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The Energy Footprint of Blockchain Consensus Mechanisms Beyond Proof-of-Work

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***Abstract*—Popular permissionless distributed ledger technology (DLT) systems using proof-of-work (PoW) for Sybil attack resistance have extreme energy requirements, drawing stern criticism from academia, business and the media. DLT systems building on alternative consensus mechanisms, particularly proof-of-stake (PoS), aim to address this downside. In this paper, we take an initial step towards comparing the energy requirements of such systems to understand whether they achieve this goal equally well. While multiple studies have analysed the energy demands of individual blockchains, little comparative work has been done. We approach this research gap by formalising a basic consumption model for PoS blockchains. Applying this model to six archetypal blockchains generates three main findings. First, we confirm the concerns around the energy footprint of PoW by showing that Bitcoin's energy consumption exceeds the energy consumption of all PoS-based systems analysed by at least three orders of magnitude. Second, we illustrate that there are significant differences in energy consumption among the PoS-based systems analysed, with permissionless systems having a larger energy footprint overall owing to their higher replication factor. Third, we point out that the type of hardware that validators use has a considerable impact on whether the energy consumption of PoS blockchains is comparable with or considerably larger than that of centralised systems.**

***Index Terms*—Blockchain, Carbon Footprint, Distributed Ledger Technology, Proof-of-Stake, Sustainability, Climate Action**

I. Introduction

In decentralised distributed ledger technology (DLT) systems, consensus mechanisms fulfil multiple purposes surrounding the proposal, validation, propagation and finalisation of data [1]. Voting is used extensively in common consensus mechanisms to resolve ambiguity arising from actors that spread incorrect or conflicting information [2]. Sybil attacks, which pose a critical problem for DLT systems, occur when an attacker creates an artificially large number of bogus identities [3] to skew the results of majority decisions on the admission and order of transactions. In *permissioned* networks, gatekeeping strategies can be applied that limit access to a network to previously vetted actors [4], thereby preventing such attacks.

However, for *permissionless* networks, in which participants can partake in consensus without any control [5], more complex mechanisms need to be applied to combat Sybil attacks. These commonly entail aligning entitlement to participate in consensus proportionally with the possession or expenditure of resources that can be digitally verified [1]. Proof-of-work (PoW) is an example of a Sybil attack resistance scheme that has been used in most early cryptocurrencies such as Bitcoin [6]. To counteract Sybil attacks, PoW uses cryptographic puzzles of configurable difficulty with efficient verification so that it becomes computationally expensive for attackers to interfere with consensus [7]. However, the energy consumption of PoW-based cryptocurrencies is connected to their respective market capitalisations, leading to extreme energy demand for popular implementations [8]. For instance, the electricity demand of Bitcoin is now in the same range as that of entire industrialised nations [9] and has been positioned as a dangerous contributor to global warming, producing up to 22.90 Mt CO_2 [10]. Against this backdrop, many alternatives to PoW have been proposed that do not rely on extensive computational effort [11]. Among these is proof-of-stake (PoS), in which participants with larger holdings of a cryptocurrency have a greater influence in transaction validation. While PoS is generally understood as being more energy-efficient than PoW, the exact energy consumption characteristics of PoS-based systems, and the influence that network throughput has on them, are not widely understood.

Two main approaches to quantifying the energy consumption of a DLT system have been used in the past. One is to measure the consumption of a representative participant node and then extrapolate from this measurement. An alternative approach is to develop a mathematical model that includes the core metrics of a DLT system to calculate its energy consumption. Extensive research efforts have cumulated in best practices for determining the energy consumption of DLT systems [12]. So far, most work has focused on PoW blockchains[1], and some research has investigated individual non-PoW systems. In this paper we propose a simple energy consumption model, applicable to a broad range of DLT systems that use PoS for Sybil attack resistance. Specifically, this model considers the number of validator nodes, their energy consumption, and the network throughput, based on which the energy consumption per transaction is estimated. We present the results of applying

[1]For the purpose of this manuscript, the term 'Blockchain' refers to any type of DLT, even if it does not make use of the 'block' concept, first described by Nakamoto [6].

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this model to six PoS-based systems. Our results suggest that, while negligible compared to PoW, the energy consumption of PoS systems can still vary significantly.

The next section reviews related work in both experimental and mathematical models. We then briefly describe the relevant architectural features of selected PoS systems. In the following section, we introduce our model in detail and describe how the underlying data were obtained. Subsequently, we apply the model to the systems selected, present the comparative results, and discuss the limitations. Finally, we conclude our study with potential avenues for future research.

