and Ethereum—the two largest cryptocurrencies by market capitalization—use to synchronize and secure their underlying blockchains. This criticism is empirically substantiated and justified, but it is often generalized to all blockchains.

As a result, blockchains have gained a negative reputation as environmental polluters even though non-PoW blockchains have comparatively low energy needs and carbon footprints. These blockchains warrant not only a more differentiated analysis but also a discussion about the environmental benefits of blockchain. In fact, there is reason to believe that non-PoW blockchains may enable applications that contribute to sustainability, for instance, by reducing wasteful practices in food supply chains,[3] container shipment,[4] and public services[5] or by facilitating more efficient carbon markets.[6]

In this commentary, we consequently argue for a broader debate on the sustainability of blockchain. We begin our argument with a discussion of the significant energy savings that can be realized for public blockchains by using proof of stake (PoS) instead of PoW. In the second part, we provide measurements for the energy consumption of prominent private blockchains to complement those for major PoW[1,2] and PoS[7] blockchains. We conclude with a discussion of blockchain applications that may well add to sustainability. Overall, we aim to provide a clearer picture of the energy needs of different blockchains and help to identify areas of application where blockchains can be a source of sustainability.

Energy-efficient public blockchains

The high energy demand of PoW blockchains is rooted in the basic challenge of blockchain networks: ensuring that the blockchain's distributed copies are updated truthfully and reliably. In public settings, the challenge is typically resolved by consensus mechanisms that financially reward network participants for the addition of a truthful new block. The reward can be a certain cryptocurrency balance or/and fees for the transactions included in this block. To guide the election of the network participant who can add the next block, these consensus mechanisms use scarce resources—that is, resources that are costly to replicate. Connecting the probability of being elected to a scarce resource helps public blockchain networks prevent Sybil attacks. With such attacks, adversaries could take control over the network's consensus process. For instance, when all participants in a blockchain network contributed to the consensus mechanism by submitting votes, an attacker could mount a Sybil attack by creating countless dummy participants that outvote honest participants.[8]

PoW blockchains are a special—and historically the first—type of public blockchains. As the scarce resource, they use computational power spent on solving cryptographic puzzles and, by extension, "mining" hardware and electric power. Submitting solutions to these puzzles, which are connected to batches of transactions, convinces the other nodes in the blockchain network that a participant has invested the corresponding scarce resource. To keep the number of transactions that a PoW blockchain can process stable, the difficulty of the puzzle automatically adjusts to the amount of computational power in the network. Rising prices of the cryptocurrency, in turn, encourage investments in more computational power, which drives up the puzzle's difficulty and leads to higher energy demand and carbon emissions.[1,2,8] This interdependence means that, for instance, in March 2022, Bitcoin has consumed as much electricity as countries like Poland or South Africa.[9] It also means that more energy-efficient hardware will not reduce the energy consumption of PoW blockchains in the long run.[8]

To avoid this effect, other cryptocurrency networks, like Polkadot and Solana—two of the largest PoS cryptocurrencies by market capitalization—use their cryptocurrency as the scarce resource. These PoS networks require that a certain amount of the cryptocurrency is "put at stake" to be elected to add the next block. In other words, they tie voting power to the amount of cryptocurrency a voter possesses instead of computational power and energy. For some PoS networks, ownership of the cryptocurrency is sufficient for a higher chance at being selected. For others, only locked cryptocurrency balances increase the odds. Locking ensures that the balance cannot be used for a certain time and turns it into a collateral that disincentivizes malicious behavior.

Consequently, the energy needs associated with consensus finding in PoS blockchains are many orders of magnitude smaller than in PoW blockchains. Recent measurements suggest that even the most energy-intensive PoS blockchains require less than 0.002% of the energy needs of Bitcoin, the most energy-intensive PoW blockchain.[7] In fact, the energy needs of PoS blockchains are comparable to conventional enterprise IT systems: that is, a payment with a PoS cryptocurrency has similar energy requirements as a payment with PayPal[10] or Visa.[11] It is true that these payment systems process significantly more transactions than common PoS blockchains, but their total energy consumption is significantly higher as well. So, when broken down to the transaction level, both types of systems are in fact comparable.

