# Energy Efficiency of Blockchain Technologies

## About this report

This is the first thematic report prepared by the new team leading the EU Blockchain Observatory and Forum, aiming to present the latest updates and developments within the EU blockchain ecosystem.

This is the first of a series of reports that will be published addressing selected topics in accordance with the European Commission priorities. The aim is to reflect on the latest trends and developments and discuss the future of blockchain in Europe and globally.

Credits

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***Special thanks to Scope for the editorial review and language proofing***


## Note

While we have done our best to incorporate the comments and suggestions of our contributors where appropriate and feasible, all mistakes and omissions are the sole responsibility of the authors of this paper.

## Disclaimer



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## Contents

# Executive Summary

The purpose of this is thematic report is to present an updated view of the aspects related to the energy efficiency of blockchain technologies. The topic of energy consumption of blockchains and especially of the Bitcoin blockchain has recently triggered a lot of discussions and a debate has started on the topic of making Bitcoin a sustainable ecosystem.

Although the Bitcoin is currently in the spotlight, this thematic report does not only focus on Proof-of-Work blockchain solutions, but also analyses the whole spectrum of blockchain technologies. In this respect the various consensus mechanisms are analysed with regards to their energy consumption, but also other aspects of the consensus protocols are taken into account, such as security and throughput, that are deemed important when considering the application of blockchain solutions in real-world use cases.

With regards to the energy efficiency of blockchain technologies, the thematic report presents the various approaches and methodologies that address the challenge of estimating the energy consumption of the Bitcoin blockchains. It should be mentioned that although the report is focusing upon the whole spectrum of consensus mechanisms, due to the high energy consumption of Bitcoin blockchain, only methodologies that analyse the energy consumption of the Bitcoin are available and, thus, covered in the report.

Apart from the various diverse applications of blockchain technologies across several sectors ranging from finance and supply chain to the pharmaceutical and energy sectors, cryptocurrencies on the various blockchains are constantly under the spotlight. To also address the topic of cryptocurrencies, the thematic report also deals with the topic of the energy efficiency of the ICT infrastructure that is used for cryptocurrency mining.

In the shade of the high energy consumption of the Bitcoin blockchain issue, the issue for a more sustainable model for Bitcoin and other Proof-of-Work blockchains is once more on the table. Given the fact that the technologies underpinning crypto are powered by electricity—just like other electricity-powered technologies such as cloud computing, data storage & processing, social networks, and artificial intelligence, industries from across the global economy are beginning to decarbonize their operations in order to facilitate widespread, sustainable industry growth. In this context the report also focuses on the most recent initiative for decarbonising the cryptocurrency scene. Inspired by the Paris Climate Agreement, the Crypto Climate Accord was launched as a private sector-led initiative for the entire crypto community focused on decarbonizing the cryptocurrency industry in record time.

From the analysis performed within the report to the topics related to the energy efficiency of blockchain technology a set of recommendations were derived. On the energy efficiency side, at the EU level, the European Blockchain Services Infrastructure needs to consider energy consumption (and efficiency) of blockchain when deciding on the underlying technology for developing the necessary digital infrastructure. Another aspect closely related to energy efficiency is the scalability and performance of blockchain solutions. Therefore, it is recommended that energy efficiency-related issues need always to be treated along with scalability and performance requirements of the blockchain-based solution under evaluation. Moreover, in order to compensate the excess energy consumption especially of Proof-of-Work blockchains, it is important to make sure that renewable energy is used to the maximum possible extent to cover the demand of energy of blockchain-based solutions. Other aspects that are related to the energy consumption of blockchain technology are the recommendation for certification of equipment used as infrastructure for the deployment of public-sector blockchain solutions at European and Member State level, as well as the introduction of specific evaluation criteria related to the performance and energy efficiency of blockchain-based solutions for the public sector need to be specified European and Member State level. Finally, it is recommended that in order to assess the energy consumption of blockchain-based solutions in an independent and unbiased manner, a

blockchain energy consumption index should be developed and agreed between the Member States, as well as knowledge-sharing and dissemination of pilot results and best practices on blockchain deployments between the Member States should be fostered.

To offer a more spherical view of the topic of energy efficiency of blockchain technologies, the thematic report approaches this interesting topic both from an academic (research and development) and an industrial approach. The thematic report is organised as follows. Section 1 presents an overview of the various consensus mechanisms and discusses their respective characteristics. Section 2 presents a deep dive into the topic of the Bitcoin energy consumption indices and analyses the different methodologies and approaches currently developed. Section 3 presents an in-depth analysis of the energy consumption and performance of the cryptocurrency infrastructure, while Section 4 presents the industry's view on the topic of scalability and performance of blockchain solutions. Finally, the Crypto Climate Accord initiative for decarbonising the crypto space is presented in Section 5, while the policy recommendations on the topic are discussed in Section 6.

# Section 1: Demystifying Consensus Protocols

## INTRODUCTION

Energy efficiency (or energy consumption) of blockchain solutions is highly related to the underlying mechanism that is used for achieving consensus between the nodes of the network. Currently, blockchains that are based on the Proof-of-Work, such as Bitcoin and Ethereum, are characterized by high energy consumption. Especially in the case of Bitcoin, there are currently several ongoing discussions on the amount of energy consumed by the miners of the network. The purpose of this section is to present an introduction to consensus mechanisms and describe their respective characteristics. Apart from the energy demanding Proof-of-Work blockchains, it can be seen that there are several other approaches to achieve consensus that guarantee both the required level of security and trust, while being at the same time energy efficient and allow for the scalability and performance of the applications that are based on them. Such alternatives are the Proof-of-Stake and Proof-of-Authority consensus mechanisms.

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## OVERVIEW OF VARIOUS METHODOLOGIES

Generally, "consensus" refers to the process of achieving agreement among different actors operating in a system. More precisely, "blockchain consensus" denotes the procedures through which the different participants of a blockchain network agree on a specific state of data on the system referred as the correct state.

### Participation Modes

Differently from traditional database where only a single entity, the owner or the administrator, keeps a copy of the database, distributed ledgers foresee multiple entities to hold a personal copy of the underlying database (i.e., ledger). This new paradigm is based on the replication of data and the distributed storage by the different nodes of the blockchain networks (i.e., the blockchain peers). Due to the distributed storage, ensuring that all networks' nodes achieve an agreement on a common state represents a difficult task. The vision of the ledger may not be the same for all the nodes as changes on the ledgers (i.e., data updates) have to be propagated to all other peers in the network. Consensus leads a common truth hence a consensus protocols (i) ensures that the data on the ledger is the same for all network nodes, and (ii) prevents malicious actors from manipulating such data.

Two main modes for operating on a blockchain exist: "*permissionless"* and "*permissioned".* These two ways of operating concern at first the access to the blockchain network and secondly the participation to the agreement procedure (consensus) responsible for maintaining the state of a blockchain system. What in literature is often referred to as *public* and *private* blockchains denote just the access to the network. Whenever there is open access, anybody is allowed to access the network and to observe (i.e., read) the data ledger. On the other hand, if access is permissioned only whitelisted participants have the rights to access the network. Concerning the participation to the ledger maintenance procedures, i.e., consensus, whenever it is open to anyone blockchain are called permissionless. Whenever, permissions are in place the system may either restrict on writing (validation) rights only, or on both reading (access) and writing rights. In the first case, the ledger is publicly readable, but any modification of the transaction ledger is entrusted to a selected set of nodes (i.e., *open-permissioned* distributed ledgers). In the so-called *full-permissioned* distributed ledgers participants are selected in advance and all network activities are restricted to these actors only. Fig. 1.1 reports the different participation modes that differentiate between less decentralized distributed ledgers (generally embedding permissions) and those that additionally offer disintermediation namely, that cut out any middleman (i.e., permissionless distributed ledgers).


Source: M. Belotti et al. "A vademecum on blockchain technologies: When, which, and how." IEEE Communications Surveys & Tutorials 21.4 (2019): 3796-3838.

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**Consensus Protocols**

Consensus problems make multi-agent systems to converge to a common vision and it leads all network agent to share the same data. Hence, consensus protocols on blockchains:

(i) ensure that the data on the distributed ledgers is the same for all network actors, and

(ii) prevent faulty nodes (acting both rationally or irrationally) from manipulating the data.

The consensus mechanisms vary between different blockchain implementations according to the system nature (permissionless and permissioned). A variety of consensus protocols exist, with currently three main classes:

- Proof-of-X (PoX) consensus protocols
- Byzantine Fault Tolerant (BFT) protocols
- Hybrid consensus protocols

The first two classes characterize consensus in blockchains while algorithms defined as 'hybrid' mix protocols' aspects from the first two classes. The recent complex consensus implementations proposed by new blockchain platforms consist in creative combinations of PoX and BFT protocols.

Consensus in distributed systems has been studied long before Bitcoin's birth and the very first class of consensus protocols was the one of "BFT algorithms". **BFT algorithms** (a class of State Machine Replication protocols) were adopted to deal with Byzantine nodes i.e., rational nodes acting maliciously. These types of protocols are based on voting procedures where network agents are called to accept or reject a specific vision of the network's state. BFT protocols generally works in systems with a limited number of participants since according to these protocols consensus *proposal* and consensus *decision* represent two separate events demanding the different system's participants to communicate between each other. Indeed, communication complexity represents the major downside of this protocol class. Hence, the necessity for closed-system adoption such as permissioned blockchains.

The advent of Bitcoin gave rise to a new technology based on a new innovative consensus protocol called Proof-of-Work (PoW). The idea behind PoW consensus was to gain the right to validate the state of the ledger by proving to have worked from a computational point of view i.e., to have used a machine (e.g., a computer) to work for the system. This idea of gaining the right to propose and validate the agreement value proposed by the PoW consensus was really innovative at the time since it gave to every node a chance to have a deciding role in the system. This gave rise to the larger category of Proof-of-X (PoX) consensus algorithms where X denotes the resource a network node is consuming/allocating to gain the right to propose and validate the agreement value. While in Bitcoin the X stands for "computational resources" for other consensus mechanisms it stands for a "stake" of the system (Proof-of-Stake), or for memory "capacity" (Proof-of-Capacity) or again wireless network "coverage" (Proof-of-Coverage). All these alternative

PoX-schemes try to replace the energy consumption implicated by the PoW consensus by the consumption of alternative resources.

The advent of permissioned participation modes and the raise of permissioned blockchains and DLTs make the industry reconsidering traditional BFT. Here blockchains are no more peer-to-peer (P2P) systems where every node is given the chance to participate to the consensus of a blockchain but blockchains can be closed systems as the traditional distributed ones studied in the XX century. This consensus phase is marked by protocol experimentation with BFT-based algorithms with the aim of preserving permissionless consensus while keeping the process efficient by reducing the number of participating nodes to the consensus. Hence, consensus is divided in two phases; the first one that determines the formation of a committee of voters elected through a PoX mechanism and the second one where nodes vote according to BFT consensus.

## CONSENSUS EVOLUTION

Agreement problems saw abundant applications in complex systems since the 1980s. Hence, consensus problems existed prior to blockchain and therefore specific consensus protocols have been proposed to deal with blockchains and DLTs. A digression might be opened regarding consensus evolution and the three types of distributed ledgers with the permissionless/permissioned nature of a DLT.

Consensus theory evolved from the pre-Bitcoin phase to the post-Bitcoin one, introducing a new category of protocols i.e., the PoW consensus protocols. A second evolution of consensus took place when Bitcoin gave the way to blockchain i.e., when other blockchains were proposed and Bitcoin was anymore a solo player in the ecosystem. This second phase corresponded with the birth of the second generation of blockchains adopting PoX schemes; alternatives to the Bitcoin's PoW. A third evolution was characterized by the advent of permissioned participation modes and the raise of permissioned blockchains and DLTs. Here blockchains are no more peer-to-peer (P2P) systems where every node is given the chance to participate to the consensus of a blockchain but blockchains can be closed systems as the traditional distributed ones studied in the XX century. Consensus then evolved by reconsidering traditional BFT and by implementing such protocols in blockchains now considered as a branch of DLTs (i.e., a DLT structured as a chain of transaction blocks). The fourth evolution step was marked by consensus experimentations with BFT-based algorithms with the aim of preserving permissionless consensus while keeping the process efficient by reducing the number of participating nodes to the consensus. Hence, consensus is divided in two phases; the first one that determines the formation of a committee of voters elected through a PoX mechanism and the second one where nodes vote according to BFT consensus.

The four consensus evolution steps mark the five phases of consensus theory represented in Figure 3.2 characterizing the main consensus variants for each consensus class. Main algorithms representing the classes are associated to each consensus variant.

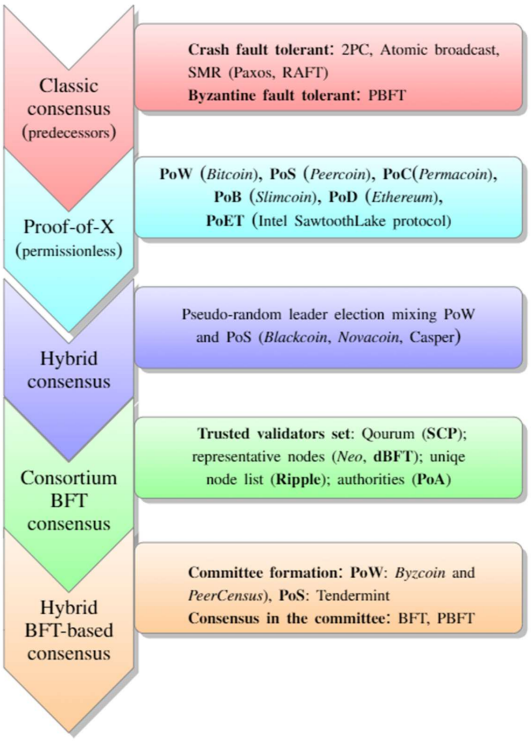


Fig. 3.2: Evolutionary route of consensus protocols in five classes: (i) Classic consensus, (ii) Proof-of-X consensus, (iii) Hybrid consensus, (iv) Consortium BFT consensus and, (v) Hybrid BFT-based consensus. Source: M. Belotti et al. "A vademecum on blockchain technologies: When, which, and how." IEEE Communications Surveys & Tutorials 21.4 (2019): 3796-3838.

ENERGY EFFICIENCY OF CONSENSUS PROTOCOLS~~Comparison of Consensus Protocols~~

In recent years, the term blockchain has often been used synonymously with inefficiency and disproportionate energy consumption. These claims usually direct the responsibility to a single component of the technology, the consensus mechanism. However, blockchain technology is not homogenous, and the amount of energy consumed by different consensus mechanisms varies by several orders of magnitude. This section aims to provide an overview of a subset of the available consensus mechanisms and their role in different blockchains while placing emphasis on their energy consumption. Considering the large number of consensus mechanisms and their minor variations, we focus on those utilized by well-known blockchains and widely used in the industry and public sector.

A Blockchain is a distributed system not controlled by a distinguished operator that maintains an append-only, ordered list of transaction records. Transaction records are disseminated, ordered, and batched in blocks through a distributed protocol followed by the participating nodes and establish a synchronized distributed database. We classify blockchains as permissioned or permissionless, based on who is eligible to become an entity that can actively participate in the decision-making on which blocks to append (Butijn et al., 2020). Another frequent classification distinguishes between public blockchains, where running a node for validation and reading transactions is allowed to anyone, and private blockchains, where read access is restricted.

Permissioned blockchains are often used by consortia in the public or private sector. Organizations that wish to participate in the operation of a permissioned blockchain must typically fulfill criteria specified by the existing nodes in the network. Some of these requirements include an identity verification process, uptime-, hardware-, or bandwidth-specifications for the nodes, a period where the node establishes trust with other nodes in the system, and more. Typically, the participating entities are companies or public organizations that can meet significant computing, storage, and bandwidth requirements. As the total number of entities is known, decisions regarding which blocks to append can be made based on a voting-like protocol and the waiting time for getting a sufficient number of votes can be controlled. Hence, permissioned blockchains tend to feature faster transaction speeds and are less susceptible to malicious users attempting to sabotage the network. The higher efficiency and additional level of security are two of the primary reasons that make permissioned blockchains the choice for many private blockchains, besides restricted data visibility and a higher degree of control of governance and transaction fees.

On the other hand, permissionless blockchains allow for unrestricted access and participation. As a result, they tend to have a larger userbase which makes them more decentralized. However, this generally comes at a substantial latency cost since additional mechanisms are necessary to ensure that malicious users do not hijack the system. Elections based on “one participant, one vote” are not feasible here, because there is no control on how many accounts a participant generates. Consequently, protection against “Sybil attacks” is required. The open participation in the network's operations makes permissionless blockchains suitable for the underlying cryptocurrencies of public blockchains.