II. Related work

We conducted an informal literature review[2] using the 'Bielefeld Academic Search Engine', a popular academic search system meeting all the necessary quality requirements for a systematic literature review [13]. We thereby obtained 413 results of prior studies analysing the energy demand of different DLT systems, with a significant focus on PoW blockchains in general, and specifically on Bitcoin Commonly, models take one of the following two forms.

Experimental models: The first form revolves around conducting experiments using mining hardware and measuring its actual energy consumption, as performed by Igumenov *et al.* with different configurations of computational resources [14]. This approach has been used to derive consumption characteristics for different usage scenarios. The 'BCTMark' framework [15], for instance, allows for the deployment of an entire experiment stack, including the DLT system under test. Using load generators, a realistic network workload can be created. The effects on the energy consumption of this setup under varying loads can subsequently be measured via energy sensors connected to the testbed. An experimental study on the energy consumption of the permissioned, non-PoW XRP ledger demonstrates that customising validator hardware can yield reductions in energy demand [16]. Metrics reported for common cryptocurrencies have been combined with testbed experiments to model the energy consumption behaviours of various consensus algorithms [17].

Mathematical models: An alternative method is to quantify assumptions about the environment in which a DLT system operates. Often, such models use a 'top-down' approach that relies on publicly observable factors – such as the hash rate in the case of Bitcoin – and associates them with common mining hardware or even seeks to determine the hardware used via surveys [12]. The papers of Gallersdörfer *et al.* [18], Küfeoglu and Özkuran [19], and Zade *et al.* [20] are examples of this hash rate-based approach. Sedlmeir *et al.* [8] undertake a basic comparison of different DLT architectures with the conclusion that the energy consumption differs significantly depending on the design chosen. A further study by the same authors [21] refines previous models for measuring the power consumption of Bitcoin, such as the one by Vranken [22], and emphasises that the driving forces behind power consumption are the Bitcoin price and the availability of cheap electricity. Eshani *et al.* [23] use a linear regression model to predict Ethereum's energy consumption based on the observed hash rate and difficulty level; however, the use of simplistic interpolation techniques alone is likely not an appropriate method for PoW blockchains [12]. Powell *et al.* [24] derive a mathematical model for the energy consumption of the PoS-based Polkadot blockchain by extrapolating from the power demand of a single validator machine.

[2]This was done using the query `("Blockchain" OR "DLT" OR "Distributed Ledger") AND ("Energy Consumption" OR "Energy Demand" OR "Electricity Demand" OR "Carbon Footprint") year:[2008 TO *]`.

III. Systems reviewed

This paper compares six DLT systems, both permissioned and permissionless, with high market capitalisation that use PoS as part of the consensus mechanism. To reiterate: PoS systems are conceptualised in such a way that the eligibility to actively participate in their consensus mechanism is proportional to the amount of cryptocurrency a participant holds. This means that the resource 'computing power', as used in PoW, is replaced by the resource 'capital' [8]. While the systems compared use different PoS-based consensus mechanisms that have different participation requirements, such as a minimum balance or a commitment to staking capital for a pre-defined period, they share important commonalities. A commonality particularly relevant to energy consumption is the need for dedicated servers, validator nodes, to validate sets of transactions and attach generation proofs. This activity is essential, irrespective of whether transactions are organised as chains of blocks [1], or as directed acyclic graphs [25]. It is this validation and proof generation aspect that attracts stern criticism in the context of PoW since it is responsible for its problematic energy consumption characteristics [1].

Platform	Permissioned	Permissionless
Ethereum 2.0		•
Algorand		•
Cardano		•
Polkadot		•
Tezos		•
Hedera	•	

Table I
Comparison of the analysed DLT systems in node permission setting.

The selection process for validation and proof generation in PoS constitutes a pseudo-random procedure in which a higher stake yields a higher probability of being selected [26]. PoS can be applied in both permissioned [27] and permissionless [28] settings (see Table I). Participants in *permissionless* networks can contribute validator nodes by following the respective admission procedures, such as broadcasting a key registration transaction in the case of Algorand [29]. The procedures often involve staking cryptocurrency and emitting messages on the ledger to indicate the willingness to act as validator [30]. In *permissioned* systems, such as Hedera, participation in the pseudo-random selection procedure is, however, limited to participants previously determined via an off-ledger process [31]. Once a node is recognised as a validator, it may participate in validation and proof generation. Depending on the particulars of the consensus mechanism, selection may require additional protocol steps, such as election onto a committee [29]. Once selected, validator nodes will verify the transactions received and generate proofs of validation, most commonly in the form of cryptographic signatures.