Besides significantly lower energy needs, research suggests that PoS can also provide a comparably high level of security as PoW blockchains,[12] at least after a phase of fair distribution. Consequently, Ethereum—the cryptocurrency with the currently second largest market capitalization—has decided to switch from PoW to PoS[13] and will likely complete this transition in summer 2022.

Low energy needs of private blockchains

In corporate and government blockchain networks, the number of nodes can be controlled. Moreover, the involved participants know the identities of other participants; that is, they can associate the public keys of the blockchain nodes with an organization or individual. In such "private" networks, identity can act as the scarce resource and enable consensus mechanisms that build on "one participant, one vote" or reputation-weighted voting. Like PoS, these "identity-based" consensus mechanisms do not require the competitive solving of cryptographic puzzles to resist Sybil attacks. Accordingly, they also have low electricity needs.

In Figure 1, we present measurement of these needs for a selection of popular private blockchains. Specifically, we selected blockchains that are both used extensively in industry and government projects and that have been subjected to performance analyses in the academic literature. For our measurements, we deployed these blockchains on Amazon Web Services, where each node ran on a separate virtual machine. We then measured the virtual machines' resource utilization for different throughput levels between 1 tx/s and the respective networks' maximum capacity. From these resource utilizations, we derived power consumption levels. Specifically, we first checked that there was a strong linear relation between transaction throughput and marginal power consumption levels; that is, we verified that energy consumption increased

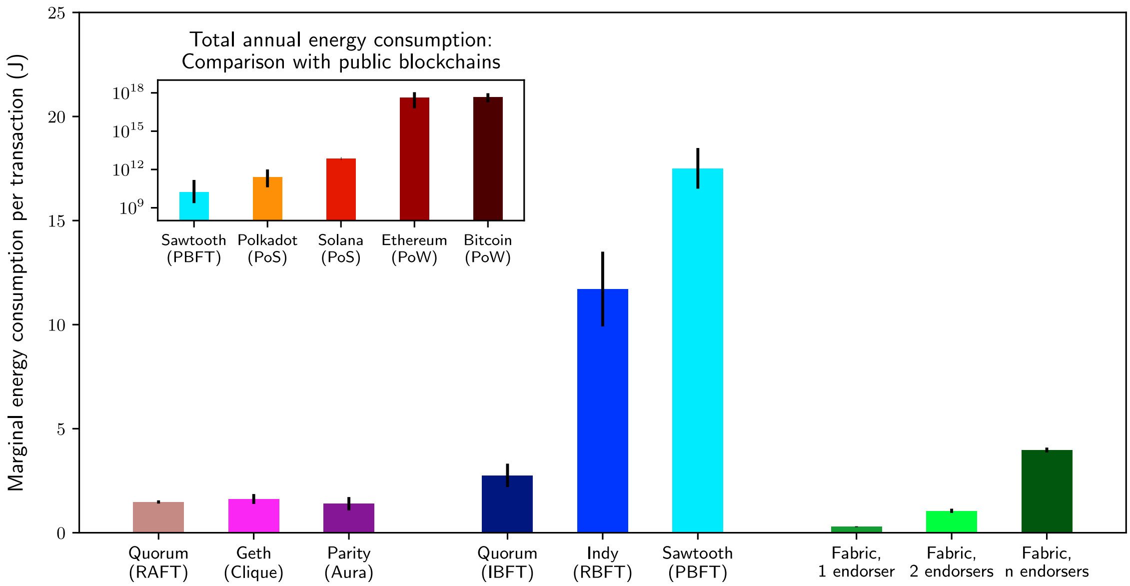

Figure 1. Marginal energy consumption per transaction for selected private blockchains (network size of 32 nodes)