Despite their differences, both types of blockchains have a few core concepts in common. One of them is that trust in a blockchain protocol should not be bestowed on a single or a very small group of nodes and that the nodes always reach a unique decision even when some of them crash or behave maliciously. To achieve these objectives, blockchains employ at least a crash fault-tolerant (which may be sufficient for a private blockchain where participants know each other and can be held accountable for misbehavior via legal contracts), and typically a fault-tolerant consensus mechanism (which is a de-facto requirement for permissionless blockchains).

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## PERMISSIONED CONSENSUS

When it comes to permissioned blockchains, the consensus mechanism can be compared to a voting-based protocol where every user has a pre-defined voting weight. Typically, the different participants have equal voting power. However, a reputation based weighting is also possible and can be useful if there is some soft hierarchical structure (imagine OEMs and small suppliers in a supply chain network, where a single supplier's vote should arguably not have the same weight as an OEM's, but a considerable number of suppliers should still be able to outvote the OEM). This kind of mechanism is often called Proof-of-Authority (PoA), although this is an umbrella term including mechanisms with different properties and levels of security (De Angelis et al., 2017). These mechanisms can be separated into crash fault-tolerant (CFT) and byzantine fault-tolerant (BFT) mechanisms.

CFT consensus mechanisms divide the network's nodes into two main categories; follower nodes and – at any time – a single leader node. The follower nodes elect the leader, interact exclusively with the leader after its election, and the leader is the sole entity responsible for ordering and committing new transactions to the blockchain. The mechanism utilizes a two-phase commit protocol (2PC) which operates as follows: In the first phase (commit-request phase), the leader communicates with the follower nodes to ensure they are ready to commit a transaction. On the second phase (commit phase), the leader commits or aborts the transaction, broadcasting the action to the followers. When the leader crashes, a new leader is elected, and through the two-phase "gradual" commit, conflicts that may arise (for instance, if the previous leader notified only a subset of the other nodes to commit before it crashed) can be resolved. CFT consensus mechanisms can operate while most nodes have not crashed but cannot cope with malicious nodes, as the followers blindly "follow" the leader as long as it is running. As a result, CFT consensus mechanisms should be used only in blockchains with a high level of trust or at least accountability between nodes, or if some degree of fault-tolerance against malicious behavior is achieved on another level (e.g., in Hyperledger Fabric). Probably the most widely used CFT consensus mechanism is RAFT (Ongaro and Ousterhout, 2014). Some of the properties that make RAFT appealing to private blockchains include fast block times (as low as 50 ms if network latency is small, e.g., a regional network), transaction finality (transactions cannot be altered retrospectively), and the fact that it does not generate empty blocks. Blockchains that use RAFT include GoQuorum and Hyperledger Fabric.

In contrast, BFT consensus mechanisms can deal with malicious activity, allowing a blockchain to remain operational as long as more than 2/3 of the nodes remain honest and available. The mechanism achieves that by adding an extra phase, creating a three-phase commit protocol (3PC). The extra phase (pre-commit phase), sandwiched between the two previously mentioned phases, allows nodes to determine whether enough other nodes are planning to commit or not before they actually commit a transaction. Because the third phase adds an extra round of message exchange between the nodes, it contributes to higher latency and increased bandwidth requirements. This makes BFT mechanisms generally slower than CFT mechanisms. Some of the most common BFT based consensus mechanisms are IBFT 2.0 (Saltini and Hyland-Wood, 2019) and QBFT used by Hyperledger Besu and RBFT (Aublin et al., 2013) used by Hyperledger Indy which are all based on PBFT (Castro and Liskov, 1999). Like in CFT, these mechanisms achieve immediate finality (assuming the network has more than three nodes), but the time it takes to add new blocks increases as the number of nodes grows. Consequently, BFT consensus can become challenging for large networks that consist of hundreds of nodes.

## PERMISSIONLESS CONSENSUS

When it comes to permissionless blockchains, a basic one-user one-vote protocol is infeasible since, under the veil of anonymity or at least pseudonymity, a user could create multiple accounts at essentially no cost and outvote the system ("Sybil attack"). To avoid this issue, permissionless blockchains associate each user's voting power with a scarce resource that cannot be replicated without considerable costs and whose possession can be proven to the network (Sedlmeir et al., 2020a). Ideally, the costs for the scarce resource are linearly dependent on the replication factor to make account splitting useless and to ensure fairness by avoiding economies of scale that would give an advantage to participants that already have a lot of voting power.

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In Proof-of-Work (PoW), the scarce resource is the computational power of each user. In this mechanism, nodes compete for the solution of a computationally expensive and – as a result – energy-intensive, cryptographic puzzle ("mining"). The winner of the competition gets to create the next block and receives a specific amount of the blockchain's native currency and fees for the transactions included in this block as a reward. This mechanism makes it practically impossible for malicious users to tamper with the blockchain, as changing one block would require tremendous amounts of computational power to "outrun" the rest of the system for some time. Additionally, it places a high economic risk because the resources invested into mining a block would likely be wasted when the next, likely honest miner does not accept the block and prefers to build on an alternative block. The complexity of the cryptographic puzzle increases as more mining power is present. Mining power, in turn, is driven by the economic incentives given through block rewards (which are proportional to the current price for the cryptocurrency) and transaction fees. As cryptocurrency prices have significantly increased over the last years, it seems that PoW has become more and more computationally demanding over time, but this may not hold forever. Notably, the regular halvings of block rewards, as implemented in many PoW cryptocurrencies such as Bitcoin (Nakamoto, 2008), would even reduce the energy consumption in the long run, given constant prices. In the early stages, when the puzzle's complexity is low, power is fairly distributed among the blockchain's participants ("one CPU, one vote"), but as the complexity rises, rich users benefit increasingly from economies of scale (electricity and specialized hardware cost increase sublinearly), and there is a substantial risk that power gets accumulated by a few groups of users. This can be observed in Bitcoin in the form of large mining pools. PoW is one of the most commonly used consensus mechanisms for permissionless blockchains used by Bitcoin, Ethereum (Buterin, 2014), Monero, Zcash, and many more.

Another popular consensus mechanism for permissionless blockchains is Proof-of-Stake (PoS), in which the scarce resource is each user's share of the blockchain's native currency. While this mechanism is considerably less energy demanding than PoW and can be made provably secure, the initial coin allocation is critical since poor distribution can result in concentration of power. There are three main variations of PoS mechanisms, Pure Proof-of-Stake (PPoS), Delegated Proof-of-Stake (DPoS), and Bonded Proof-of-Stake (BPoS):

PPoS, used for instance by Algorand (Gilad et al., 2017), allows any user to be selected as a leader or a committee member, where the likelihood of selection is proportional to the number of coins held by the user. Following the selection, the leader proposes the next block. Next, the committee members vote on whether to commit the block in a BFT-like protocol. After the creation of the block, a new round starts, and new members are selected. This approach makes it impossible for malicious users to control the system because they cannot control who is chosen as leader or committee members. Although rich users have a higher chance of being selected, dishonest activity on their side would diminish the value of the currency they have heavily invested in, which acts as a deterrent. The probability of creating the next block is proportional to the number of coins held. Consequently, remuneration corresponds to interest at a rate that is – on average – the same for every participant. While rich users get more rewards in absolute figures, their relative stake and, thus, their voting weight does not change over time. This likely avoids the long-term centralization tendencies observed in PoW (Roşu and Saleh, 2021).

Used by EOS and TRON, for instance, DPoS allows users to elect a specific number of delegates with voting power proportional to the coins they are holding. Following their election, delegates take turns creating the next blocks. The difference with PPoS is that delegates stay in power for extended periods of time and are not re-elected after each block. This mechanism allows for higher throughput as the hardware and bandwidth requirements on delegates can be increased. However, it also comes at the expense of decentrality since, at any point, only a handful of delegates have power over the system. Additionally, this mechanism could expose the delegates to denial of service attacks that would cause the blockchain to stall; consequently, being a delegate is challenging.

In BPoS, used for example by Ethereum 2.0 and RChain, users can lock a portion of their balances for a certain period of time, and the probability of being chosen as the next validator is proportional to the number of coins they have locked. The selected users, after creating the block, receive the transaction fees as a reward. The mechanism prevents users from behaving maliciously by burning the locked coins in the event of fraudulent activity. Since this mechanism does not incentivize, and in some cases does not allow, users with

small amounts of coins to lock their balances, it enables rich users to accumulate more wealth over time, potentially damaging the decentrality of the blockchain.

It is important to note that this classification is not exhaustive, and there are PoS mechanisms combining ideas from different categories. One of them is Ouroboros Praos (David et al., 2018), used by Cardano, in which users are not required to lock any amount of their balance, they can be selected as leaders based on the number of tokens they hold (there is no committee like in PPoS), but they have the option to delegate their power to another user if they choose. Additionally, the distinction between permissioned and permissionless consensus is not as clear as it may seem. For example, although highly theoretical at this point, a voting-based consensus mechanism built on a certificate-based European digital identity (European Commission, 2021) could potentially provide high performance while keeping a low eligibility threshold, making it accessible to all citizens. This mechanism is technically permissioned, but because of the low entrance criterion it may be much closer to permissionless than to permissioned systems with high-end hardware criteria.

## COMPARISON OF ENERGY CONSUMPTION

While the consensus mechanisms bear the lion's share of the responsibility for PoW blockchains' energy consumption, several components contribute to the energy consumption of blockchains in general. They can be divided into three main categories: the consumption deriving from consensus mechanisms, the redundant computation and storage associated with the blockchain's operations, and the idle energy consumption of each node.

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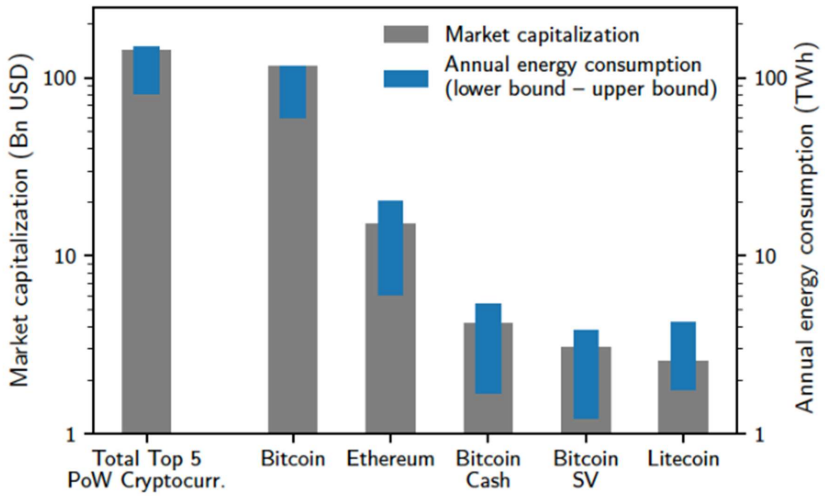
In major blockchains that utilize PoW, idle energy consumption and consumption due to redundant operations are negligible compared to the enormous consensus mechanism's energy consumption for typical network sizes (e.g., around 100,000 nodes for Bitcoin) (Sedlmeir et al., 2020b). As a result, we can accurately estimate the blockchain's energy usage by focusing exclusively on the consensus mechanism. Because of this, energy consumption per transaction, a frequently used measure, tends to provide inaccurate estimations since even when the transaction output increases, the energy consumption of PoW, and therefore of the blockchain, practically remains constant: Block size can be increased without changes in consensus; in fact, more transactions and, thus, larger blocks may not only decrease the energy per transaction because the base load is split to more transactions, but even reduce the blockchain's total energy consumption because there is less competition for transaction slots, which can reduce overall transaction fees and, thus, mining rewards and ultimately energy consumption. While criticism of PoW's the energy consumption is arguably justified, predictions that suggest that the energy consumption will massively increase in the future obtained by interpolating the energy consumption by the expected number of transactions, as conducted by (Mora et al., 2018), should not be taken seriously (Lei et al., 2021).

Due to the nature of permissionless blockchains, certain variables required for accurately estimating the energy consumption of PoW blockchains, such as the number of miners and hardware specifications of each miner, cannot be measured easily. Consequently, researchers must rely on approximations to provide lower and upper bounds on energy consumption. Nonetheless, reasonable estimates are available based on the work of Vranken (2017), Krause and Tolaymat (2018), and De Vries (2018). An important factor that influences the energy consumption of PoW-based blockchains is whether the network permits highly specialized mining equipment or just general-purpose hardware. More specifically, a lower bound on energy consumption can be determined through the observable hash rate and the most energy-efficient mining hardware on the market. On the other hand, an upper bound can be determined via the assumption that mining is profitable, so the costs for electricity do not exceed the accumulated block rewards and transaction fees. Hence, the upper bound depends on the price of the cryptocurrency, the number of new coins created per block, transaction fees, and the smallest electricity costs on the market. Taking these factors into consideration, Sedlmeir et al. (2020a) estimated that in early 2020 the energy consumption of Bitcoin ranged between 60 TWh and 125 TWh per year and provided estimates on the energy consumption of the five highest valued (by market capitalization) PoW cryptocurrencies, as illustrated in figure 1. Additionally, since the upper bound depends on the value of the cryptocurrency, considering the substantial increase in the value of several cryptocurrencies in recent months indicates that the upper bounds of these estimates have increased substantially. This brings the upper boundary of Bitcoin's electricity usage to be higher than that of nations like Norway and Argentina.

A detailed analysis also suggests that Bitcoin's energy consumption dominates the energy consumption of all other PoW cryptocurrencies combined: In their study, Gallersdörfer et al. (2020) estimated that Bitcoin accounts for approximately 2/3 of the consumption generated by all PoW blockchains.

It is also worth noting that improving the energy efficiency of mining hardware does not reduce the power consumption of PoW blockchains in the long run. This is because the network adjusts the complexity of the cryptographic puzzle based on the network's computational power. As a result, when improved hardware is available, a vicious cycle is created where users using this hardware solve more and more puzzles, and the puzzle's complexity gets higher and higher. Consequently, although the energy efficiency of mining hardware has increased dramatically over the past decade, the energy consumption of PoW blockchains has increased rather than decreased.




Market capitalization and the computed bounds on energy consumption for the 5 highest valued Proof-of-Work cryptocurrencies in early 2020. Note the logarithmic scale on the y-axis
Source: (Sedlmeir et al., 2020a)

When it comes to PoS, CFT, and BFT based blockchains, the consensus mechanism consumes orders of magnitude less energy than PoW. The range is typically specified by a 99.95 %, 99.98 % or even higher reduction in energy consumption (Beekhuizen, 2021) However, in BFT based mechanisms, consensus' complexity increases super-linearly with the number of nodes, which also implies increasing amounts of energy as more nodes participate. However, their energy consumption remains very limited for practical network sizes. In the end, in contrast to specialized mining hardware with high power consumption used in high numbers in PoW, CFT and BFT blockchains are usually running on commodity servers. As a result, a permissioned blockchain with 20 nodes will not consume significantly more than 1 kW of electrical power when it is running, compared to a double-digit number of GW for Bitcoin – not considering that Bitcoin currently operates a single-digit number of transactions per second while a permissioned blockchain can operate hundreds to thousands. However, as mentioned, energy per transaction is not always a good metric, and proponents of Bitcoin rightfully claim that the transactions that happen on the Lightning Network (Poon and Dryja, 2016) could scale to thousands or even millions of transactions per second without a considerable increase in energy consumption.

In permissionless blockchains using non-PoW-based consensus mechanisms and in permissioned networks that do not operate consistently at high load, the major share of energy usage derives from idle power

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consumption and, typically to a lesser extent, from the network's redundant operations. Because of this, energy consumption per transaction again provides inaccurate estimates also for these blockchains, as idle consumption remains unaffected by the number of transactions. As a general guideline, a network with N nodes based on these mechanisms consumes approximately N times the energy of a centralized system using hardware similar to that of the nodes (without taking into consideration potential backups on the one side and a larger number of cryptographic operations on the other side). However, it is practically impossible to estimate the idle consumption of nodes as users, particularly in public blockchains, tend to use a wide variety of hardware consuming various amounts of energy, and the differences between a desktop computer that runs only for a blockchain node (consuming on the order of 50 W) and a raspberry pi or a cloud instance that only consume on the order of 5 W is significant. For this reason, we place emphasis on the consumption coming from the blockchain's redundant operations, which dominates the estimate as soon as the hardware is tailored to the requirements of a node.

Two factors influence the energy consumption associated with redundant operations: the number of nodes performing specific operations concerning the consensus mechanism and the complexity of the workload (Sedlmeir et al., 2020a). Over the years, multiple methods have been developed to reduce the energy consumption of these two factors. For example, blockchains can employ sharding to reduce the consumption coming from the number of nodes that must perform the operations, i.e., reducing the degree of redundancy. Using sharding, a blockchain divides the nodes into subsets, and the transactions are verified only in one of these subsets, spending only a fraction of the recourses. Implementing sharding is heavily consensus-specific and can be challenging in blockchains using PoW but is rather straightforward in PoS. However, since fewer nodes validate the transactions, sharding makes a system more centralized and, thus, less secure. Hence, sharding can help balance the need for redundancy and efficiency but allows only for a bounded factor of improvement.