In summary, the commonalities of the protocols analysed can be described as follows: in all protocols, participants can act as validators, thereby qualifying to perform transaction validation and proof generation. In permissioned networks, the set of participants that can act as validators is limited. In permissionless networks, there are no such limitations. To act as a validator, a participant needs to be operating a computer that can send and receive data across the Internet. This computer must be able to perform the computations required to establish the correctness of proposed transactions and to make other calculations mandated by the consensus protocol. Operating such a validator node is an opt-in process, which means that participants can choose whether to run a validator node. Validator nodes need to remain in an active state as, due to pseudo-random selection, periods of activity often cannot be predicted in advance. Focusing on these similarities allows us to devise a method that is applicable to all six analysed systems.

IV. Method

Our model differs from previous work (see Section II) in that we also consider energy consumption *per transaction*, as opposed to only the overall energy consumption of an entire DLT system. Nevertheless, existing models can be combined with additional data arising from the scientific literature, reports, and public ledger information to form a baseline that can be used to avoid time-consuming experimental validation. Powell *et al.* [24] define an elementary mathematical model for the energy consumption of the Polkadot blockchain that can be generalised as:

$$p_t = p \cdot n_{\text{val}}, \tag{1}$$

where p_t is the overall average power the DLT system consumes, p is the average power consumed by a validator node, and n_{val} is the number of validator nodes. As this model forms the baseline of our work, the results it yields for the Polkadot blockchain are comparable to ours. Due to the comparatively low computational effort associated with PoS and the intentionally relatively low throughput of permissionless blockchains to avoid centralisation because of computing, bandwidth, or storage constraints [32], it can be assumed that validating nodes run on similar types of commodity server hardware, irrespective of the network load.

Under this assumption, the overall energy need of such a protocol is solely contingent on the number and hardware configuration of validator nodes. In the context of this paper, we only consider the energy footprint of the consensus mechanism itself. We therefore only consider *validators*[3], i.e., nodes that actively participate in a network's consensus mechanism by submitting and verifying the proofs necessary for Sybil attack resistance [1]. The overall number of nodes, including other *full nodes* that replicate the transaction history without participating in consensus, is likely higher for all systems analysed. A key model parameter, therefore, is the number of validator machines running concurrently (n_{val}). This number can be established reliably, since it is stored on-chain as a key aspect of any PoS-based protocol. Table II shows the number of validators currently operating on each of the networks considered.

[3]Nodes fulfilling this role go by various names, e.g., 'participation nodes' for Algorand, or 'bakers' for Tezos.

Platform	# Validators	TPS Cont. (tx/s)	TPS Max. (tx/s)
Ethereum 2.0	2649☆	15.40☆	3000
Algorand	1126	9.85	1000
Cardano	8874	0.36	257
Polkadot	297	0.12	1000
Tezos	399	1.70	40
Hedera	21	48.20	10 000

☆ Ethereum Mainnet measurements used as approximation

Table II
The current number of validators, contemporary throughput, and the upper bound of throughput postulated (see Appendix A).

Energy consumption per transaction: To arrive at an energy consumption per transaction metric (c_{tx}), the number of transactions per unit of time needs to be considered. The actual numbers are dynamic and fluctuate over time. The contemporary network throughput (*Cont.*) is defined as the actual throughput recently experienced by a system. As a key metric, this can be derived from approximate timestamps that are associated with transactions on public ledgers. The maximum postulated sustainable system throughput (*Max.*) of the different protocols is derived from casual sources (see Appendix B). Note that these postulated figures are probably optimistic, that is, not necessarily reliable, as they originate not from controlled experiments, but are anecdotal or come from promotional materials. However, we consider these estimates acceptable as they have no direct influence on the energy consumption per transaction for a fixed contemporary network throughput. They merely dictate the domain of the consumption function $f_{c_{\text{tx}}}(l)$ that calculates the consumption per transaction depending on the overall system throughput l (measured in tx/s). Treating the average power consumed by a validator node (p, measured in W) as a constant means that an inverse relationship between consumption per transaction (c_{tx}) and system throughput (l) can be established within the bounds of $(0, l_{\max}]$:

$$f_{c_{\text{tx}}}(l) = \frac{n_{\text{val}} \cdot p}{l}. \tag{2}$$

Modelling c_{tx} as a function of the number of transactions per second: Equation (2) depends on two variables: n_{val} and l. We will now present a model for c_{tx} that depends on one variable, namely l, only. Data from the Cardano blockchain[4] suggest that the number of validators n_{val} and the number of transactions per second l are positively correlated. Namely,