The "marginal energy per transaction" values in the main panel exclude idle consumption; the corresponding error bars represent standard deviations across several measurements and throughput levels. We chose a network size of 32 nodes for the panel as this size is representative of many larger private networks, such as the European Blockchain Services Infrastructure.[5] See the supplemental information for details on the underlying calculations of the main panel. The small panel in the top-left corner offers a comparison against selected public blockchains on a "total annual energy consumption" basis. It applies a logarithmic scale. For the public PoS blockchains, we used measurements by the Crypto Carbon Ratings Institute for Polkadot and Solana.[7] Polkadot and Solana are the public PoS blockchains with the smallest and largest "total annual energy consumption" among the six public PoS blockchains with the highest market capitalization.[7] For the public PoW blockchains, we used Digiconomist values to calculate lower bounds and best guesses for Ethereum and Bitcoin,[9] as well as current cryptocurrency prices, transaction fees, and a lower bound of 0.05 USD per kWh of electricity for their upper bounds.[1,2] We illustrate these lower and upper bounds with the error bars in the small panel. Ethereum and Bitcoin are the public PoW blockchains with the highest market capitalization and energy consumption.

with the number of processed transactions. We then calculated the values presented in Figure 1 as the average over the different throughput levels. The error bars in the main panel represent the standard deviation over these averaged levels.

Figure 1 highlights that private blockchains, like public PoS blockchains, have low energy needs. These needs naturally increase with network size and tend to grow with the required level of resilience to failure and attack (Figure 2). Yet, total energy consumption remains low even for high transaction throughput because most private blockchain networks are comparatively small due to performance, data privacy, and data separation considerations. In essence, private blockchain networks are just a small collection of servers that host a shared database.

The interpretation of Figures 1 and 2 requires some caveats. The marginal energy consumption per transaction metric is useful for non-PoW blockchains in which transaction processing can represent a major share of the overall energy needs. However, it is not perfect, as "idle" consumption can also present a sizable share for these blockchains.[5] Moreover, it should not be used for PoW blockchains in which overall energy consumption is largely independent of the number and complexity of processed transactions; that is, a higher number and complexity of transactions, such as for the creation of non-fungible tokens (NFTs), would not increase the total power consumption of PoW blockchains in a meaningful way.[8] Slightly elevated energy needs are nevertheless possible due to increased cumulative transaction fees and a higher cryptocurrency price as a result of popularity gains.

Sustainability with blockchain

While the debate on energy consumption, e-waste, and other environmental and health impacts of blockchain is extensive,[1,2,7,8] potential benefits are often marginalized. This is surprising because companies and governments increasingly use blockchain applications that could contribute to sustainability. For instance, blockchain has gained traction for sustainable supply chain management, where its use can ensure increased efficiency and prevent unnecessary waste and surplus production. IBM FoodTrust is a prominent example.[3] IBM created FoodTrust in collaboration with major retailers such as Walmart and Unilever to enable extensive product monitoring across supply chains and to prevent fresh produce from being disposed of due to insufficient monitoring. This, in turn, can boost the sustainability of food supply chains. Other blockchain applications enable the digitalization of previously