On the other hand, reducing the energy consumption associated with the verification of new blocks and the transactions included, specifically if operations are computationally intensive (for instance, a large matrix multiplication), can be achieved using succinct proofs, the most prominent representative of which may be Zero-Knowledge-Proofs (ZKP) (Canetti and Garay, 2013). These methods can utilize that instead of having all nodes re-compute the operation, a single party performs the computation in a more intricate way and generates a proof for the correctness of the computation that is much easier to verify than re-compute the original operation. The necessary calculations are hence carried out off-chain with just the computationally light verification taking place on-chain. When the number of nodes is large, the cumulative energy savings for the verifiers significantly outweigh the additional energy consumed by the “prover.” Consequently, this approach can help save energy (besides being beneficial from a privacy and performance perspective, which is the main reason for using ZKPs on blockchains).

Most public blockchains can run on low-end hardware today, like a raspberry pi, which consumes less than 5 W per device. Given that VISA and PayPal consume approximately 5,400 J (Visa, 2019) and 73,000 J (PayPal, 2020) per transaction when the companies’ overall consumption is considered, a blockchain with low-end hardware could consume as much energy as VISA while operating around 1,000 nodes, and 15,000 nodes in the case of PayPal. Consequently, medium-sized blockchains that run on reasonable hardware are comparable in energy consumption on a per-transaction basis, and with the stated optimizations, large permissionless blockchains like Ethereum will – once they run on PoS – likely not consume considerably more energy than today’s centralized payment systems. Permissioned blockchains, on the other hand, only have a low degree of redundancy and – despite being more energy intensive than a centralized server – still have an energy consumption comparable to common software applications and will likely generate energy savings rather than additional consumption when new workflows can be digitized.

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# ENERGY CONSUMPTION OF THE ENERGY WEB BLOCKCHAIN

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Energy Web (EW) is a global nonprofit organization accelerating a low-carbon, customer-centric electricity system by unleashing the potential of open-source, decentralized technologies. EW focuses on building core infrastructure and shared technology, speeding adoption of commercial solutions, and fostering a community of practice.

In 2019 EW launched the Energy Web Chain (EW Chain), the world's first open-source, enterprise-grade blockchain platform designed for the energy sector's regulatory, operational, and market needs. Since launch, it has become the industry's leading choice as the foundational digital infrastructure on which to build and run blockchain-based decentralized applications (dApps). With a virtual machine identical to public Ethereum, developers can begin writing smart contracts and dApps for EW Chain with little to no additional learning curve.

The EW Chain boasts high scalability, low transaction costs, and lean energy consumption, thanks to its unique consensus mechanism. In contrast to Proof-of-Work (PoW) blockchains such as Bitcoin and Ethereum that rely on anonymous miners to operate the network via energy-intensive crypto mining, EW Chain uses a permissioned Proof-of-Authority (PoA) consensus mechanism in which a pool of known and trusted computers—called validator nodes—are responsible for validating transactions and creating blocks. The EW Chain's PoA consensus mechanism consumes a staggering six orders of magnitude less energy than Ethereum, while offering certain security, regulatory transparency, and considerable capacity benefits over Ethereum.

## EW CHAIN'S ENERGY FOOTPRINT

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A blockchain network like EW Chain or Ethereum is akin to a single computer that is replicated across many individual computers across the internet. Decentralized blockchain computers need a consensus mechanism - or a method by which a temporary "leader" is chosen to make decisions for the whole network for a short period of time. Consensus mechanisms can be competitive and energy-intensive like Ethereum's PoW method, or highly orderly and energy-efficient, like EW Chain's PoA method where "authority" validator nodes take turns proposing blocks to add to the chain in a round-robin fashion. By contrast, the most common alternative to PoA consensus, PoW, involves computers racing to solve arbitrarily difficult math problems - using vast amounts of computing power and energy in the process. Stripping away the competitive "mining" aspect from a blockchain drastically reduces its energy consumption. In fact, the energy footprint of a single *non-mining* blockchain node is comparable to a typical desktop computer.

A blockchain's energy footprint is the sum of the individual footprints of all of its miners or validator nodes - at present EW Chain has about 50 validator nodes across the globe. We estimate that each node consumes between 50 and 150 Watts of power at all times, depending on its components and HVAC cooling requirements. Taking the top end of this estimate, EW Chain's instantaneous power draw is about 7.5 kilowatts. In comparison, Ethereum draws roughly 1,000,000 times more power and Bitcoin consumes roughly 2.2 million times more power than EW Chain.

Measurements of EW Chain nodes over time suggest that power consumption is relatively constant, regardless of whether the blockchain is under heavy or light load. Power requirements may slowly grow over time as the blockchain "state" (the total stored smart contracts and account data) grows, more validators join the network, and transactions become more computationally intensive. But for now, it is safe to treat EW Chain's energy consumption as a constant.

## AN ENERGY DAPP'S FOOTPRINT

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Since the EW Chain is essentially a decentralized computer purpose-built for the energy sector, it has resource constraints like any other computer. When you evaluate one of the many decentralized apps (dApps) running on the EW Chain, you can easily calculate how much of the blockchain's resources it consumes and hence, its share of EW Chain's energy footprint. Things get interesting when you explore the impact design decisions have on the amount of blockchain resources a dApp needs to consume to deliver value to the energy sector.

For instance, a dApp designed to track thousands of home batteries participating in grid services might do the vast majority of its data processing activities off-chain and only make a total of four on-chain transactions per hour; whereas another application for a *single home* could be designed to do its data processing on-chain and use the chain significantly more than the dApp supporting thousands of homes. Not all energy dApps are designed with the same constraints or considerations in mind, and some applications that leverage digital identifiers (DIDs) anchored on the EW Chain could use the chain only *once per year* or less, yet still enjoy many of the security, authentication, and transparency benefits the EW Chain has to offer. Hence, it might be better to evaluate how much *value* a dApp derives from its share of the EW Chain's resources rather than how much energy it consumes. With proper use of DIDs and the surrounding suite of EW Utility Layer Services, the EW Chain could support 100's of millions of devices and applications.

## HASHNET BLOCKCHAIN - ~~FIRSTLY, WE HAVE TO DIVE INTO WHAT CONSENSUS MEANS AND WHAT ALGORITHMS MEANS, HOW A COMBINATION OF THEM IS BRINGING CONSENSUS PROTOCOLS BASED ON AUTOMATED PROCESS FOR A MULTIPARTY SCENARIO, NOT ONLY INVOLVEMENT RATHER THAN CONSEQUENCES IN EFFECT OF A FACT WITH RESPONSIBILITIES BEHIND. A~~ DISTRIBUTED ~~CONSENSUS MECHANISM STARTS WITH NO LEADER AND IT ESTABLISHES~~ TRUST ~~BETWEEN THE STAKEHOLDERS WHICH INCLUDE THE EXCHANGE OF PROOFS AND VALUES.~~

## OVERCOMING SCALABILITY AND PERFORMANCE BARRIERS

HashNET platform is focused on providing a new type of scalable, fast, secure, and fair decentralized solution, leveraging Distributed Ledger Technology (DLT) and consensus algorithm which keeps all positive characteristics of blockchain technology (decentralized, transparent, pseudo-anonymous) while significantly increasing transaction throughputs. HashNET uses an Improved Redundancy Reduced Gossip (Improved RRG) and "Virtual Voting" protocol for information transfer on a suitably designed network, which make possible to achieve considerably lower traffic load than conventional push-based gossip protocols and traditional push-pull gossip. And it is the consensus mechanism that ultimately determines the level of security, speed of transactions and scalability of a network, making it possible to increase the number of transaction executed in second for more than 50 times, keeping the time to finality up to three times lower compared to existing, tested solutions (at the level of 3 to 8 seconds).

Scalability turns out to be often mentioned as one of the biggest challenges related to wide spread usage of the blockchain technology. HashNET was built to support up to 50,000 transactions per second on layer 1 and is able to support millions of transactions per second on layer 2 (when form of sidechains applied). Even with hundreds of nodes, HashNET network is able to process all transactions in a matter of seconds, since the Improved RRG and "Virtual Voting" mechanism innovation eliminate inefficiency imposed by other based blockchain solutions.

Various efforts have been made by development team to move scalability solutions to a second layer, to mentioned sidechains. Usage of the sidechain ensures that user interactions are shifted from the blockchain layer (1) onto a second layer (2), while guaranteeing risk-free P2P transactions between participants. Sidechains are separate blockchain networks, compatible with the mainchain. Sidechains have their own consensus mechanism, their own level of security, and their own tokens. Throughput of the blockchain would be a cumulative value of main and sidechain, thus creating enormous scalability potential of HashNET technology. It's also important to emphasize that if the security of a sidechain network is compromised, the

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damage will not affect the mainchain or other sidechains. Both networks are linked to each other via a “two-way peg” and can transfer any state. This way, tokens can be exchanged at a predetermined rate between the mainchain and the sidechain. The mainchain guarantees overall security and dispute resolution, and the transactions that are outsourced to the sidechain – although the mainchain contains the information on each event alongside with timestamp and transaction signature information.

To take a look in depth, how the described scalability is achieved, is important to describe HashNET consensus mechanism. Each node in the network keeps a representation of the HashNET in its memory. The HashNET that each node has can differ, but through the process of gossip, the yet unknown events to the node are added to its HashNET representation. Next, we need to introduce the term of an event object as a data structure created by some node and containing the two hashes of the preceding events – parent event created by the same node ("self-parent") and the parent event created by some other node ("other-parent"). The node that is the creator of the transaction also puts a timestamp to the event object at the creation time, and the event is thus digitally signed. Each event object can optionally contain zero or more transactions making the event a container for those transactions. When the event gets gossiped the signature is sent along with it. Events can have zero transactions either when a node receives a sync event (HashNET difference) or when the node has just been spawned, thus creating the first event with no self-parent and no other-parent, and there are no pending transactions that this node is aware of in its transaction pool.

The goal of the HashNET algorithm is for nodes in the network to come to a consensus. The consensus is defined as agreement on the order of events. Furthermore, by agreeing on the timestamps for each event, the order and timestamps for each transaction are determined as well. Nodes can call each other at random for syncing and determining which events they don't have recorded yet in their instance of the graph.

Since a green energy transition has been a central pillar of EU policy-making, it is necessary to adapt energy infrastructure to the future needs of the energy system, within decentralised network. It is clear that if building blockchain applications move toward less energy-intensive methods of verification, there should be a resultant decrease in blockchain energy consumption. It does not require miners to create a chain of blocks in order to record transactions, and thus, the enormous amount of energy is saved.

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While Redundancy Reduced Gossip (RRG) and other asynchronous distributed consensus protocols provide communicational and computational efficiencies, additional implementation improvements are necessary to handle large fast-growing systems. A direct implementation of such protocols could require exchanging as much as O(n^3) messages for reaching a consensus on a single binary outcome, which would make them not practical and unsustainable for systems where the number of nodes, n, is large. Thus, the imperative of HashNET development strategy was to implement the consensus protocol in a way that minimizes communicational load due to information transfer among nodes. It leverages the fact that every node has a sufficient information on the entire HashNET structure, including information about events and their propagation through the network to compute content of the vast majority of messages required by Improved Redundancy Reduced Gossip (IRRG) protocol, thereby eliminating the need for sending them and, consequently, significantly reducing communication requirements. A somewhat similar approach towards reducing communication requirements in an implementation of a different consensus protocol has been proposed before, but unlike the HashNET system, a critical requirement imposed by each was that the number of nodes is constant and must remain fixed constant throughout. An important prerequisite for an efficient computation of consensus is that the total number of nodes (“voters”) needs to be known. HashNET overcomes this difficulty by assigning to every node the vote weight that is equal to their stake at a given point of time. By assigning node weight to be its stake in network, HashNET achieves the ability to calculate votes instead of waiting for and/or sending actual votes over the network. As long as two-thirds of the nodes are safe, consistency of consensus can be ensured, while in worst scenario of cyber-attack of more than one third of the nods in network, all history of transaction remains unchanged and can be replicated. All the servers at same time would need to be destroyed to erase the history.

For high volume and velocity of transaction, the additional note has to be made - HashNET poses specific functionality of ordering transaction, allowing fair execution. If main chain (layer 1) alongside with sidechains installed to handle millions of transaction proves not to be enough in peeks of, let us say, IoT based large number of applications, the HashNET will adjust to the terms. Additionally, if keeping it on layer 1, it poses a property of creating the (optimized size) bulks of transaction proposals, HashNET would make fair ordering action, imposing 'first in – first out' method on transaction requests. Validation phase would be executed for each bulk of transaction request, again imposing same 'first in – first out' method to ensure fairness. Hereby is important to emphasize that the metod of adding a sidechain and creating a batch of transaction bulks are not mutually exclusive ant they add up to solution scalability. It's the matter of the use case the blockchain is used for how many if any sidechain needs to be used or batching option is efferent enough.

HashNET key blockchain infrastructure capabilities:

1. Ensures completion of 50.000 transactions per second on layer 1,
2. High latency since the time to finality is 3 to maximum 7 seconds

   and both achieved just on layer 1,
3. Solution is able to support millions of transactions per second introducing layer 2, as additional sidechains.

Hashnet reach high scalability with limited increase of the energy demand without compromising on security. Consensus mechanism used in HashNET requires minimum electrical consumption while the way transactions are recorded need minimum storage space. Efficiency-wise, the HashNET protocol eliminates many obstacles. The communication for consensus in the network is very energy-efficient, since information exchange is kept at a minimum, thereby needing no computing power. The gossip protocol allows sending a lot of information quickly through the network at low computing power input, making it even more suitable for energy efficient applications. Unlike other consensuses that requires every node to receive an updated graph that tend to lead to performance inefficiency with an increasing number of nodes, HashNETs' Improved Redundancy Reduced Gossip (Improved RRG) protocol achieves considerably lower traffic load than conventional push-based gossip protocols and conventional push-pull gossip protocols while maintaining the same probability of successful delivery. When the event gets gossiped, the signature is sent along with it. Events can have zero transactions either when a node receives a sync event (HashNET difference) or when the node has just been spawned, thus creating the first event with no self-parent and no other-parent, and there are no pending transactions that this node is aware of in its transaction pool. This eliminates potential performance inefficiency the blockchain can face with increasing number of nodes.

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*Consensus Protocols can be divided into two major families, and a comparison could be understandable from the problems they afront and solve in a different manner.*

- *Those existing before bitcoin, Byzantine based consensus;*
- *Those that only exist after bitcoin, family of Nakamoto consensus;*

*Byzantine general´s problem, addressed in **1982** by Leslie Lamport, Robert Shostak and Marshall Pease:*

*"Reliable computer systems must handle malfunctioning components that give conflicting information to different parts of the system. This situation can be expressed abstractly in terms of a group of generals of the Byzantine army camped with their troops around an enemy city. Communicating only by messenger, the generals must agree upon a common battle plan. However, one or more of them may be traitors who will try to confuse the others. The problem is to find an algorithm to ensure that the loyal generals will reach agreement. It is shown that, using only oral messages, this problem is solvable if and only if more than two-thirds of the generals are loyal; so, a single traitor can confound two loyal generals. With unforgeable written messages, the problem is solvable for any number of generals and possible traitors".*

*This family is called Byzantine fault tolerant protocols whereby there are algorithms that are robust enough for randomly types of failures in a distributed manner with which a Byzantine Agreement protocol is commonly adopted. There are two basic consensuses in a different way, those based on a lottery and those based on election.*

*In 1985, Michael Fisher, Nancy Lynch and Michael Patterson **"Impossibility of Distributed Consensus with One Faulty Process"** and their job is called FLM impossibility whereby demonstrated that every protocol has the possibility of non-termination, "even with only one faulty process" where asynchronous systems are needed and some of them are unreliable, in contrast with synchronous cases where Byzantine general´s problem is solved efficiently. These aspects essentially raised the Consistency, Availability, Partition tolerance theorem approach where properties are Consistency, Availability and tolerance to Partitioning. Although in 2002 Seth Gilibert and Nancy Lynch demonstrated that Coherence can be relaxed in a partially synchronous distributed network to secure Availability and Partitioning.*

*The famous FLP impossibility problem is essential for Richard Guerraoui, Matej Pavlovic and Drago-Adrian Seredinschi in **their work** with which they present the problem based on the state machine replication and consensus whereby the adversary can control various parts of the system with two assumptions: behaviour (how much control the adversary has over the nodes´ behaviour) and Synchrony (how much control has over the message transmission delays and delivery guarantees of the network) which conclude into a question "What is necessary to compromiso the liveness and/or safety of a blockchain protocol?" and consume their questions with A-indulgent protocols (maintaining safety while minimal restrictions on the adversary in synchrony) or B-indulgent protocols (which are indulgent towards malicious nodes although require additional synchrony to remain safe).*