[4]https://data.mendeley.com/datasets/4jv2wmwrc5/1

Pearson's correlation coefficient[5] for n_{val} and l for 375 data points from 29 July 2020 to 7 August 2021 is 0.80. The correlation coefficient for n_{val} delayed by 28 days and l (not delayed) for the same data is 0.87. This is plausible for the following reason: as the total number of users in a permissionless system increases, of the new users, a share becomes validators and another non-disjoint share executes transactions, meaning that n_{val} and l are positively correlated. For permissioned systems, it is still conceivable that the number of validators and throughput are positively correlated because, as new partner organisations are invited to run validator nodes, these partners may decide to use the system for their own applications, thereby increasing the number of transactions. We also observe that in the case of Hedera, the number of validators and the throughput are positively correlated: the number of validator nodes has been continuously increasing, and throughput, while fluctuating from month to month, has increased year to year (see Appendix A). Furthermore, it can be observed for the Algorand and Hedera systems that n_{val} and l have increased from July to August 2021. On the Polkadot blockchain, n_{val} has remained constant from February to July 2021. An exception is the Tezos blockchain for which n_{val} has decreased while l has increased from February to August 2021. This trend has so far held true throughout the lifetime of the Tezos blockchain. We note that, in this case, an affine function is not appropriate for modelling the dependence of n_{val} on l because n_{val} would become negative for large values of l. We will still compute the affine best approximation of n_{val} in terms of l for the Tezos blockchain, as it is an approximation of the first Taylor polynomial of n_{val}, and therefore a local model for n_{val}.

For simplicity we assume that the correlation is perfect, i.e., $n_{\text{val}} = \kappa + \lambda \cdot l$ for some $\kappa, \lambda \in \mathbb{R}, \lambda > 0$, and using (2) we obtain

$$f_{c_{\text{tx}}}(l) = \frac{(\kappa + \lambda l) \cdot p}{l}. \tag{3}$$

Because we could not obtain high-resolution historic data for Algorand, Polkadot, Tezos, and Hedera, we will compute κ, λ later based on two data points. For Cardano, we use linear regression implemented as ordinary least squares regression to compute κ, λ that have the maximum likelihood of modelling $f_{c_{\text{tx}}}(l)$ under the assumption that $f_{c_{\text{tx}}}(l)$ is an affine function with Gaussian noise. The resulting values for κ, λ can be found in Table III.

Platform	κ	λ
Algorand	102.8	103.9
Cardano	3803.4	8877.6
Polkadot	297	0
Tezos	440.7	−24.6
Hedera	7.6	0.3

Table III
ESTIMATES FOR κ, λ USED IN EQUATION 3 TO MODEL THE NUMBER OF VALIDATORS DEPENDING ON THE NUMBER OF TRANSACTIONS PER SECOND.

[5]The correlation coefficient takes values in $[-1, 1]$ and a value of ± 1 would imply that n_{val} is an affine function in l.

Hardware type and compute resource utilisation considerations: In contrast to energy-intensive PoW systems, in PoS, the computational effort relating to the participation in the consensus protocol can almost be considered independent of extraneous factors like cryptocurrency capitalisation. Numerous factors influence the overall energy consumption of a server, with central processing unit (CPU) activity, hard disk drive operations, and cooling being the most significant [33]. The consensus-related energy demand in PoS is generally constant, meaning it occurs irrespective of system load [33]. Energy demand relating to CPU time and input/output operations is, however, highly load-dependent [34]. Therefore, a realistic energy consumption estimate for a validator node needs to factor in both the minimum hardware requirement (i.e., how many CPU cores or how much memory is required) as well as the utilisation of that hardware.

Since it is nearly impossible to determine which type of hardware is used by validators, we use an approximation derived from industry recommendations. Dramatically different hardware recommendations are put forward for permissionless systems and permissioned systems. The permissionless systems analysed in this study, all traditional blockchains with comparatively large numbers of validators running full nodes that verify every transaction [32], demand comparatively low-powered hardware. Hedera, the only permissioned system analysed here, constitutes a high-tps (transactions per second) system. Such systems are characterised by a small number of nodes maintaining consensus [32]. The maximum network performance is determined by the lowest-performing validator node[6]. Therefore, to achieve the postulated maximum throughput values, the network operator demands highly performant server hardware. We assumed that similar high-tps systems would have energy requirements in the same range. This explains the difference in the energy consumption per validator node between Hedera and the other traditional Blockchain systems.

Configuration	Hardware Type	Exemplar	Demand (W)
Minimum	Small single-board computer	Raspberry Pi 4	5.5
Medium	General purpose server	Dell PowerEdge R730	168.1
Maximum	High-performance server	Hewlett Packard Enterprise ProLiant ML350 Gen10	328

Table IV
CONCEIVABLE UPPER AND LOWER BOUNDS FOR THE POWER DEMAND OF A VALIDATOR MACHINE.