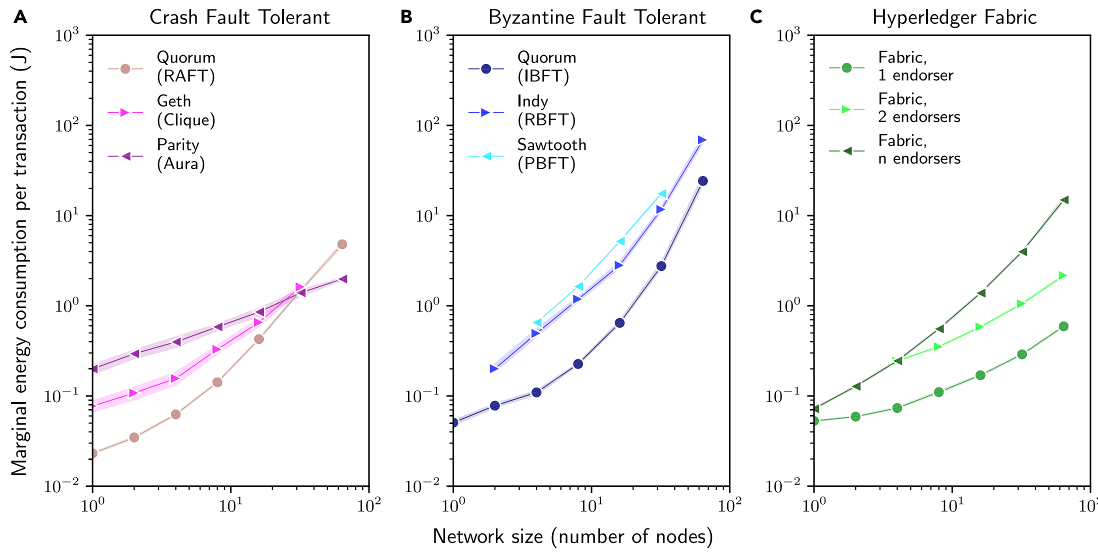

Figure 2. Scaling behavior of the marginal energy consumption per transaction for selected private blockchains

(A–C) Private blockchains have low energy needs—irrespective of their tolerance to faults and manipulations.

The consensus mechanisms in (A; crash fault tolerant) are resistant to a certain number of faulty nodes. The mechanisms in (B; Byzantine fault tolerant) can additionally cope with a certain number of malicious nodes. Hyperledger Fabric networks (C) are resistant to failure and certain attacks. The error regions represent standard deviations across three series of measurements.

See the supplemental information for more details on the consensus mechanisms and underlying calculations.

paper-based processes, such as TradeLens.[4] TradeLens was developed by IBM and Maersk, the world's largest container shipping company, to reduce paper- and often airmail-based data exchange in container shipment.

Even if we assume that these private blockchain applications were completely powered by coal (average 2020 US emission factor for coal: 1.01 kg or 2.23 pounds CO_2 eq per kWh[14]), this translates into a carbon footprint of 2.81×10^{-7} kg CO_2 eq for each joule. In comparison to the possible carbon savings, this value is marginal. For instance, it would be enough if one FoodTrust transaction helped to avoid the disposal of 1 gram of field vegetables (estimated carbon footprint of 3.30×10^{-4} kg CO_2 eq[15]) or if one TradeLens transaction shortens the voyage time of a container ship by 0.001 s (estimated 2018 carbon footprint of international shipping: 1.33 kg CO_2 eq per s[16]). Of course, these estimates are subject to some degree of uncertainty, and the total CO_2 footprint of private blockchains may be higher—for instance, due to the additional footprint of the underlying hardware. However, it is unlikely that more precise estimates will add the several orders of magnitude required to offset possible savings. In effect, there is growing indication that companies and governments can contribute to the sustainability of supply chains with blockchain, not despite blockchain.

Naturally, using blockchain for increased sustainability is not limited to supply chain management. Similar efforts to reduce inefficiencies in public administration are under way with the European Union's European Blockchain Services Infrastructure.[5] Blockchain technology is also frequently discussed as a key to more efficient carbon markets.[6] Overall, the use of blockchain technology could contribute to sustainability in areas where it can (1) make processes more efficient, (2) replace the paper-based exchange of sensitive information, or (3) reduce the use of fossil fuels or loss of produce and where the environmental costs of using blockchain do not exceed sustainability benefits.[3–5]

Conclusion

Given the broad range of blockchains beyond PoW, we argue for a more differentiated debate about the sustainability of blockchain technology. We particularly caution against blindly extending the critique of PoW to PoS and private blockchains, which both have low energy needs. Since some of them may even add to sustainability, we also see a need for a more balanced debate that goes beyond environmental costs and reflects on environmental benefits. This debate can build on ongoing efforts to identify areas of application in which blockchain could contribute to sustainability.[8] Moreover, it can add to a comprehensive overview of reference projects, their benefits and costs, and the consensus mechanisms used.