*Both families differ in a critical aspect, nodes in PBFT choose leaders and commit on values after consulting with a majority of the system and Nodes in Bitcoin commit on a value after some time passed and accumulate the value confirmations where relies on timing assumptions. Although raised three elemental properties which are validity, agreement and termination.*

*There is a very interesting survey by IEEE on Consensus Mechanism and Mining Strategy Management in Blockchain Networks distinguishes three properties of Nakamoto Protocols in comparison with Byzantine agreement: common-prefix property, Chain-quality property and Chain-growth property within a context of primitive PoW scheme whereby its correspondences as agreement, validity and liveness in the context of*

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~~**Byzantine Agreements allow to reach a wide variety of PoW Schemes for Permissionless Blockchains. https://arxiv.org/pdf/1805.02707.pdf (TABLE III).**~~

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~~*Figure 1: Comparison of Different PoX Schemes for Permissionless blockchains by Wang et al.*~~

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~~**The properties of the consensus protocol allow to evaluate the node´s behaviour in particular the validator nodes with which Integrity, authentication, termination and independence are the main criteria aborded by the Study Report by ISO TC 307 on regards on Security Evaluation of Consensus Models; however it is extremely interesting mixed properties and hybrid consensus protocols based on incentive capabilities, not only economic incentives.**~~

~~**At the deliverables of ITU-T FG DLT in 2019 the Technical Report D.5.1, Outlook on DLT presented another Comparative table, TABLE 4 which compare based on properties as safety and performance.**~~

Table III
COMPARISON OF DIFFERENT POX SCHEMES FOR PERMISSIONLESS BLOCKCHAINS

| Puzzle Name | Origin of Hardness (One-way Function) | Designing Goal | Implementation Description | ZKP Properties | Simulation of Random Function | Features of Puzzle Design | Network Realization |
|---|---|---|---|---|---|---|---|
| Primitive proof of work [23], [86] | Partial preimage search via exhaustive queries to the random oracle | Sybil-proof | Repeated queries to cryptographic hash function | Yes | Yes | Single challenge | Bitcoin [1], Litecoin [92] |
| Proof of exercise [105] | Matrix product | Computation delegation | Probabilistic verification | N/A | No | Single challenge | N/A |
| Useful proof of work [84] | $K$-orthogonal vector, 3SUM, all-pairs shortest path, etc. | Computation delegation | Non-interactiveness via Fiat-Shamir transformation | Yes | Yes | Single challenge with sequential hash queries | N/A |
| Resource-efficient mining [100] | N/A | Computation delegation | Guaranteed by TEE | Yes | Yes | Trusted random oracle implemented by dedicated hardware | N/A |
| Proof of retrievability [110] | Merkle proofs of file fragments in the Merkle tree | Distributed storage | Non-interactiveness via Fiat-Shamir transformation and random Merkle proofs | Yes | Conditional | Two-stage challenge | Permacoin [109], KopperCoin [70] |
| Proof of space -time [36] | The repeated proof of retrievability over time | Decentralized storage market | Repeated PoR | Yes | Conditional | Two-stage challenge and repeated PoR over time | Filecoin [36] |
| Equihash [81] | The generalized birthday problem | ASIC resistance | Time-space complexity trade-off in proof generation [81] | Yes | Yes | Memory-hard | ZCash [44] |
| Ethash [114] | Random path searching a random DAG | ASIC resistance | Repeated queries to cryptographic hash function | Yes | Yes | Sequential, memory-hard puzzle | Ethereum [35] |
| Nnonoutsourceable scratch-off puzzle [82] | Generalization of proof of retrievability | Centralization resistance | Random Merkle proof | Yes | Yes | Two-stage challenge | N/A |
| Proof of space [116] | Merkle proofs of a vertex subset in a random DAG | Energy efficiency | Random Merkle proof | Yes | Yes | Two-stage challenge and measurement of proof quality | SpaceMint [116] |
| Proof of human work [102] | Radom CAPTCHA puzzle requiring human effort | Useful work and energy efficiency | CAPTCHA and PoW | Yes | Yes | Human in the loop | N/A |

~~*Figure 1: Comparison of Different PoX Schemes for Permissionless blockchains by Wang et al.*~~

**Table 4: Comparative analysis of consensus schemes**

| | Systems | Committee Formation (Resources) | Strong Consistency | Single Committee | | | | Multiple Committee | | | Safety | | | Performance | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | Committee Configuration | Inter-Committee Consensus | | | Intra-committee Configuration | Intra committee Consensus | | | | | | | | |
| | | | | | Incentives (Join,Participate) | Leader | Msg. | | Mediated | Incentives | Transaction Censorship Res. | DoS Res. | Adversary Model | Throughput | Scalable | Latency | Exp. Setup |
| Hybrid | ByzCoin [b-Kogias] | PoW | √ | Rolling (singl) | √ × | Internal | O(n) | / | / | / | √ | part | 33% | 1000 tx/s1 | × | 10–20s 1 | Real |
| | Solidus [b-Abraham] | PoW | √ | Rolling (singl) | √ √ | External | O(n2) | / | / | / | × | part | 33% | / | / | / | / |
| | Algorand [b-Gilad] | Lottery | √ | Full swap | ×× | Internal | O(n2) | / | / | / | × | √ | 33% | 90 tx/h 2 | × | 40s 2 | Real |
| | Hyperledger [b-Vukolic-b] | Permissioned | √ | Static | / | Flexible | Flexible | / | / | / | √ | √ | 33% | 110k tx/s 3 | × | <1s 3 | Real |
| | Tencent TrustSQL | Permissioned | √ | Static | / | / | / | / | / | / | √ | √ | 50% | 50k+tx/s 12 | × | 20ms 12 | Real |
| | RSCoin [b-Danezis] | Permissioned | √ | Static | / | Internal | O(n) | × | Client | × | √ | √ | 33% | 2k tx/s 4 | √ | <1s 4 | Real |
| | Elastico [b-Luu] | PoW | √ | Full swap | √ × | Internal | O(n2) | Dynamic (Random) | ! | ! | × | √ | 33% | 16 blocks/110s 5 | √ | 110s/ 16 blocks | Real |
| | Omniledger [b-Kogias-b] | PoW/PoX | √ | Rolling (subset) | √ × | Internal | O(n) | Dynamic (Random) | Client | × | √ | √ | 33% | ≈10k tx/s 6 | √ | ≈1s 6 | Real |
| | Chainspace [b-Baasam] | Flexible | √ | Flexible | ×× | Internal | O(n2) | × | × | × | √ | part | 33% | 350 tx/s 7 | √ | <1s 7 | Real |
| Proof-of-X | Ouroboros [b-Kiayias] | Lottery | × | Full swap | √ √ | Internal | O(nc) | / | / | / | × | √ | 50% | 257.6 tx/s 9 | × | 20s | Simulation |
| | Praos [b-David] | Stake | × | Rolling (subset) | √ √ | Internal | O(1) | / | / | / | × | part | 50% | / | / | / | / |
| | Snow-white [b-Daian] | Stake | × | Full swap | √ √ | Internal | O(1) | / | / | / | × | √ | 50% | 100-150 tx/s 9 | √ | ? | Simulation |
| | PermaCoin [b-Miller] | PoW/PoR11 | × | Rolling (singl) | × √ | Internal | O(1) | / | / | / | √ | √ | 50% | / | × | / | / |
| | SpaceMint [b-Hereu] | PoS | × | Rolling (singl) | × √ | Internal | O(1) | / | / | / | √ | √ | 50% | ? | × | 600s | Simulation |
| | Intel PoET [b-Intel] | TH12 | × | Rolling (singl) | × √ | Internal | O(1) | / | / | / | √ | √ | TH12 | 1000 tx/s 10 | √ | / | Real |
| | REM [b-Zhang] | TH12 | × | Rolling (singl) | × √ | Internal | O(1) | / | / | / | √ | √ | TH12 | ! | √ | / | Real |
| Proof-of-work | Bitcoin [b-Nakamoto] | PoW | × | Rolling (singl) | × √ | Internal | O(1) | / | / | / | √ | √ | 50% | 7 tx/s | × | 600s | Real |
| | Bitcoin-NG [b-Eyal] | PoW | × | Rolling (singl) | × √ | Internal | O(1) | / | / | / | √ | part | 50% | 7 tx/s | × | <1s | Simulation |
| | GHOST [b-Sompolinsky-b] | PoW | × | Rolling (singl) | × √ | Internal | O(1) | / | / | / | √ | √ | 50% | / | × | / | / |
| | DECOR+HOP [b-Lerner] | PoW | × | Rolling (singl) | × √ | Internal | O(1) | / | / | / | √ | √ | 50% | 30 tx/s 8 | × | 60s | Simulation |
| | Tencent TrustSQL | PoW | √ | Rolling (singl) | × √ | Flexible | O(1) | / | / | / | √ | √ | 50% | 50k+ tx/s 12 | × | 50ms | Real |
| | Spectre [b-Sompolinsky-a] | PoW | × | Rolling (singl) | × √ | Internal | O(1) | / | / | / | √ | √ | 50% | / | × | / | / |

1 144 nodes/committee.
2 50k nodes/committee.
3 4 nodes/committee (corresponding to BFTSmart [b-Kim]) corresponding to HyperLedger v0.6, new consensus scheme [b-Thakkar] is used after v0.6.
4 3 nodes/committee. 10 committees.
5 100 nodes/committee. 16 committees.
6 72 nodes/committee (12.5% adversary). 25 committees.
7 4 nodes/committee. 15 committees.
8 1 minute average interval; 1 block = 1 MB.
9 40 nodes.

~~*Figure 2: Comparative analysis of consensus schemes*~~

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~~*Every consensus protocol can offer a different property or a set of properties to the network. There are examples like Bitcoin where mining is required to add a block in the chain, while other examples are not relying on mining and implement a minting system to add a block in the chain based on transactions. The latter examples contemplate numerous cases that apply an election or voting mechanism. The following figure briefly includes these examples.*~~

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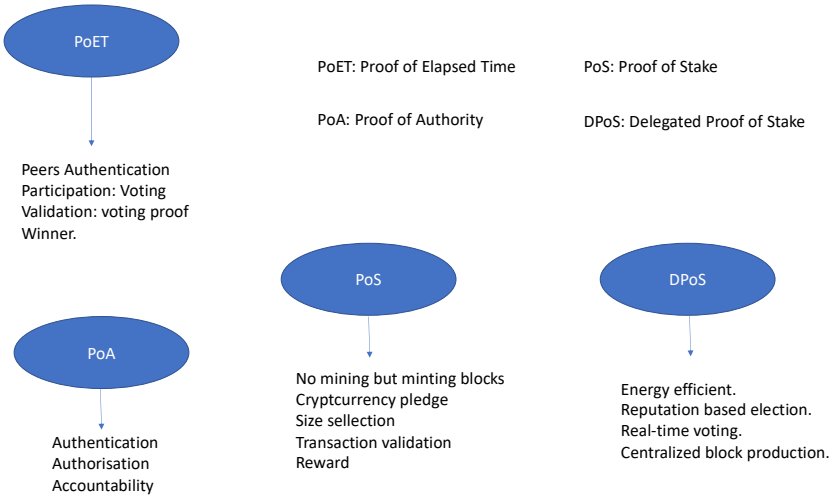


~~*Figure 3: Summarization of consensus algorithms and properties*~~

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# Section 2: Blockchain Energy Consumption Indices

## OVERVIEW OF VARIOUS METHODOLOGIES

It's a challenging task to accurately quantify the electricity consumption of the Bitcoin network, and what one finds across methodologies is that it's largely an oversimplification based on several educated assumptions. Overall, it's an iterative ongoing process of adding more pools, and extrapolating more accurate data in order to be able to accurately estimate the global electricity consumption and ultimately the carbon footprint of Bitcoin. It should be mentioned that solid methodologies for the estimation of the energy consumption of blockchain technologies are only available for the PoW, therefore the energy efficiency analysis is mainly focused around the Bitcoin blockchain.

Often however, significance lies on providing basis to reason with the terawatt-hours (TWh) consumed rather than to only quantify this metric. Reasoning comes by asking questions such as whether the electricity consumed is worth the utility which Bitcoin provides, but this too is a flawed approach. Although Bitcoin may consume a relatively significant amount of energy, the right question to ask perhaps draws back to whether the electricity produced is from renewable or non-renewable sources. Or to take this one step further, challenge the entirety of non-renewable energy production rather than speculate on what consumes it. What's clear is that there remain two diametrically opposed viewpoints on Bitcoin's environmental mining footprint, both of which (often incorrectly) use various data points to support their own narratives.

In September 2020, Cambridge Centre for Alternative Finance (CCAF) published research showing that although 76% of hashers report using renewables as part of their energy mix, non-renewables still represent 39% of the total hashing energy consumption (Blandin et al., 3rd Global Cryptoasset Benchmarking Study - CCAF publication 2020). Bitcoin hashers' preference for renewable energy sources are perhaps relatively higher than other electricity uses, the reason being that Bitcoin miners often identify remote inaccessible locations that are not connected to the grid. This is common practice to maximize revenue margins. Here, miners are able to reap the benefits of cheaper renewable electricity which may be produced in surplus and cannot be used, transported or efficiently stored, for example surplus hydro, solar, and wind power production. (CBECI 2019)

Various methodologies have been implemented in recent times to estimate the electricity being consumed. The two variables (Bitcoin price and mining hashrate) are volatile metrics and so it makes sense for these indices to track real time data rather than use more distributed periodic snapshots. The two most widely referenced real-time models are the Cambridge Bitcoin Electricity Consumption Index (CBECI) and the Digiconomist Bitcoin Energy Consumption Index. Both of these methodologies use interesting economic models, based on certain assumptions.

Contrasting these two methodologies from a high-level; CBECI implements a bottom-up techno-economic approach by looking at the actual mining equipment to build a model based on the hardware being used at a specific time and then using the efficiencies or specs of that mining equipment to extrapolate the annualized Bitcoin electricity consumption. (CBECI 2019)

Whereas the Digiconomist index, created by Alex de Vries, implements an economic top-down approach by estimating Bitcoin miner revenues and then using an assumption that a portion of that revenue is used to pay for electricity. By modeling an average electricity cost globally, the Digiconomist index can then calculate the energy being used. (de Fries, Digiconomist, Bitcoin Energy Consumption Index)

Neither of these methodologies (CBECI or Digiconomist) are seen as incorrect, and in research its always useful to have diverse approaches to provide multiple perspectives to a single question. As these methodologies develop in the future and more reliable data becomes available on both ends, the delta between their respective underlying assumptions would ideally get smaller.

## THE CAMBRIDGE BITCOIN ELECTRICITY CONSUMPTION INDEX (CBECI)

The Cambridge Bitcoin Electricity Consumption Index mentioned herein, was developed and launched in July 2019 by the Cambridge Centre for Alternative Finance; a research institute of Cambridge University based in Judge Business School.

The CBECI aims to provide real-time estimates of the total electricity consumed by the Bitcoin Network while also providing live comparisons of alternate electricity uses, thus putting the annualized terawatt-hours (TWh) into perspective.

CBECI provides neutral and independent data visualizations and interpretations for researchers, regulators, policy makers, the media and others to be able to see the non-biased facts. The extrapolation of estimated electricity consumption is derived by charting a theoretical lower bound and upper bound of Bitcoins electricity consumption at any time. The theoretical lower bound assumes every Bitcoin miner is using the most efficient commercial mining equipment; whereas equally unrealistically the theoretical upper bound assumes that every miner is using the least efficient, but still profitable equipment at the time (CBECI 2019). As the price of bitcoin increases more equipment potentially becomes profitable and as a result this equipment comes online and the network hashrate increases.

The actual Bitcoin electricity consumption estimate sits somewhere between the theoretical upper and lower bound and is calculated using a real-time weighted average of a basket of hardware that is included based on equipment specs (CBECI 2019). Interestingly, the divergence between the theoretical upper and lower bound increases over time as BTC price spikes. Today the upper bound is ten times the lower bound, whereas in 2018 it was only about three times.

CBECI also displays a Mining Map (either global or China-focused), which visualizes the approximate geographic distribution of Bitcoin hashrate. The average hashrate share by country is also available for display in monthly intervals starting from September 2019.

## EXISTING/FUTURE EXTENSIONS OF THE METHODOLOGIES TO CALCULATE ELECTRICITY CONSUMPTION OF OTHER BLOCKCHAINS.

As Bitcoin mining data becomes more accessible, democratized and reliable, we expect electricity consumption estimates to become more accurate and precise. This includes the overall distribution of data being collected. Currently, there is a bias of data mainly from China, as this is predominantly where Bitcoin miners are located. Not all mining pools are willing to share data. For example, CBECI currently collects data from 3 of the largest pools (Poolin, BTC.com and ViaBTC). This represents on average 37% of global hashrate for the displayed period (2019.09-2020.04) and is skewed toward China (CBECI 2019). Ultimately, the next phase of CBECI, once reliable geographical data is obtained, is to estimate the global carbon footprint of Bitcoin mining.