To capture the uncertainty regarding appropriate hardware and expected hardware utilisation in the model, three different validator configurations are considered (see Table IV): a single-board computer, a general-purpose rackmount server for midsize and large enterprises, and a high-performance server. For all configurations, hardware utilisation based on

[6]https://docs.hedera.com/guides/mainnet/mainnet-nodes/node-requirements

typical workloads is assumed (see Appendix C). For traditional blockchains, we assume a power demand in the minimum to medium range (5.5 W to 168.1 W). For high-tps systems, the medium to maximum range (168.1 W to 328 W) is assumed.

V. Results

Table V illustrates the application of the models described in (2) and (3) to estimate the energy consumption of the protocols considered under contemporary throughput, i.e., based on recent throughput measurements (see Section IV). To facilitate a broad overview, we also provide the global system-wide consumption of each DLT system according to the model. Furthermore, the table presents two estimates for energy consumption per DLT system: an *optimistic* estimate assuming validator nodes are operated on the lower bound of the system range and a *pessimistic* estimate that assumes validators utilise hardware on the higher bound (see Table IV). As the merging of Ethereum Mainnet with the Beacon Chain is outstanding, no contemporary throughput figures for Ethereum 2.0 can be established. Instead, the current throughput of Ethereum Mainnet (15.40 tx/s) is presented (see Appendix B).

All estimates are based on the validator counts established earlier (cf. Section IV). The plot of the model function shown in Figure 1 visualises the inverse relationship described earlier within the boundaries of the postulated throughput values (see Table II). It also provides a projection of energy consumption as a function of system load, based on the model presented earlier which predicts the number of validators as a function of system load. This projection is equally illustrated within the boundaries of the postulated throughput values, except in the case of the Tezos Blockchain, for which no global model could be derived.

Based on this data, we can compare the energy consumption per transaction on two related systems: first, the PoW cryptocurrency Bitcoin, and second, the VisaNet payment network (cf. Figure 1). It becomes evident that the consumption of Bitcoin – overall and per transaction – is at least three orders of magnitude higher than that of the highest consuming PoS system even under favourable assumptions. While the difference between PoS systems and VisaNet is less pronounced, it is evident that most of the former undercut the energy consumption of VisaNet in many configurations.

Platform	Global (kW)		Per transaction (kW h/tx)	
Eth. 2.0 ☆	14.6 –	445.3	0.000 26 –	0.008 03
Algorand	6.2 –	189.3	0.000 17 –	0.005 34
Cardano	48.8 –	1491.7	0.037 16 –	1.135 62
Polkadot	1.6 –	49.9	0.003 78 –	0.115 56
Tezos	2.2 –	67.1	0.000 36 –	0.010 96
Hedera	3.5 –	6.9	0.000 02 –	0.000 04
Bitcoin	3 373 287.7 –	34 817 351.6	360.393 00 –	3691.407 00
VisaNet		22 387.1		0.003 58

☆ Ethereum Mainnet measurements used as approximation

Table V
Global power consumption ranges (i.e., the network-wide consumption of the DLT systems under consideration and of VisaNet) and ranges of the energy consumed per transaction for contemporary throughput.

Pronounced differences between PoS-based systems are equally evident from the results. We observe a low energy demand per transaction in active permissioned DLT systems that are characterised by high throughput and comparatively small numbers of validators with a corresponding low degree of decentralisation. Less active permissionless systems show a higher energy demand per transaction due to comparatively low throughput and a high number of validators. This illustrates that not only for PoW [35], but also for PoS blockchains, 'energy consumption per transaction' should not be the only metric considered for assessing sustainability. In particular, when utility is not approximately proportional to throughput, total energy consumption may be a more appropriate key figure.

VI. Discussion

A. Interpretations

These results can primarily be understood as a clear confirmation of the common opinion that the energy consumption of PoW systems, especially Bitcoin, is excessive. Therefore, they can be interpreted as a strong argument for the modernisation of PoW-based systems towards PoS. Ethereum is taking a commendable lead in this respect with the development of Ethereum 2.0. Furthermore, the results indicate that the energy consumption of different non-PoW blockchains is surprisingly divergent. In absolute terms, however, the consumption rates of PoS-based systems are moderate and thus also much closer to the figures for traditional, centralised payment systems such as VisaNet. The main reason why our model yields considerable divergence between PoS systems is the difference in the number of validators and throughput. Specifically, in permissioned systems, energy consumption can be controlled through the ability to limit the number of validators on a network, so the permissioned network analysed in this study is characterised by low energy consumption.