Standardization bodies could also make an important contribution to differentiation and balance with a carbon accounting framework for blockchain applications. With such a framework, companies could evaluate different blockchain designs and hosting options and establish the corresponding net carbon emissions. Moreover, such a framework would allow auditors to certify the sustainability of blockchain applications. A promising starting point can be established frameworks for corporate carbon accounting.

SUPPLEMENTAL INFORMATION

Supplemental information can be found online at https://doi.org/10.1016/j.joule.2022.04.013.

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DECLARATION OF INTERESTS

The authors declare no competing interests.

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Supplemental information

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Supplemental Information

Figure 1

The values in Figure 1 are based on measurements with the Distributed Ledger Performance Scan[1,2], an open-source framework for determining performance characteristics of various blockchain technologies. With the DLPS, we deployed blockchain networks as a cluster of virtual machines (one node per virtual machine) on Amazon Web Services' (AWS) EC2 platform. Each of the nodes in our setup had 4 virtual cores (corresponding to 2 physical cores) and 8 GB of RAM. This m5 series configuration yields a good tradeoff between throughput and costs for many of the examined blockchains[3]. Moreover, we set up client virtual machines to broadcast transactions to the cluster of blockchain nodes. We then measured the nodes' resource utilization (CPU and memory) for different rates of throughput (transactions per second sent from the client virtual machines).

To translate resource utilization into power consumption levels, we used available power consumption estimates for instances of the AWS EC2 m5 server series, which is based on Intel Xeon 8175 processors with 48 physical cores[3]. Specifically, we assumed around 100 W for idle consumption up to 550 W for maximum CPU and memory usage. These estimates are in line with those used by the Crypto Carbon Ratings Institute (CCRI)[4] to calculate the energy needs of PoS networks. For instance, the CCRI estimates that a Solana node consumes around 80 W for idle consumption and 220 W under average load. Manufacturer specifications for the hardware used by the CCRI, in turn, suggest 280 W for maximum CPU usage.

As data centers typically use a single processor for multiple virtual machines, we calculated the virtual machines' idle consumption by proportionally attributing the idle consumption of the physical processor. More specifically and considering an idle consumption of around 100 W for the Intel Xeon 8175 socket with 48 physical cores, we calculated an idle consumption of 4/96 times 100 W for each of our virtual machines with 4 virtual cores. In a second step, we did the same attribution for 100 % CPU and memory utilization respectively. In the third and last step, we interpolated the power needs for 0 % and 100 % resource utilization, which gave us a function to translate resource utilization into power consumption levels.

To increase robustness, we conducted our measurements for different throughput rates and conducted each measurement three times (sending requests with a fixed throughput rate for 20 seconds to a blockchain network with 32 nodes). We chose 20 seconds to balance costs and reliability of our measurements. We also conducted several spot-checks with measurements over 5 minutes to make sure that there are no long-term effects that negatively affect throughput, such as congestion or accumulating memory consumption. After validating that marginal resource utilization was approximately linearly dependent on throughput, we then worked with averaged values for Figure 1.

Figure 2

Networks with a crash-fault tolerant consensus mechanism have energy needs that scale approximately quadratically. Those of networks with more secure, byzantine-fault tolerant consensus mechanisms scale quadratically to cubically[5]. The scaling behavior of Hyperledger Fabric networks depends on their endorsement polices; that is, their energy needs scale approximately quadratically if an increasing number of nodes is required for endorsement, otherwise they increase approximately linearly.

All values in Figure 2 are again based on DLPS[1,2] measurements of CPU and memory utilization for virtual machines with 4 virtual cores and 8 GB RAM on the AWS EC2 platform as well as the same estimation approach that we used for Figure 1. For those consensus mechanisms that require a certain minimum network size or become instable beyond a certain size, we report only a subset of measurements.

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