Over time the Cambridge Centre for Alternative Finance plans to increase the Bitcoin mining sample size, update the mining map, update and add more comparisons, (for example a comparison to gold production is currently being worked on. This is a daunting task since data disclosure is mostly vague and unreliable from mining stakeholders. Not to mention that the gold mining industry relies on multiple subcontractors within the

supply chain to get the gold from extraction to market. Even the energy consumption for transportation of gold is significantly energy intensive. Other complexities include a reliance on diesel generators where consumption data is often unclear (Peyravi & Girard, CCAF).

Ethereum mining is more diverse than Bitcoin mining which is evidently more industrially scaled. The reason being that Ethereum mining is an area dominated more so by a larger variety of retail players, using a wider range of available equipment, with the price they pay for electricity varying anywhere between $0 (stolen electricity) to $0.20 per kilowatt-hour. This complicates and drastically increases the theoretical aforementioned divergence of a potential electricity consumption estimate, with a probable massive difference between CBECI's theoretical upper and lower bound estimates, when compared to Bitcoin (Dek, CCAF).

Ethereum in particular, is an interesting example. In the short term, with Ethereum Improvement Proposal (EIP1559) expected to be included in the London hard fork sometime in July 2020, there is an evident divide on sentiment as developers support this fork, while many miners still oppose it believing they are less incentivized to include EIP1559 when it becomes available. In the longer term with Ethereum 2.0 planned to be rolled out, this represents a complete overhaul of the Ethereum consensus mechanism from the current proof of work (PoW) algorithm to a proof of stake (PoS) alternative. As becomes quite evident, any index to estimate Ethereum's electricity consumption is more volatile, less accurate and ultimately only temporary until PoS is implemented. Digiconomist currently displays a beta index of Ethereum Energy Consumption (de Fries, Ethereum Energy Consumption Index), while the Cambridge Centre for Alternative Finance also plans to explore implementing an Ethereum Electricity Consumption Index, using the unique bottom-up techno-economic approach (Dek, CCAF).

On a more experimental note, research is being done to identify the proportion of mining chips connected to the network (Helmy, 2020). By plotting the winning nonce value against block height (or time) often unique patterns emerge. The cause of these patterns varies across network and generally they have been associated with either pool, software or hardware activity. If the pattern is caused by hardware one can refine the assumption made by existing electricity estimates such as CBECI. This is an area of ongoing research. (Eisermann, CCAF).

It is evident that this is an ongoing process of iterative progress, and across all methodologies its' a matter of refining research and gathering more reliable data. Electricity consumption indices today are representative of the current state of research and data available.

In conclusion, it should be mentioned that CBECI (bottom-up methodology) measures the specific hardware consumption of various mining hardware, using a published updated list of hardware specs. It then assumes that certain hardware is being used when the BTC price is at a level for that specific hardware model to be profitable. On the other hand, Digiconomist (top-down methodology), looks at miner revenues and makes certain financial assumptions again based on the BTC price at the time for that miner to be profitable. Extrapolating the expense part of miners (ie. primarily electricity consumption). One may observe that both methodologies are based on reason but rely on certain assumptions. The data set and sample size is limited in all studies thus far, which is the also the main limitation of both approaches. CBECI will be updating data sets in the short term as well as broadening participants who provide this valuable data, so we are not too concerned. Already existing data is already representative enough. CBECI is also in the process of extrapolating algorithms that would accurately estimate energy mix and carbon footprint of bitcoin mining.

# Section 3: Blockchain Performance

## BLOCKCHAIN PERFORMANCE COMPARISON

Since 2009, numerous cryptocurrencies have been developed, however, Bitcoin is the largest and most popular representing over 60% of the total market of cryptocurrencies. The combined market capitalization of all cryptocurrencies is approximately USD $1.72 trillion (as of March 2021). Other key currencies in this market are Ethereum, Cardano, Litecoin and Bitcoin Cash. However, it should be mentioned that the performance analysis carried out in this section is not only related to cryptocurrencies, but also to the other use cases that used the underlying blockchain technologies that correspond to these cryptocurrencies.

Top 5 Mineable Cryptocurrencies by Market Capitalization on 03/08/2021

| Name | Symbol | Algorithm | Market cap [USD bn] | Protocol |
|---|---|---|---|---|
| Bitcoin | BTC | SHA-256 | 1 044 | PoW |
| Ethereum | ETH | Ethash | 211 | PoW |
| Cardano | ADA | Ouroborous | 37 | PoS |
| Litecoin | LTC | Scrypt | 13 | PoW |
| Bitcoin Cash | BCH | SHA-256 | 10 | PoW |

In order to understand the performance of these blockchains and to evaluate their energy consumption a number of key parameters should be analyzed. Thus, Bitcoin, Ethereum, Litecoin, Cardano were compared based on following indicators: block time, block size and number of transactions over the period of three years from October 2017 to March 2021 as all these values directly or indirectly affect the above-mentioned index.

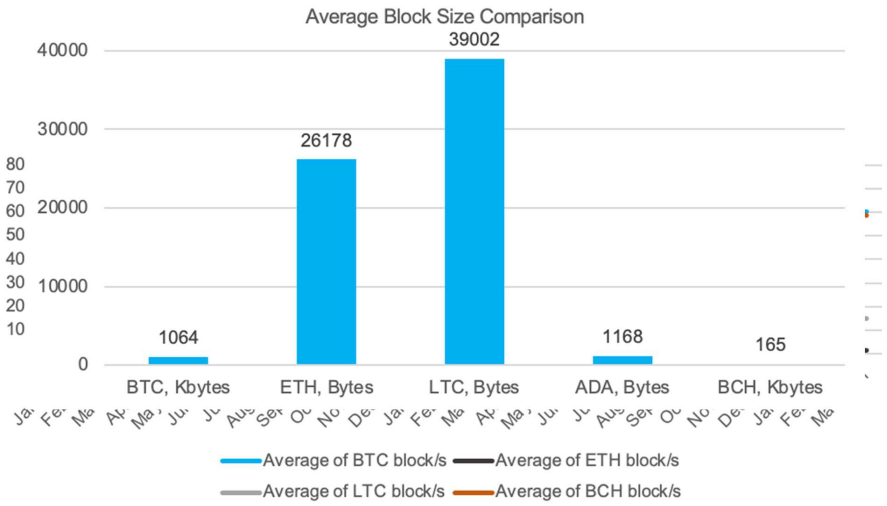
Firstly, block size. Block size is a key metric since bigger blocks lead to heavier data storage costs. Moreover, when the block size approaches the maximum value problems may arise, such as a slowdown of the network and increasing transaction fees. Network utilization is an important metric in understanding transaction fees – it can be used to understand how much demand there is for the available block space. Block space is scarce, in a Proof of Work blockchain such as Bitcoin the decision on which transaction to include are partially dependent on the transaction fee users are willing to pay. Miners are monetarily incentivized to include transactions that have the highest fees. Per the law of supply and demand if demand to include transactions in a block increase, but supply is capped based on block size, then the determining factor will be the price users are willing to pay to have their transaction included. Through this blockchain users start competing for the right to include their transaction in the block and pay increasingly higher fees to maintain priority. Moreover, this leads to the confirmation of other transactions taking more time.

Figure 1 depicts the average block size comparison among BTC, ETH, LTC, ADA and BCH in the period from 2017 to 2021.

Based on data, the size of Bitcoin blocks remained on average 1MB while the size of Ethereum and Litecoin blocks are almost 1000 times smaller and equal to 26178 bytes and 39002 bytes respectively. The average Bitcoin Cash block size is also high in comparison to other coins and equals to 165 Kilobyte or 0.165MB. As for Cardano, the average block size is around 1200 bytes. So, BTC transactions usually have a higher average fee as users are competing for the right to include their transaction in the block and pay increasingly higher fees to maintain priority. On the other hand, miners compete against each other for limited block rewards, and

they are interested in joining miners network that leads to hashpower increasing (will be considered further). Moreover, the data storage costs are also higher.

Figure 1: Average Block Size Comparison among Bitcoin, Ethereum , Litecoin, Cardano and Bitcoin Cash (2017-2021)




A second indicator to analyze is block time as this parameter directly affects the difficulty of mining. Based on data, Bitcoin takes almost 600 seconds on average to generate a block as well as Bitcoin Cash. A bit less time is taken by LTC and it is around 150 seconds or almost 3 minutes. On the other hand, Ethereum needs 14 seconds. As for ADA, historical data is not available, but average block time is about 40 seconds.

Figure 2: Average Block Time Comparison among Bitcoin, Ethereum, Litecoin and Bitcoin Cash

The third indicator important for understanding blockchain performance is the number of transactions. Figure 3 shows that transacting on the Ethereum network has become popular compared to other protocols. The popularity of Ethereum among investors from software developers, healthcare advisors, finance professionals, hardware producers, to mention a few, has rocketed upwards due to some of its unique characteristics. As it offers users to access to several Decentralized Finance (Defi) projects, dApps, and smart contracts. For this reason, investors are increasingly moving capital into Ethereum – rather than simply using it for transactions the protocol is become the base layer for practical usage across different industries, including energy distribution, finance, medicine, art, and gaming.

The total number of the ETH transactions reached almost 36,000 in February 2021. Regarding the average number of transactions per day and per second for the period from October 2017 to March 2021 they are as follows:

- Bitcoin 290,598 transactions per day on average or 3.3 transactions per second
- Ethereum 777,787 transactions per day on average or 9 transactions per second
- Litecoin 39,981 transactions per day on average or 0.46 transactions per second
- Cardano 5,678 transactions per day on average or 0.07 transactions per second
- Bitcoin Cash 52,646 transactions per day on average or 0.6 transactions per second

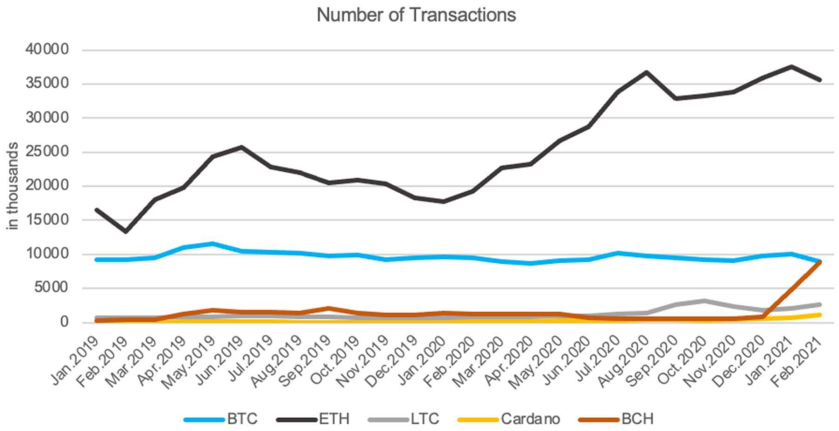



Figure 3: Number of Transactions Comparison among Bitcoin, Ethereum, Litecoin, Cardano and Bitcoin Cash

The final indicator to be covered is difficulty, or network difficulty. It is a value that indicates how hard is to find a hash below a given target, in other words it is a parameter that shows the cost of finding one block in the cryptocurrency network. For better understanding, the notion of "hash rate" should be identified. The hash rate reflects corresponds to the total power of the mining equipment used in the cryptocurrency system and is displayed in hash/sec (H/s).

Thus, difficulty is a relative measure of the amount of resources required to mine coins which rises or falls based on the amount of computing power consumed by the network, known as its hashrate. The difficulty of mining is constantly growing in order to keep the target block time.

The designation H/s is not commonly used, it is orders of magnitude too small and rates displayed in H/s would be a number with at least eighteen zeros. The following designations are mainly used: terahesh/sec (TH/s) and exahesh/sec (EH/s), where TH/s = 1,000,000,000,000 H/s, and EH/s = 1,000,000 TH/s.

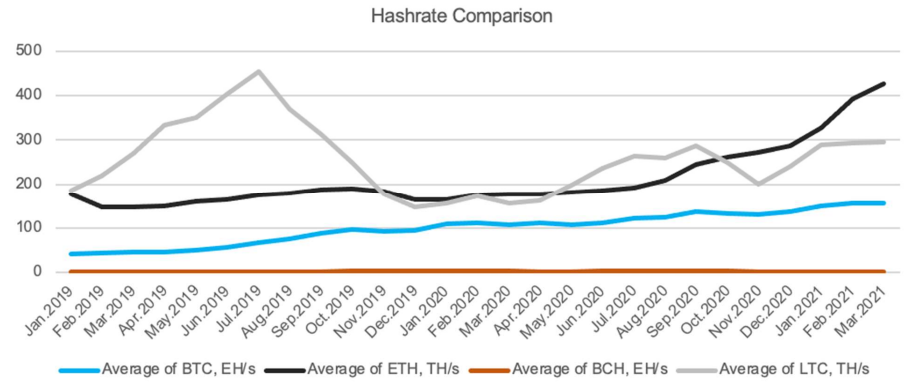



Figure 4: Difficulty Comparison among Bitcoin, Ethereum, Litecoin and Bitcoin Cash

As a cryptocurrencies become more popular, the number of computers participating in the network increases. As it was mentioned above miners compete against each other for limited block rewards.

As more and more miners are attracted to mine bitcoin and reap financial rewards, the complexity to generate a new block accordingly increases – thereby reducing the rate at which new blocks are mined. The difficulty of mining in the Bitcoin network is adjusted automatically after 2,016 blocks have been mined. Adjusting the difficulty up or down depends on the number of participants in the mining network and their aggregate hash power. If new participants have joined the cryptocurrency mining, it means the hash rate has grown and more energy is consumed.

Figure 4 shows the difficulty of generating a new block among main cryptocurrencies. Bitcoin difficulty rose as high as 155 million TeraHash per second. The difficulty of mining a block in other blockchains is also growing, but Bitcoin remains the highest consumer of hashing power.

Furthermore, based on the figure below it is clear that Bitcoin and Ethereum energy consumption increase and reached the highest rates in March that are 78.04 TWh and 25.19 TWh, respectively. In addition, total carbon footprint for BTC transactions equals to 41 Mt $CO_2$ yearly and 14 Mt $CO_2$ for ETH transactions.

According to Digiconomist research almost 792 kWh of electrical energy is consumed to proceed one transaction in Bitcoin that equals to 376 kg$CO_2$ of carbon footprint, which is same as Bolivia's average electrical energy consumption per capita. Concerning Ethereum, one single transaction takes 63 kWh of electrical energy or almost 30 kg$CO_2$ of carbon footprint or Liberia's average electrical energy consumption per capita. With increasing popularity and usage of the Bitcoin blockchain, as well as the increased security requirements associated with the increased economic value of the cryptocurrency, the PoW system will lead to an increasing demand for energy.

Based on bitinfocharts.com data, it is possible to calculate the amount of value transacted per CO2-emitted. The average BTC transaction value is 39,960 USD for the last year and 2,158 USD for ETH transactions. That means that 106 USD on the average in BTC transacted per 1 kg CO2-emitted or 71 USD in ETH.

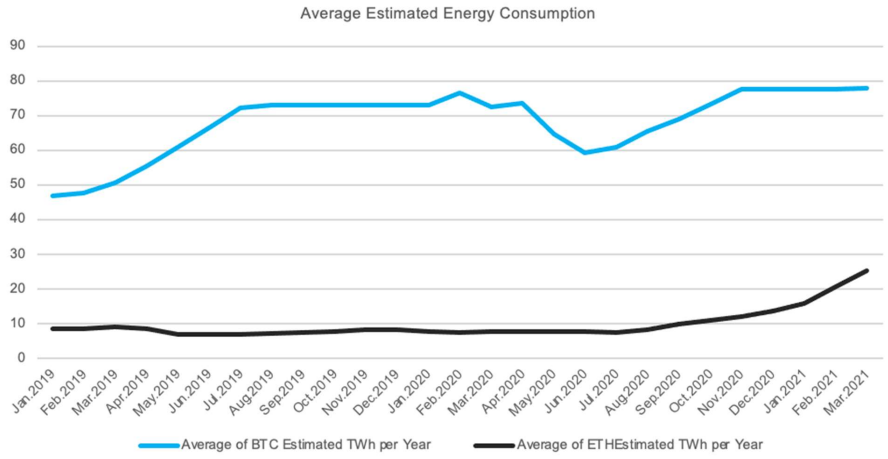



Figure 4: Bitcoin and Ethereum energy consumption worldwide

When it comes to blockchain performance there are clear advantages and disadvantages of each unique protocol and consensus mechanism, the main problem of Bitcoin is its scaling as it is restricted to a maximum number of transactions because of its block size. Each block, generated in around 10 minutes reaching 1MB which limits the transaction throughput to 2-4 transaction/sec. The average Bitcoin Cash block size is also high in comparison to other coins and equals to 165 Kilobyte or 0.165MB, however its throughput is 0.6 transactions per second. Both, BTC and BCH have high difficulty levels and reached the highest rates in March. As for LTC and ADA their average block size is 39002 bytes and 1200 bytes respectively, block time is 150 sec and 40 sec and throughput is constantly smaller just 0.46 LTC transactions per second and 0.07 ADA transactions per second.