This result should not be misinterpreted as an argument for increased centralisation or for permissioned networks over permissionless ones. This becomes obvious when considering a permissioned DLT system in extremis: such a system would consist of only a single validator node and would thus be effectively centralised. This hypothetical scenario shows that, if a permissioned paradigm is applied, close attention should be paid to system entry barriers enforced through gatekeeping capabilities. If not, there is a risk of centralisation, which may offer minuscule advantages in terms of energy consumption but will negate the functional advantages of a decentralised paradigm. The fact that the selection of suitable validator hardware is central to energy consumption is also of practical relevance. Information regarding adequate hardware for validators is often inconsistent. Therefore, standardised recommendations should be put forward to help operators of validator nodes in selecting the most energy-efficient hardware configurations.

This study is only a first step towards quantifying the energy consumption of PoS systems. However, despite its limitations, it gives impetus to designers of decentralised systems by revealing the dependency between validator number, load, and hardware configuration. Our model can thus be used to

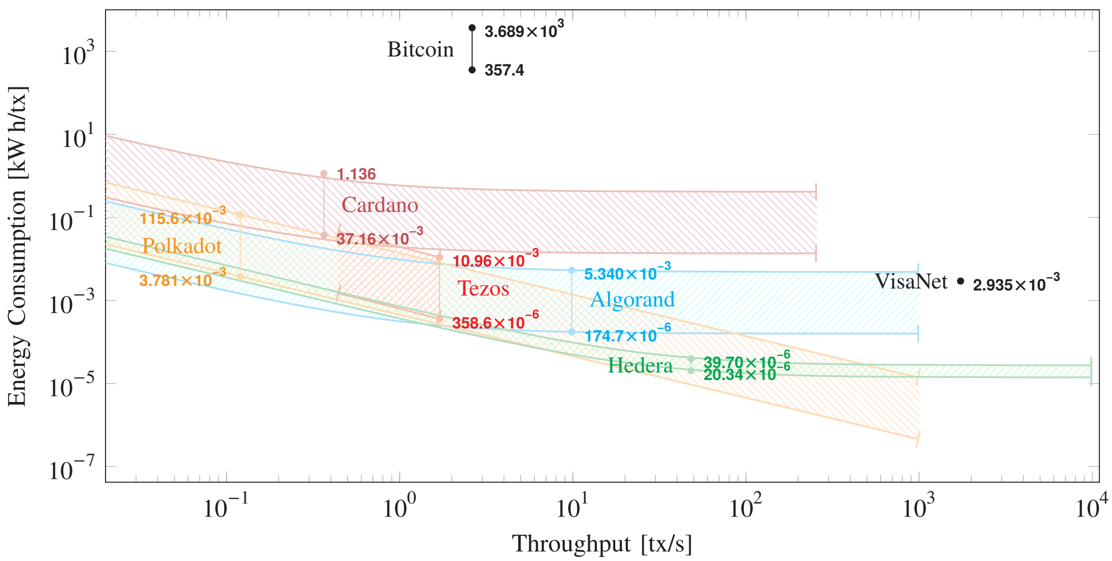

Figure 1. The energy consumption per transaction is close to inversely correlated with throughput. For each system, the lower mark indicates the energy consumption under an optimistic validator hardware assumption while the upper mark indicates a pessimistic model. The consumption figures for Bitcoin and VisaNet are plotted for comparison (see Appendix D). Ethereum 2.0 is not plotted as Ethereum has not yet merged with the Beacon Chain. For Algorand, Hedera Hashgraph, Polkadot and Tezos, contemporary throughput and validator count data points lie exactly on the graph because the interpolation was computed by requiring the graph to pass through them; for Cardano, the graph is a regression obtained from many data points, so the contemporary data points do not lie exactly on the graph.

determine the carbon footprint of a particular use case. It can, furthermore, prompt operators of validator nodes to carefully select suitable hardware.

B. Limitations

So far, we have used broad consumption ranges to model the energy consumption of individual validator nodes. While we are confident that the actual energy consumption is in fact within these ranges, the underlying characteristics of different PoS protocols that might impact energy consumption, such as the accounting model, have been ignored. Second, while assuming that the electricity consumption of a validator node is independent of system throughput is well justified for the permissionless systems analysed [32], permissioned systems that are designed to support high throughput may not warrant such an assumption. We have accounted for this by assuming more powerful hardware for permissionless high-tps systems, but more work is needed to better understand permissioned blockchains' energy consumption characteristics. Moreover, the impact of different workloads on energy consumption should be considered; for example, simple payment transactions may have lower computational requirements when compared to more complex smart contract invocations, but we have not so far distinguished between transaction types.