ETH performance shows that it needs just 14 seconds to generate the block with average size of 26,178 bytes, plus it is the most popular cryptocurrency based on the number of transactions with throughput of 9 transactions per second. Hashrate for this currency is also growing and reached the indicator of 425 TH/s in March. Moreover, based on Digiconomist research, Bitcoin and Ethereum energy consumption increase and reached the highest rates also in March that are 78.04 TWh and 25.19 TWh, respectively.

## COMPARISON OF CRYPTOCURRENCY MINING INFRASTRUCTURE

Rapid advances in technological innovation, including through automation, digitization, and electrification, are having a fundamental impact on the cryptocurrency mining sector.

The technology used by miners has advanced over time. Early miners were able to earn Bitcoin relatively easily with unspecialized equipment. On January 3rd, 2009, Satoshi Nakamoto created the first block of the Bitcoin Blockchain, hashing using the central processing unit (CPU) of his computer. However, as more units began to mine the network, the difficulty of the hashes they were trying to solve for increased.

As interest in Bitcoin mining increased, miners discovered that graphics cards (GPUs) could more efficiently run hashing algorithms and aid in mining. These chipsets provided very fast processing power, more specialised in parallel computing when compared to CPUs. The world leading GPU designers and manufacturers have been Nvidia and AMD (post the ATI acquisition in 2006), maintaining a global dominance in this market up to this day.

Field Programmable Gate Arrays (FPGAs) then replaced graphic cards, as the circuits in an FPGA could be configured and programmed by users after manufacturing. FPGAs are more expensive than CPUs and GPUs but they are also quite efficient in their use of electricity.

Finally, in 2013 fully customized Application Specific Integrated Circuit (ASIC) appeared and replaced these and graphic cards. ASICs are designed for a particular use such as Bitcoin mining.

The launch of Bitcoin ASICs spurred professionalization of the mining industry. ASICs used to mine Bitcoin are usually housed in temperature-controlled data centers with access to inexpensive electricity.

Mining data centers are now industrial-scale facilities with management and servicing on par with traditional cloud data centers.

There are several factors which contribute to ideal mining locations and include energy costs, regulations, and technology. Often the energy costs are affected by geographical characteristics like proximity to hydroelectric or other renewable power or lower ambient temperature that reduces the need for cooling. Simultaneously, cooling energy, the power required to keep mining devices and mining farms cool, adds extra 30-50% on power consumption globally.

Historically, most large mining farms such as Poolin, F2Pool etc have set up their operations in China because of electricity cost and various available sources of electricity. As the People's Republic of China is skeptical about Bitcoin and other cryptocurrencies, mining operations are diversifying geographically with the cost of electricity being the main consideration. Local and national governments around the world have reacted differently to the rise of Bitcoin, with some are actively developing cryptocurrency industries, some are restricting cryptocurrencies, and some are regulating cryptocurrencies to balance financial innovation and risk management. Many countries offer competitive electricity rates, including Iceland, Canada, and the US.

It should be underlined that there are three main factors that contribute to energy consumption of cryptocurrency mining:

1. hardware computing power.
2. network hashrate or the difficulty.
3. the thermal regulation for the hardware.

The two most popular methods of mining BTC, ETH, LTC or BCH are ASIC and GPU mining.

Elwood research suggest that when comparing ASIC miners versus GPUs, the benefits are not as clear as there is a deliberate effort to keep the network running on easily accessible hardware rather than purpose-specific mining hardware. Nonetheless, ASICs have managed to outperform GPUs. Actually, the efficiency gains from ASICs could not be matched by any of the more general-purpose devices that preceded it.

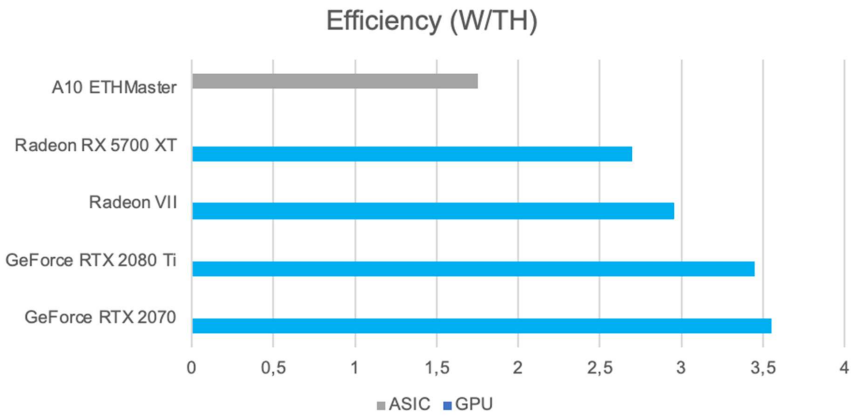



Figure 4. Efficiency: GPU vs. ASIC miners (Ethereum mining)

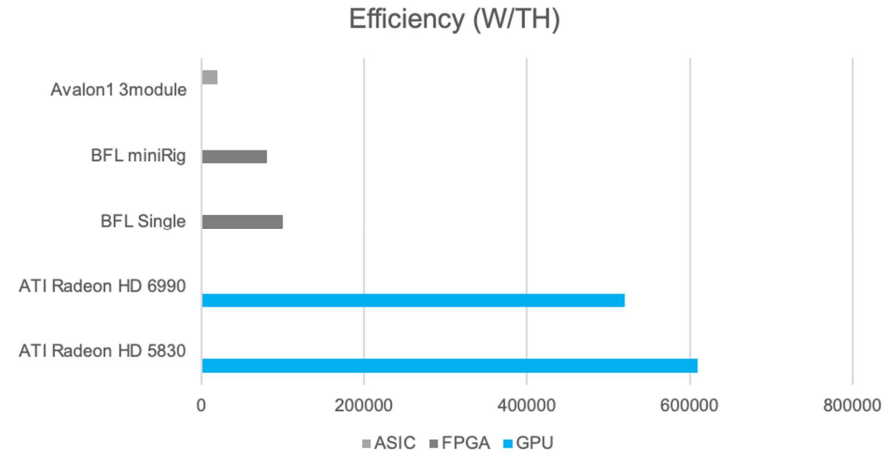



Figure 5. Efficiency: GPU and FPGA vs. ASIC miners (Bitcoin mining)

To analyze the energy consumption by the most popular mining infrastructure the manufacturers that are still in business and that have released machines since 2017 are shortlisted.

| Manufacturer | Brand | Latest series |
|---|---|---|
| Bitmain | Antminer | S19 |

| | | |
|---|---|---|
| Bitfury | Bitfury | Tardis |
| Canaan | AvalonMiner | Series 12 |

It is important to analyze main characteristics of these machines.

Comparison of Recent Bitcoin ASIC Miner Machine Types

| Machine | Hash rate (TH/s) | Power Consumption (Wh) | Power Efficiency (J/TH) |
|---|---|---|---|
| Antminer S19 | 95 | 3,250 | 34.5 |
| Antminer T19 | 84 | 3,150 | 37.5 |
| Antminer S19 Pro | 110 | 3,250 | 29.5 |
| Bitfury Tardis (Optimal CAPEX) | 72 | 6,300 | 88 |
| Bitfury Tardis Boost | 100 | 6,300 | 63 |
| AvalonMiner 1246 | 90 | 3,420 | 38 |
| AvalonMiner 1166Pro | 81 | 3,400 | 42 |
| AvalonMiner 1146Pro | 63 | 3,276 | 52 |
| AvalonMiner 1166 | 68 | 3,196 | 47 |

Needless to underline **that mining hardware has evolved**, the above table depicts improvement of both the hash rate and power efficiency, whereas the power consumption gradually decreases. The mining industry continues to evolve today, competition for bitcoin mining rewards will continue to spur technological evolution. As a result, mining machines will become more energy efficient and less power consuming.

In theory, having main characteristics of the most popular and technical mining equipment it is possible to calculate the minimum level of energy consumption by bitcoin network.

As mentioned above, Bitcoin difficulty rose as high as 155 million TeraHashes per second. The calculation of the minimum energy consumption level by a mining machine can be done by dividing 155 mln TH/s by each machine's hash rate. As shown in the table below 0.00458TWh is the minimum volume of consumed energy with the condition that all mining machines in the world are Antminer S19 Pro.

Of course, it is raw calculations as miners use different types of equipment and not all of that items consume the same amount of energy. However, this is an optimal representation of the minimum required level of energy to proceed bitcoins transactions.

Calculation of Energy Consumption

| Machine | Items Needed to Mine BTC (based on difficulty), mln | Energy Consumption (TWh) |
|---|---|---|
| Antminer S19 | 1.631 | 0.0053 |
| Antminer T19 | 1.845 | 0.0058 |
| Antminer S19 Pro | 1.409 | 0.00458 |
| Bitfury Tardis (Optimal CAPEX) | 2.152 | 0.0136 |

| | | |
|---|---|---|
| Bitfury Tardis Boost | 1.55 | 0.00977 |
| AvalonMiner 1246 | 1.722 | 0.0059 |
| AvalonMiner 1166Pro | 1.913 | 0.0065 |
| AvalonMiner 1146Pro | 2.460 | 0.008 |
| AvalonMiner 1166 | 2.279 | 0.0072 |

To summarize the calculation of the minimum level of energy consumption, daily and yearly numbers should be considered. In the issue, lower bound consumption equals to 0.11 TWh per day or 40.12 TWh per year. In real world terms the energy consumption of blockchains is difficult to make tangible, on the one hand it should be noted that the same amount of electric energy is consumed by New Zealand every year. On the other hand, Bitcoin uses less than half the electricity as banking system, and similarly pales in comparison to 241 Terawatts per hour consumed by the gold industry's mining operations.

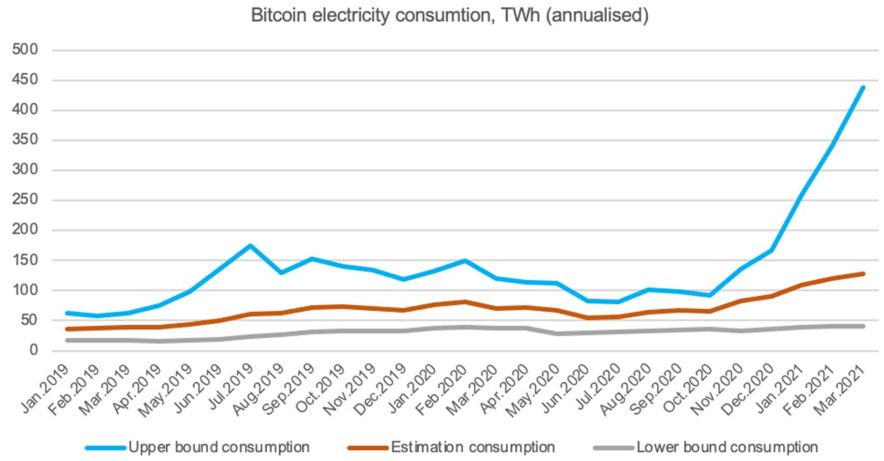



Figure 4: Bitcoin electricity consumption, TWh (annualized)

Based on Cambridge University research, the lower bound consumption is almost the same and equals to 40.46 TWh per year and the estimated consumption is 128 TWh. That exceeds the energy consumption level of such countries as Argentina, Norway or Netherlands.

As it was highlighted, based on digiconomist analysis the carbon footprint of bitcoin energy consumption equals to 37.3 Mt CO2 that is comparable to the carbon footprint of Trinidad and Tobago. As for Ethereum, carbon footprint is 12.35 Mt CO2 that is the same as Panama emits.

Based on these analyses and data from IPO filings of hardware manufacturers and insights on mining facility operations and pool compositions, bitcoin mining is likely responsible for 10-20 Mt CO2 per year, or 0.03-0.06% of global energy-related CO2 emissions.

However, it should be mentioned that electricity generation in some bitcoin mining centers are dominated by renewables, including Iceland (100%), Quebec (99.8%), British Columbia (98.4%), Norway (98%), and

Georgia (81%). Globally, CoinShares analysis estimates that the bitcoin is powered by at least 74% renewable electricity as of June 2019.

Moreover, there are several strategies to achieve lower electricity costs and even level of consumption:

1. Usage of renewable energy in general yield lower costs (as the electricity cost are lower), plus it is not harmful to the environment
   The use of blockchain technology is growing at a rapid rate, leading to soaring energy consumption. Blockchain technology is secured and maintained by a vast network of miners to solve increasingly-complex computational problems. It's important that clean-energy technology is used to satisfy the rising blockchain ecosystem's usage needs. According to Bloomberg, the global power required to generate cryptocurrencies is equal Argentina's entire electricity demand and serve as a growth engine for renewable energy producers from the United States to China.
2. Dynamic usage of datacenters – as electricity cost varies during the day, operate the datacenter only when the electricity cost is lower mining will yield more overall profit.
3. Usage of excess energy that cannot be stored – the cost goes to zero or in some cases the power manufacturers might even pay the datacenter to use the extra energy as it must be used. Some countries have the problem of limiting the distribution of electricity from nuclear power plants. Consequently, the emergence of data centers in the area of nuclear power plants should solve the problem. Bitfury has entered a contract with the Ukrainian government to begin building of data centers with this consideration of highest priority.

# Section 4: Scalability and Performance Considerations

## INTERVIEW WITH WALTER KOK, CEO, ENERGY WEB

**Walter Kok is CEO of the Energy Web Foundation. He brings nearly three decades of experience leading customer solutions and operational teams in complex, global organizational environments, including in the fields of fintech, telecommunications and information technology (IT). Prior to joining EWF originally as COO, Kok was COO of bank-wide operations at ING Bank, where he drove a series of transformation programs and built a new type of operating model better equipped to deal with the challenges of regulatory requirements and technological disruption. In addition to ING, Kok's prior experience also includes senior board positions at Vodafone Global Enterprise, BT, NEC Corporation and several startups. He holds a Masters of Science in Digital Currency from the University of Nicosia and a Master of Science in computer systems networking and telecommunications from the Eindhoven University of Technology.**

**Question: What is Energy Web? What are you trying to achieve?**

Energy Web is a global, mission-driven nonprofit accelerating the zero-carbon energy transition by harnessing the potential of public, open-source digital technology. Our technology stack includes both blockchain and other decentralized solutions as well as traditional, off-chain systems such as cloud-based IoT. The anchor of our tech stack is the Energy Web Chain, which launched in June 2019 as the world's first enterprise-grade blockchain tailored to the needs of the complex, highly regulated energy sector. In tandem, the Energy Web ecosystem has blossomed from an initial group of about ten affiliates when Energy Web was founded in 2017 to more than 100 companies globally today, comprising major energy companies, grid operators, renewable energy developers, automakers, and telcos. Together, we are building digital solutions that more fully tap into the value of zero-emissions distributed energy resources as a core component of the future energy system. Almost 50% of our members operate a validator node and actively contribute to operating our publicly accessible blockchain.

**Question: There has been a lot of renewed debate so far this year about the high energy consumption of the Bitcoin blockchain. Also there are voices debating about making blockchains "green". What is your personal take on this?**

With the current conversation about blockchain energy consumption and making crypto green, we need to talk about two sides of a coin. On one hand, we have the issue of the energy efficiency and energy intensity of different blockchain networks. That's a demand-side topic. On the other hand, we have the related issue of powering blockchain operations with renewable energy. That's a supply-side topic.

With respect to the former issue—demand-side energy efficiency of blockchain networks—that highlights the important differences in various blockchains and how they achieve consensus. Bitcoin has of course made headlines for its energy-intensive Proof-of-Work approach to consensus. But many blockchains are migrating to energy-efficiency alternatives (such as Ethereum's move to Proof-of-Stake) or being built from scratch with energy efficiency baked into the platform (such as our Energy Web Chain, which uses Proof-of-Authority).

These energy-efficient alternatives are exciting, but let's also remember: debating whether Bitcoin might ever move to a PoW consensus alternative only focuses on half the equation: demand-side energy consumption. Regardless of any given blockchain's energy intensity and consumption, we still have the supply-side option: powering blockchains with 100% renewable energy. This is just as important, if not more so, and analogous to what we have seen happen in other industries.

For example, consider the built environment. Energy efficiency in buildings has been a hot topic for decades. Today, the two newer trends are: a) electrifying remaining fossil-fueled energy demand (such as hot water and space heating) and b) sourcing that electricity demand from clean renewables. Crypto finds itself at a simple juncture: it is already electrified by virtue of being a digital currency. The energy efficiency of blockchain networks is under more scrutiny than ever before. Now the challenge before us is to ensure that the electricity powering blockchains is generated with renewables.

To be clear: the solution to making crypto green is *not* to mark individual tokens as green or not green. When you pay at the store with your Visa or Mastercard, there isn't 'green' credit and 'brown' credit. The underlying currency remains totally fungible. The same must remain true with cryptocurrencies like BTC and ETH. This is one of the primary benefits of crypto.

**Question: You mentioned that Energy Web is building an enterprise-grade blockchain for the energy sector. How do you deal with energy efficiency and performance issues in such a highly demanding and highly complex sector?**

The regulatory, market, and pure physical complexities of the world's power grids are some of the chief reasons why we launched the Energy Web Chain in the first place. From the outset, it was designed to be robust, fast, energy-efficient, and with low transaction costs.

Perhaps just as importantly, almost 50 companies and counting on four continents and 19 timezones host validator nodes that collectively maintain the network. Those companies go through a KYC vetting process, and the majority are grid operators and other legacy enterprises from the energy sector, including Eletrobras, Mercardos Eléctricos, Tenaska, and UTE in the Americas; Acciona, Elia Group, Engie, and Shell in Europe; and PTT Group, SB Energy, and SP Group in Asia.

Moreover, the Energy Web tech stack is not a blockchain-only solution. In addition to the foundational Energy Web Chain, we also leverage other decentralized digital technologies (such as for the utility services layer of our tech stack) as well as integrations with legacy IT systems (including SCADA and DERMs, in the case of grid operators).

But the far more important thing is not how the Energy Web tech stack works, but rather what it enables. A focus only on decarbonizing crypto and blockchains misses the bigger picture: how this new generation of digital technology—including Energy Web's—can accelerate the global energy transition in a time of growing climate action urgency. That is the consistent theme behind all of Energy Web's work.

**Question: You are leading Energy Web as the CEO. Which are in your opinion the most important challenges that your organization will face in the future in its effort to scale up its solutions?**

As we look ahead to the COP26 United Nation's climate change conference later this year in Glasgow, many are calling the 2020s the 'decisive decade' for global climate action. The energy transition needs to move a lot faster, and achieve bigger emissions reductions sooner. Insofar as blockchain can help accelerate the energy transition, the biggest challenges we face are those that impede solutions becoming adopted at scale fast.

In other words, the tech is already here. The Energy Web ecosystem alone has completed myriad successful pilots, proofs of concept, and early deployments with grid operators, energy companies, renewables developers, and electric vehicle stakeholders around the world.

For example, we've partnered on digital, blockchain-based renewable energy marketplaces in Asia with Minden in Japan, PTT Group in Thailand, SP Group in Singapore, and Foton in Turkey; in Europe with Engie in France and Accione and Iberdrola in Spain; and in the Americas with PJM in the United States, Mercados Eléctricos in El Salvador, and Eletrobras in Brazil. We can point to other examples for use cases such as virtual

power plants, distributed energy resources providing grid flexibility, and digital 'passports' for lifecycle management of batteries. We know the technology performs. Now, how quickly can we scale adoption?

We see several key levers to make that happen, including: a) clearer regulations on crypto in general that are consistent across Europe and even better globally; b) standardization around blockchain technologies in general (e.g., Energy Web is participating in standardization bodies such as IEEE 2418.5 and EU-based initiatives, such as INATBA); and c) increasing utility comfort with digital tech overall, beyond blockchain specifically (e.g., utility investment in software 'infrastructure' has lagged investment in 'hard' poles-and-wires infrastructure. On this last point, we believe that a new era of decentralized service-level agreements (DSLAs) can help speed utility adoption of this new class of digital tech (i.e., blockchain).

For me it is now down to a question of leadership. We need more executives and politicians to get out of their comfort zone and lead the way. I am in a fortunate position that a lot of our members are at the forefront of this transformation but we need to go faster.

**Question: Recently EW together with RMI and AIR launched the Climate Crypto Accord initiative. What is the vision of CCA? What are you trying to achieve?**

The Crypto Climate Accord (CCA) is a private-sector led initiative to decarbonize the crypto and blockchain industry. The fast-growing community of CCA Supporters now includes more than 45 companies spanning the crypto, finance, technology, NGO, and energy and climate sectors as a signal of support for developing solutions to decarbonize the crypto industry. More recently, we have also welcomed the first four Signatories, who make a public commitment to achieve net-zero emissions from electricity consumption associated with all of their respective crypto-related operations by 2030 and to report progress toward this net-zero emissions target using best industry practices.

Based on initial feedback from CCA Supporters, Energy Web has identified three activities that will underpin how Supporters make progress toward the CCA's objectives:

1. **Benchmarking & good industry practices:** Establish an enhanced baseline of the crypto industry's renewable energy use to bring greater clarity to this issue and define good industry practices based in alignment with renewable energy and carbon standards;
2. **Solution toolbox development:** Develop a toolbox of open-source solutions that help crypto holders directly decarbonize their crypto holdings and enable crypto networks to decarbonize from the bottom-up (more details here);
3. **Proof of progress:** Share measurable progress toward the CCA's objectives and highlight challenges where additional stakeholders are needed to lend support.

Our Supporters approve of the Accord's objectives and are involved with helping advise, develop, and scale solutions in support of the CCA. Becoming a CCA Supporter does not verify that a Supporter organization has already decarbonized. The Crypto Climate Accord is also supported by the UNFCCC Climate Champions. Supporters are already developing solutions to convert the crypto industry's energy use into a new class of renewable energy buyer. For example, Energy Web will launch the first operational version of Energy Web Zero in Q1 2022 to provide crypto investors, hodlers, application developers, exchanges, and mining facilities a freely accessible and easy to use tool to buy verified renewables in an entirely digitized manner. In addition, bitcoin mining facility companies are beginning to explore the potential and needs for "green hash rate" software that can illustrate increasing renewable energy use by mining facilities.

**Question: If you were asked to state your predictions for the future of scalability and performance of blockchain technology for the next 10 years, what would you say?**

Blockchain technology is here to stay. There are many use cases being built now and already I can see the enormous potential for transforming the way people and businesses live and work around the world. I often

compare where we are in the blockchain sector today with where we were with the Internet in 1995. The best is yet to come real impact on our day-to-day lives still has to be made.

Scalability is an important aspect of that. Not just from a technology perspective only but also from an ESG perspective. In my view we will see many competing initiatives in the coming years around money and the different use cases there. Central Bank Digital Currencies, Bitcoin, Diem, other crypto currencies still to be developed. Decentralized Finance will be going through major scaling challenges too. I also expect the more common purpose chains (Ethereum, Polkadot, Cardano and the likes) tackling the challenges of how to scale in a more decentralized way,  building the new internet.

When blockchains become a more integral part of the way we live our lives and do business we will automatically see the sector having to deal with existing laws and regulations. This can become a big issue when it comes to the speed of scaling this new infrastructure. Take a simple topic like the classification of the tokens. Is it a security, a utility, a payment token? These discussions take years and in some countries laws of 1931 are being applied to make an assessment. Clearly our regulatory bodies also need to go back to the drawing table, understand the impact of this new technology and take a more pragmatic approach to how regulation will work in this new industry. From where I am sitting I can see some countries really taking advantage by creating simple rules and a more agile approach to how the final regulations will be defined. I think this is very smart and will bring a lot of economic activity to these countries.

Energy Web has a unique position where we build an open-source, publicly accessible, digital infrastructure for the energy industry. To help decarbonize the electricity grid faster. We develop our stack with the sector, for the sector. I expect more of these sector-driven initiatives as it is really working very well. No vendor lock-in, an open environment for innovation and a public infrastructure that takes into account all relevant legislation like GDPR and others. The way we scale for our mission is by using our blockchain for what it does best: providing trust. All the services and common components that are relevant for the Energy Sector are built in the utility layer that is built on top of the trust layer. This allows us to scale, whilst honouring the principles of decentralized architectures and self-sovereign people and their energy assets.

We are ready for a future where hundreds of millions of energy devices with their own digital identity will form the new, customer centric electricity grid. Removing the need for carbon intensive electricity production. The sooner this becomes a reality, the better as far as I am concerned.

# Section 5: Decarbonizing Blockchains

## INTRODUCTION

Cryptocurrencies like Bitcoin and Ether are becoming increasingly mainstream. And the primary technology underpinning the cryptocurrency industry—blockchain—is earning its place in dozens of industries, from healthcare to logistics to the energy sector.

Crypto demand is at an all-time high. Large enterprises are starting to accept cryptocurrencies as an alternative to conventional, fiat payment. Non-fungible tokens issued on top of blockchain-platforms are supporting artisans in new and exciting ways. Meanwhile, major corporations and institutional investors have started adding cryptocurrencies to their balance sheets.

This surging demand for cryptocurrencies and accelerating adoption of blockchain-based solutions have highlighted a critical issue: the technology's growing energy consumption and its impact on our climate.

The cryptocurrency industry is not alone in dealing with this dual energy-and-climate challenge. The technologies underpinning crypto are powered by electricity—just like other electricity-powered technologies such as cloud computing, data storage & processing, social networks, and artificial intelligence. Industries from across the global economy are beginning to decarbonize their operations in order to facilitate widespread, sustainable industry growth. That's why in April 2021 the Crypto Climate Accord (CCA) was born.

Inspired by the Paris Climate Agreement, the Accord is a private sector-led initiative for the entire crypto community focused on decarbonizing the cryptocurrency industry in record time. Nonprofits Energy Web, the Alliance for Innovative Regulation, and RMI launched the CCA with more than 20 supporting organizations, including the UNFCCC Climate Champions, CoinShares, Consensys, Web 3 Foundation, Hut 8, Ripple, and the Global Blockchain Business Council.

There are three provisional objectives to be finalized in partnership with Accord supporters:

- Enable all of the world's blockchains to be powered by 100% renewables by the 2025 UNFCCC COP Conference;
- Develop an open-source accounting standard for measuring emissions from the cryptocurrency industry; and
- Achieve net-zero emissions for the entire crypto industry, including all business operations beyond blockchains and retroactive emissions, by 2040.

Activities under the Accord will be focused on quickly closing the gap between today's industry emissions and industry-wide decarbonization for all blockchains, service providers, and other crypto industry activity, such as non-fungible tokens.

The Accord is organized around the following core principles:

- Build on existing forward progress: The electricity that powers our sector is decarbonizing. Renewables have become cost competitive in energy markets around the world. As a result, a growing share of the grid (and by extension our industry) is becoming cleaner;

- Mind the gap: recognize that significant work remains to be done. There is a substantial opportunity to close the gap between crypto emissions today and a net-zero emissions industry;
- Move quickly: Crypto's roots in open-source, agile, and technology innovation make crypto an ideal candidate to achieve something the world has yet to see: rapid industry-wide decarbonization;
- Decentralized, open-source technology can accelerate progress: The same open source, decentralized technology underpinning the global crypto industry — blockchain — can bring transformational levels of data transparency and trust to decarbonization efforts;
- Voluntary, market-oriented, and value-added: Voluntary, private-sector led action on industry decarbonization should be powered by a shared vision and market-driven solutions that accelerate market growth and create long-term value for everyone; and
- Community-driven: All crypto communities should work together, with urgency, to ensure crypto does not further exacerbate global warming, but instead becomes a net positive contributor to the vital transition to a low carbon global economy. This process will be collaborative and based on shared interests and co-investment; no central body will dictate solutions.

## HOW TO DECARBONIZE BLOCKCHAINS

Blockchains are the single biggest source of energy consumption in the cryptocurrency industry. Yet given the decentralized nature of blockchains, how can they be decarbonized? Based on innovation already taking place today, we see two high-level paths to decarbonizing them.

**Supply side: leverage the innate transparency of blockchains to fully decarbonize from the bottom up.**

The solution to making crypto green is not to mark individual tokens as green or not green. We want cryptocurrencies like BTC and ETH to remain 100% fungible. This is one of the primary benefits of crypto.

The real long-term solution is to ensure all blockchains are powered by 100% renewables. For some blockchains, industry can achieve this by further investing in consensus mechanisms and solutions that are more energy-efficient (e.g., proof-of-stake). For other blockchains, proof-of-work consensus is here to stay. In this space, industry has an opportunity to leverage the transparency of blockchains themselves to measure just how much entire networks are powered by renewables.

Today, innovative companies are launching crypto mining sites in areas rich with renewables and in some cases using crypto mining to absorb renewable electricity that would otherwise be lost. To accelerate green mining further, we can use open-source technology to measure and report — on a completely anonymous basis — how much mining is green.

Strong precedent exists: renewable energy certification schemes are already active in markets across the globe that track renewable power generation. We can use a similar approach here to measure renewable power consumption tied to crypto mining activities.

This concept is almost identical to what technology giants Microsoft and Google are currently experimenting on with regards to data centers. Their intention is to prove that their data centers are being powered twenty-four hours a day, seven days a week by renewable energy. We can apply a similar technology approach to the crypto industry. If successful, crypto producers will be able to verifiably claim and prove their contribution to making an entire blockchain green—all while maintaining complete privacy for the businesses involved in crypto production

Under the Accord, we will support development of open-source software that crypto producers, together with grid operators and renewable energy companies, can install to prove the origin of the

electricity they use to mine crypto. This software will in turn help miners build stronger relationships with local/regional/national policymakers and regulators since they can use the proof of their renewable energy procurement to show their support for decarbonization efforts and eliminate concerns among policymakers and regulators about their energy use.

This technology—paired with governance structures that already exist in the renewable energy industry—can enable the entire industry to track and prove the green-ness of entire blockchains.

**Demand side: enable crypto investors and users to decarbonize their crypto holdings from the top down.**

Corporates around the world are already decarbonizing their businesses using renewable electricity.

According to the RE 100 — a global initiative of nearly 300 large corporates committed to 100% renewable electricity — these companies are driving over 315 terawatt-hours of renewable electricity demand per year (for comparison, the BTC network uses ~120 terawatt hours / year according to the Cambridge Bitcoin electricity consumption index).

The same products used by these companies to decarbonize their businesses can be applied to the crypto industry. Corporates, institutional investors, and even retail cryptocurrency holders can choose to purchase renewable energy that is directly tied to their crypto.

Depending on the geography and crypto investor preferences (around price, impact, etc.), there are many renewable energy options to choose from. In the end, crypto investors receive energy attribute certificates reflecting the proof of their renewables procurement from existing or not-yet-built renewable energy facilities, from local or highest-impact geographies (e.g., off-grid or conflict zone context), and bundled or unbundled with their electricity bills from their electric utility to name a few.

Here are two examples:

A major corporate or institutional crypto investor with strong sustainability commitments calculates the amount of non-renewable electricity attributable to their current cryptocurrency holdings. They then enter into a bilateral agreement with a renewable energy developer to purchase renewables over a multi-year period. The size of the project is directly correlated to the amount of non-renewable electricity used behind their crypto holdings.

A retail crypto investor purchasing crypto through an exchange chooses a “green crypto” option. This option charges a small percentage on top of the crypto transaction and places that value into an escrow account. This account is then used to purchase renewables from qualified renewable energy projects just like the corporate example above.

In both cases, open source technologies can be used to link these transactions to specific renewable energy projects around the world in order to prove their impact on decarbonizing crypto.

The Accord will be used as a coordinating framework to help crypto and renewable energy market participants deploy solutions like these,

## THE PATH FORWARD

The Accord’s collective ambition will create wins for both the planet and the global economy. Throughout the rest of 2021, Accord founders will:

- Engage a broad variety of crypto stakeholders to profile existing solutions for industry decarbonization and identify areas for further innovation,
- Help crypto holders decarbonize existing crypto holdings via mature renewable energy products and services already in-use by other industries around the world,
- Bring verified renewables to crypto mining and production at a global scale,
- Report on the Accord's impact, and
- Host the inaugural Crypto Climate Accord Congress.

# Section 6: Policy Recommendations

This section proposes a set of policy recommendations based on the topics addressed in this thematic report.