While our model suggests that PoS systems can remain energy-efficient while scaling up to VisaNet throughput levels, there is no hard evidence in support of this argument, as, to our knowledge, no DLT-based system has experienced a sustained volume of this magnitude to date on the base level. On the other hand, we ignored the possibility of achieving effectively higher throughput than the specified maximum through layer 2 (L2) solutions, such as the Lightning network or via optimistic rollups and zero-knowledge (zk)-rollups that are receiving increasing attention.

Finally, although there are reasons to support its plausibility, the assumption that an affine function can be used to express the number of validators in terms of throughput is questionable. While we assume that it is applicable to Hedera, this might not be a justifiable assumption for other permissioned settings. The applicability of this model to other permissioned systems should therefore be more formally analysed, for example, by collecting more data points and comparing these with the model outputs.

VII. Conclusion

The increasing popularity of DLT systems since the invention of Bitcoin, and with it the energy-intensive PoW consensus mechanism, has produced a variety of alternative approaches. PoS is a particularly popular method that is commonly assumed to be more energy efficient than PoW. In this paper, we tested this hypothesis using a mathematical consumption model that predicts expected energy consumption per transaction as a function of network load. Applying this model to six different PoS-based DLT systems supports the hypothesis and suggests that their energy consumption per transaction is indeed at least three orders of magnitude lower than that of Bitcoin. Furthermore, we discover significant differences among the analysed PoS-based systems themselves. Here, a permissioned system was found to consume significantly less energy per transaction than a permissionless system. This difference can be attributed to the gatekeeping capabilities offered by permissioned systems.

These results can be understood as an urgent call for the modernisation of PoW systems and a shift towards PoS, as well as a recommendation to practitioners to consider energy-saving hardware which aligns with minimal supported configurations. They are also intended to provide a basis for the future comparative study of the energy friendliness of PoS systems and to facilitate the development of more rigorous consumption models. Given the enormous challenges posed by climate change, avoiding unnecessary energy consumption needs to be a high priority. Our work shows that PoS-based systems can contribute to this and could even undercut the energy needs of traditional central payment systems, raising hopes that DLT can contribute positively towards combatting climate change.

Future research should further develop and confirm these initial findings by improving the sophistication of the model and considering factors beyond network throughput that may influence validator count. It should, furthermore, consider the network-wide energy consumption beyond validator nodes (i.e., by including all full nodes and auxiliary services) to arrive at a more holistic view of the overall energy consumption of DLT systems. Applying benchmarking frameworks [36] to measure the actual energy consumption might be particularly worthwhile in the context of permissioned systems that aim for high performance. In addition, analysing the actual hardware configurations, instead of relying on rough estimates, might prove a worthwhile extension. Finally, future work should assess the effects of moving from a permissioned to a permissionless model.

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Author contributions

Conceptualisation: M.P., J.X., P.T., N.V. and J.I.I.; Data curation: M.P., J.S. and D.P.; Formal analysis: D.P.; Investigation: M.P., J.S., D.P., J.X and J.I.I.; Methodology: M.P., J.S. and D.P.; Visualisation: M.P. and D.P.; Writing – original draft: M.P.; Writing – review and editing: M.P., J.S., D.P., J.X., P.T., N.V. and J.I.I.

Competing interest statement

M.P. declares that he is bound by a confidentiality agreement that prevents him from disclosing his competing interests in this work.

Acronyms

CPU	central processing unit
DLT	distributed ledger technology
L2	layer 2
PoS	proof-of-stake
PoW	proof-of-work
tps	transactions per second
zk	zero-knowledge

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Appendix

A. Validator Metrics

Chain	Source	Metric	Obs. Period	Value
Ethereum 2.0	https://etherscan.io/nodetracker	Number of all the nodes running on the Ethereum 1 network	27/10/2021	2649
Algorand	https://metrics.algorand.org/	Number of nodes	12/8/2021	1126
Cardano	https://cardanoscan.io/	Estimated total number of nodes, i.e. 3×number of stake pools, see https://www.climateneutralcardano.org/offset-calculation/	6/9/2021	8874
Polkadot	https://polkadot.subscan.io/validator	Number of validators	5/7/2021	297
Tezos	https://tzstats.com/bakers	Number of bakers	12/8/2021	399
Hedera	https://docs.hedera.com/guides/mainnet/mainnet-nodes	Numbers of mainnet nodes	13/8/2021	21

Table VI
Sources for data on contemporary validator machine count

Chain	Source	Metric	Obs. Period	Value
Polkadot	https://web.archive.org/web/*/https://stakers.info/	Number of validators	27/2/2021	297
Tezos	https://api.tzstats.com/explorer/cycle/324	Number of bakers	5/2/2021	430
Algorand	https://metrics.algorand.org/	Number of validators	5/7/2021	1298
Hedera	https://docs.hedera.com/guides/mainnet/mainnet-nodes	Number of validators	5/7/2021	20
Hedera	https://github.com/hashgraph/hedera-docs/commits/master/mainnet/mainnet-nodes/README.md	Number of validators	7/7/2020–26/8/2021	20