## RECOMMENDATIONS

- **Energy efficiency**
  At the EU level, the European Blockchain Services Infrastructure needs to consider energy consumption (and efficiency) of blockchain when deciding on the underlying technology for developing the necessary digital infrastructure. At Member State level, national blockchain-based deployments should also be transparent on their energy consumption. As also discussed in Section 1 of this report, blockchain solutions based on the Proof-of-Work consensus mechanisms should be avoid due to their significantly higher energy consumption compared to other consensus protocols, such as the Proof-of-Stake or Proof-of-Authority for example. Also, considering publicly accessible blockchain solutions using a limited number of validator nodes (e.g., public consortium-based blockchains based on Proof-of-Authority) can also be a way of providing the necessary trust and performance while preserving energy efficiency.
- **Scalability and performance**
  The topic of energy efficiency of blockchain-based solutions should also be considered under the light of scalability and performance on the underlying blockchain technologies. It is quite common that energy consumption increases exponentially when applications move from the proof-of-concept phase into production. Therefore, it is recommended that energy efficiency-related issues need always to be treated along with scalability and performance requirements of the blockchain-based solution under evaluation. As presented in Section 1 of this report and further analysed in Section 3, scalability and performance is closely related to the type of the underlying consensus mechanism in use. To this extent and in order to meet the necessary performance needed by specific applications, one may consider using a limited number of validators following a publicly accessible Proof-of-Authority blockchain solutions, as also in the case of energy efficiency discussed above.
- **Use of renewable energy**
  Since energy consumption is an intrinsic aspect of applications based on blockchain technology, it is important to make sure that renewable energy is used to the maximum possible extent to cover the demand of energy. In EU, the Guarantees of Origin (GOs) serve as the Energy Attribute Certificates. However, GOs reflect average consumption and production over longer time periods, in practice a year. Therefore, they do not take into account when the production and consumption take place, thus they consider the total in the time period, not the consumption or production patterns within it. To implement a more efficient mechanism for the use of renewable energy for blockchain operations, a 24/7 hourly matching of consumption and production of renewables schemes need to be in place. This means that we would be in the position to know if the consumption matches renewable production every day, every hour. Several initiatives are currently trying to compensate for the energy consumption of the Proof-of-Work blockchains, and especially those related to Bitcoin, that require the purchase of Energy Attribute Certificates from the miners according to their energy consumption. Such an initiative called Crypto Climate Accord that is presented and discussed in Section 5 of this report.
- **Certification**
  Certification of equipment used as infrastructure for the deployment of public-sector blockchain solutions at European and Member State level should be in place. These certifications may take the form of an “Energy Performance Certification” similar to the ones already applied in Europe and are related to building, equipment, or infrastructure. This process should be based on the benchmarking of the equipment used in mining facilities as analysed and presented in Section 3 of this report.
- **Energy efficiency evaluation criteria**
  It is recommended that specific evaluation criteria related to the performance and energy efficiency of blockchain-based solutions for the public sector need to be specified European and Member State level. These criteria could also be used to evaluate the performance in terms of energy consumption

not only of existing solutions, but also can become part of the evaluation process of public tenders at a European or Member State level that are requesting blockchain-based solutions as part of the technical specification of the tender. This way, a common and standardised European framework for assessing the energy consumption of public sector blockchain-based solution can be developed. This process is also closely related to the certification process of the equipment used in mining facilities as discussed in Section 3 of this report.

- **Blockchain energy consumption index**
  To assess the energy consumption of blockchain-based solutions in an independent and unbiased manner, a blockchain energy consumption index should be developed and agreed between the Member States. The blockchain energy consumption index should leverage the available information on the energy balance for each Member State to also provide insights on the type of energy that is used to power the blockchain solutions at European and Member State level. Moreover, the blockchain energy consumption index should also try to model the energy consumption of other blockchains apart from Bitcoin.
- **Guidance and knowledge sharing**
  Create programs for knowledge-sharing and dissemination of pilot results and best practices on blockchain deployments between the Member States. Moreover, guidance should also be provided along with guidelines and recommendations to foster and promote the knowledge around the topic of energy efficiency of blockchain technology.

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# Annex

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## COMPARISON OF CONSENSUS PROTOCOLS

Firstly, we have to dive into what Consensus means and what algorithms means, how a combination of them is bringing Consensus Protocols based on automated process for a multiparty scenario, not only involvement rather than consequences in effect of a fact with responsibilities behind. A **distributed consensus** mechanism starts with no leader and it establishes **trust between the stakeholders** which include the exchange of proofs and values.

**Consensus Protocols** can be divided into **two major families**, and a comparison could be understandable from the problems they afront and solve in a different manner.

- Those existing **before bitcoin**, Byzantine based consensus;
- Those that only exist after bitcoin, family of Nakamoto consensus;

Byzantine general´s problem, addressed in 1982 by Leslie Lamport, Robert Shostak and Marshall Pease:

*"Reliable computer systems must handle malfunctioning components that give conflicting information to different parts of the system. This situation can be expressed abstractly in terms of a group of generals of the Byzantine army camped with their troops around an enemy city. Communicating only by messenger, the generals must agree upon a common battle plan. However, one or more of them may be traitors who will try to confuse the others. The problem is to find an algorithm to ensure that the loyal generals will reach agreement. It is shown that, using only oral messages, this problem is solvable if and only if more than two-thirds of the generals are loyal; so, a single traitor can confound two loyal generals. With unforgeable written messages, the problem is solvable for any number of generals and possible traitors".*

This family is called Byzantine fault tolerant protocols whereby there are algorithms that are robust enough for randomly types of failures in a distributed manner with which a Byzantine Agreement protocol is commonly adopted. There are two basic consensuses in a different way, those based on a **lottery** and those based on **election**.

In 1985, Michael Fisher, Nancy Lynch and Michael Patterson "Impossibility of Distributed Consensus with One Faulty Process" and their job is called FLM impossibility whereby demonstrated that every protocol has the possibility of non-termination, "even with only one faulty process" where asynchronous systems are needed and some of them are unreliable, in contrast with synchronous cases where Byzantine general´s problem is solved efficiently. These aspects essentially raised the Consistency, Availability, Partition tolerance theorem approach where properties are Consistency, Availability and tolerance to Partitioning. Although in 2002 Seth Gilibert and Nancy Lynch demonstrated that **Coherence** can be relaxed in a partially synchronous distributed network to secure Availability and Partitioning.

The famous FLP impossibility problem is essential for Richard Guerraoui, Matej Pavlovic and Drago-Adrian Seredinschi in their work, with which they present the problem based on the state machine replication and consensus whereby the adversary can control various parts of the system with two assumptions: behaviour (how much control the adversary has over the nodes´ behaviour) and Synchrony (how much control has over the message transmission delays and delivery guarantees of the network) which conclude into a question *"What is necessary to compromiso the liveness and/or safety of a blockchain protocol?"* and consume their questions with **A-indulgent** protocols (maintaining safety while minimal restrictions on the adversary in synchrony) or **B-indulgent** protocols (which are indulgent towards malicious nodes although require additional synchrony to remain safe).

Both families differ in a critical aspect, nodes in PBFT choose leaders and commit on values after consulting with a majority of the system and Nodes in Bitcoin commit on a value after some time passed and accumulate the value confirmations where relies on timing assumptions. Although raised three elemental properties which are validity, agreement and termination.

There is a very interesting survey by IEEE on Consensus Mechanism and Mining Strategy Management in Blockchain Networks distinguishes three properties of Nakamoto Protocols in comparison with Byzantine agreement: common-prefix property, Chain-quality property and Chain-growth property within a context of primitive PoW scheme whereby its correspondences as agreement, validity and liveness in the context of Byzantine Agreements allow to reach a wide variety of PoW Schemes for Permissionless Blockchains. https://arxiv.org/pdf/1805.02707.pdf (TABLE III).

The properties of the consensus protocol allow to evaluate the node´s behaviour in particular the validator nodes with which Integrity, authentication, termination and independence are the main criteria aborded by the Study Report by ISO TC 307 on regards on Security Evaluation of Consensus Models; however it is extremely interesting mixed properties and hybrid consensus protocols based on incentive capabilities, not only economic incentives.

At the deliverables of ITU-T FG DLT in 2019 the Technical Report D.5.1. Outlook on DLT presented another Comparative table, TABLE 4 which compare based on properties as safety and performance.

Table III
COMPARISON OF DIFFERENT POX SCHEMES FOR PERMISSIONLESS BLOCKCHAINS

| Puzzle Name | Origin of Hardness (One-way Function) | Designing Goal | Implementation Description | ZKP Properties | Simulation of Random Function | Features of Puzzle Design | Network Realization |
|---|---|---|---|---|---|---|---|
| Primitive proof of work [23], [86] | Partial preimage search via exhaustive queries to the random oracle | Sybil-proof | Repeated queries to cryptographic hash function | Yes | Yes | Single challenge | Bitcoin [1], Litecoin [92] |
| Proof of exercise [105] | Matrix product | Computation delegation | Probabilistic verification | N/A | No | Single challenge | N/A |
| Useful proof of work [84] | $K$-orthogonal vector, 3SUM, all-pairs shortest path, etc. | Computation delegation | Non-interactiveness via Fiat-Shamir transformation | Yes | Yes | Single challenge with sequential hash queries | N/A |
| Resource-efficient mining [100] | N/A | Computation delegation | Guaranteed by TEE | Yes | Yes | Trusted random oracle implemented by dedicated hardware | N/A |
| Proof of retrievability [110] | Merkle proofs of file fragments in the Merkle tree | Distributed storage | Non-interactiveness via Fiat-Shamir transformation and random Merkle proofs | Yes | Conditional | Two-stage challenge | Permacoin [109], KopperCoin [70] |
| Proof of space -time [36] | The repeated proof of retrievability over time | Decentralized storage market | Repeated PoR | Yes | Conditional | Two-stage challenge and repeated PoR over time | Filecoin [36] |
| Equihash [81] | The generalized birthday problem | ASIC resistance | Time-space complexity trade-off in proof generation [81] | Yes | Yes | Memory-hard | ZCash [44] |
| Ethash [114] | Random path searching a random DAG | ASIC resistance | Repeated queries to cryptographic hash function | Yes | Yes | Sequential, memory-hard puzzle | Ethereum [35] |
| Nnonoutsourceable scratch-off puzzle [82] | Generalization of proof of retrievability | Centralization resistance | Random Merkle proof | Yes | Yes | Two-stage challenge | N/A |
| Proof of space [116] | Merkle proofs of a vertex subset in a random DAG | Energy efficiency | Random Merkle proof | Yes | Yes | Two-stage challenge and measurement of proof quality | SpaceMint [116] |
| Proof of human work [102] | Radom CAPTCHA puzzle requiring human effort | Useful work and energy efficiency | CAPTCHA and PoW | Yes | Yes | Human in the loop | N/A |

*Figure 1: Comparison of Different PoX Schemes for Permissionless blockchains by Wang et al.*

## Table 4: Comparative analysis of consensus schemes

| | Systems | Committee Formation (Resources) | Strong Consistency | Single Committee | | | | Multiple Committee | | | Safety | | | Performance | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | Committee Configuration | Inter-Committee Consensus | | | Intra-committee Configuration | Intra committee Consensus | | | | | | | | |
| | | | | | Incentives (Join,Participate) | Leader | Msg. | | Mediated | Incentives | Transaction Censorship Res. | DoS Res. | Adversary Model | Throughput | Scalable | Latency | Exp. Setup |
| Hybrid | ByzCoin [b-Kogias] | PoW | √ | Rolling (singl) | √ × | Internal | O(n) | / | / | / | √ | part | 33% | 1000 tx/s1 | × | 10–20s 1 | Real |
| | Solidus [b-Abraham] | PoW | √ | Rolling (singl) | √ √ | External | O(n2) | / | / | / | × | part | 33% | / | / | / | / |
| | Algorand [b-Gilad] | Lottery | √ | Full swap | ×× | Internal | O(n2) | / | / | / | × | √ | 33% | 90 tx/h 2 | × | 40s 2 | Real |
| | Hyperledger [b-Vukolic-b] | Permissioned | √ | Static | / | Flexible | Flexible | / | / | / | √ | √ | 33% | 110k tx/s 3 | × | <1s 3 | Real |
| | Tencent TrustSQL | Permissioned | √ | Static | / | / | / | / | / | / | √ | √ | 50% | 50k+tx/s 12 | × | 20ms 12 | Real |
| | RSCoin [b-Danezis] | Permissioned | √ | Static | / | Internal | O(n) | × | Client | × | √ | √ | 33% | 2k tx/s 4 | √ | <1s 4 | Real |
| | Elastico [b-Luu] | PoW | √ | Full swap | √ × | Internal | O(n2) | Dynamic (Random) | ! | ! | × | √ | 33% | 16 blocks/110s 5 | √ | 110s/ 16 blocks | Real |
| | Omniledger [b-Kogias-b] | PoW/PoX | √ | Rolling (subset) | √ × | Internal | O(n) | Dynamic (Random) | Client | × | √ | √ | 33% | ≈10k tx/s 6 | √ | ≈1s 6 | Real |
| | Chainspace [b-Baasam] | Flexible | √ | Flexible | ×× | Internal | O(n2) | × | × | × | √ | part | 33% | 350 tx/s 7 | √ | <1s 7 | Real |
| Proof-of-X | Ouroboros [b-Kiayias] | Lottery | × | Full swap | √ √ | Internal | O(nc) | / | / | / | × | √ | 50% | 257.6 tx/s 9 | × | 20s | Simulation |
| | Praos [b-David] | Stake | × | Rolling (subset) | √ √ | Internal | O(1) | / | / | / | × | part | 50% | / | / | / | / |
| | Snow-white [b-Daian] | Stake | × | Full swap | √ √ | Internal | O(1) | / | / | / | × | √ | 50% | 100-150 tx/s 9 | √ | ? | Simulation |
| | PermaCoin [b-Miller] | PoW/PoR11 | × | Rolling (singl) | × √ | Internal | O(1) | / | / | / | √ | √ | 50% | / | × | / | / |
| | SpaceMint [b-Heneu] | PoS | × | Rolling (singl) | × √ | Internal | O(1) | / | / | / | √ | √ | 50% | ? | × | 600s | Simulation |
| | Intel PoET [b-Intel] | TH12 | × | Rolling (singl) | × √ | Internal | O(1) | / | / | / | √ | √ | TH12 | 1000 tx/s 10 | √ | / | Real |
| | REM [b-Zhang] | TH12 | × | Rolling (singl) | × √ | Internal | O(1) | / | / | / | √ | √ | TH12 | ! | √ | / | Real |
| Proof-of-work | Bitcoin [b-Nakamoto] | PoW | × | Rolling (singl) | × √ | Internal | O(1) | / | / | / | √ | √ | 50% | 7 tx/s | × | 600s | Real |
| | Bitcoin-NG [b-Eyal] | PoW | × | Rolling (singl) | × √ | Internal | O(1) | / | / | / | √ | part | 50% | 7 tx/s | × | <1s | Simulation |
| | GHOST [b-Sompolinsky-b] | PoW | × | Rolling (singl) | × √ | Internal | O(1) | / | / | / | √ | √ | 50% | / | × | / | / |
| | DECOR+HOP [b-Lerner] | PoW | × | Rolling (singl) | × √ | Internal | O(1) | / | / | / | √ | √ | 50% | 30 tx/s 8 | × | 60s | Simulation |
| | Tencent TrustSQL | PoW | √ | Rolling (singl) | × √ | Flexible | O(1) | / | / | / | √ | √ | 50% | 50k+ tx/s 12 | × | 50ms | Real |
| | Spectre [b-Sompolinsky-a] | PoW | × | Rolling (singl) | × √ | Internal | O(1) | / | / | / | √ | √ | 50% | / | × | / | / |

1 144 nodes/committee.
2 50k nodes/committee.
3 4 nodes/committee (corresponding to BFTSmart [b-Kim]) corresponding to HyperLedger v0.6, new consensus scheme [b-Thakkar] is used after v0.6.
4 3 nodes/committee. 10 committees.
5 100 nodes/committee. 16 committees.
6 72 nodes/committee (12.5% adversary). 25 committees.
7 4 nodes/committee. 15 committees.
8 1 minute average interval; 1 block = 1 MB.
9 40 nodes.

*Figure 2: Comparative analysis of consensus schemes*

Every consensus protocol can offer a different property or a set of properties to the network. There are examples like Bitcoin where mining is required to add a block in the chain, while other examples are not relying on mining and implement a minting system to add a block in the chain based on transactions. The latter examples contemplate numerous cases that apply an election or voting mechanism. The following figure briefly includes these examples.

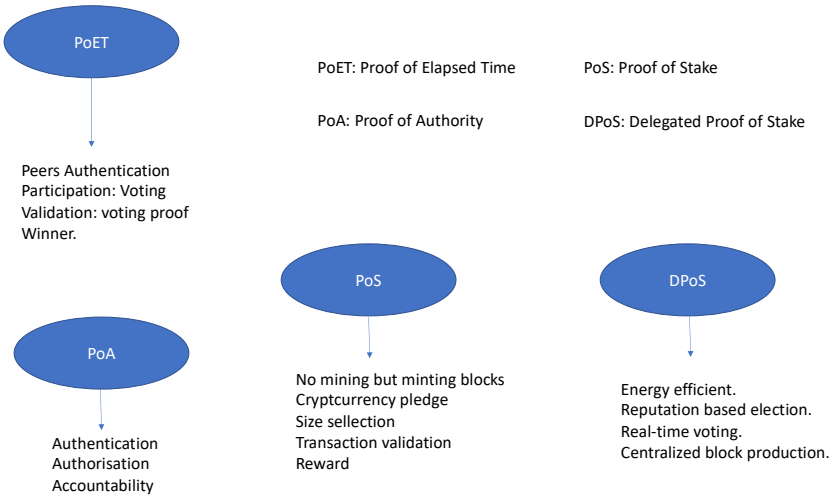


*Figure 3: Summarization of consensus algorithms and properties*