Table VII
Sources for data on historic validator machine count

B. Throughput Metrics

Chain	Source	Metric	Obs. Period	Value
Algorand	https://algoexplorer.io/	Average transaction volume	16/7/2021-12/8/2021	9.845 tx/s
Cardano	https://explorer.cardano.org/en	Number of transactions in epoch	Epoch 282 (3/8/2021-8/8/2021)	157 622 tx
Polkadot	https://polkadot.subscan.io/extrinsic	Mean of the lowest and the highest daily transaction volume	5/6/2021-5/7/2021	0.1200 tx/s
Tezos	https://tzstats.com/	Average number of transactions per second	13/7/2021-12/8/2021	1.700 tx/s
Hedera	https://hedera.com/dashboard	Transaction volume by network service	13/8/2021	48.20 tx/s

Table VIII
Sources for data on contemporary throughput

Chain	Source	Metric	Obs. Period	Value
Algorand	https://algoexplorer.io/	Transactions per second	2/6/2021-2/7/2021	11.5 tx/s
Tezos	https://messari.io/asset/tezos	Average number of transactions per second	6/1/2021-5/2/2021	0.4 tx/s
Hedera	https://hedera.com/dashboard	Transactions per second	5/7/2021	44.6 tx/s
Hedera	https://app.dragonglass.me/hedera/home	Transactions per second	8/2020–8/2021	-

Table IX
Sources for data on historic throughput

Chain	Source	Metric	Value
Ethereum 2.0	https://twitter.com/VitalikButerin/status/1277961594958471168	Transactions per second with Ethereum 1 as data layer	3000 tx/s
Algorand	https://www.algorand.com/resources/blog/algorand-2021-performance	Current maximum transactions per second	1000 tx/s
Cardano	https://vacuumlabs.com/blog/lifevacuum/what-we-love-about-cardano-a-technical-analysis	Maximum theoretical throughput	257 tx/s
Polkadot	https://twitter.com/gavofyork/status/1255859146127179782	Sustained transactions per second	1000 tx/s
Tezos	https://blockfyre.com/tezos-xtz/	Transactions per second	40 tx/s
Hedera	https://hedera.com/hbar	Transactions per second	10 000 tx/s

Table X
SOURCES FOR DATA ON MAXIMUM THROUGHPUT

Bound	Source	Metric	Obs. Period	Value
Lower	https://etherscan.io/	Throughput of Ethereum 1	24/7/2021	15.40 tx/s
Upper	https://twitter.com/VitalikButerin/status/1277961594958471168	Postulated maximum transactions per second	-	3000 tx/s

Table XI
SOURCES FOR THROUGHPUT ESTIMATES FOR ETHEREUM 2.0

C. Validator Energy Consumption

Hardware	Source	Metric	Value
Raspberry Pi 4	https://www.tomshardware.com/uk/reviews/raspberry-pi-4	Power consumption when idle	3.4 W
Raspberry Pi 4	https://www.tomshardware.com/uk/reviews/raspberry-pi-4	Power consumption under load	7.6 W
Dell PowerEdge R730	https://i.dell.com/sites/csdocuments/CorpComm_Docs/en/carbon-footprint-poweredge-r730.pdf	Typical yearly energy consumption	1473.5 kW h
Hewlett Packard Enterprise ProLiant ML350 Gen10	https://www.spec.org/power_ssj2008/results/res2019q2/power_ssj2008-20190312-00899.html	Power consumption under 80% load	328 W

Table XII
SOURCES FOR DATA ON HARDWARE ENERGY CONSUMPTION

D. Comparison Values

System	Source	Metric	Obs. Period	Value
Bitcoin	https://cbeci.org/	Theoretical lower bound of annualized power consumption	11/8/2021	29.55 TW h
Bitcoin	https://cbeci.org/	Theoretical upper bound of annualized power consumption	11/8/2021	305 TW h
Bitcoin	https://www.blockchain.com/charts/transactions-per-second	Transactions per second	30 day average on 11/8/2021	2.620 tx/s
VisaNet	https://usa.visa.com/content/dam/VCOM/global/about-visa/documents/visa-2020-esg-report.pdf	Approximate total energy consumption of the Visa corporation	2020	706 000 GJ
VisaNet	https://usa.visa.com/run-your-business/small-business-tools/retail.html	Transactions per day	8/2010	150 Mtx/d

Table XIII
SOURCES FOR DATA ON REFERENCE SYSTEMS