Final Report: Exploration of Environmentally Friendly Blockchains

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I. Introduction

Traditional blockchain with Proof-of-Work as the consensus algorithm requires a huge amount of computing power to work out the puzzles, which translates to enormous energy consumption. In [1], the annual energy consumption involved in mining by PoW Cryptocurrencies with the top 5 market capitalization was estimated to be over 100TWh in total. They determined electricity consumption to be between 60 and 125 TWh per year for Bitcoin. As said in the paper, competition in the mining hardware market, resulting from the hype around cryptocurrencies, has dramatically increased the energy efficiency of mining hardware in the last decade.

Moreover, the price of Bitcoin keeps climbing higher and higher, which is incentivising more and more people to mine Bitcoin, and the total energy consumption of the Bitcoin network keeps growing fast that we can now even compare it with the energy consumption of some countries. According to [12], Bitcoin and Ethereum are by far the largest Proof-of-Work based coins and their combined energy consumption is estimated to be 90.72 TWh per year, which is in the range of the annual energy consumption of countries such as Pakistan (87.4 TWh) and Netherlands (113.21 TWh), as shown in Fig. 1.

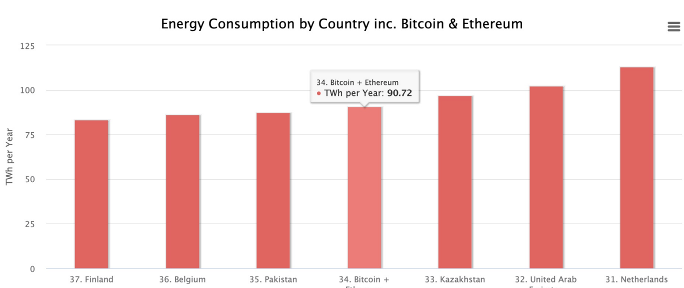

Fig. 1. Comparison of Energy Consumption by Country

II. Project Overview

As introduced above, building environmentally friendly blockchains is a vital problem we need to think about for the sake of our environment and also for the long-term development of blockchains.

In this project, there are mainly 3 goals for us. First, in terms of measuring how environmentally friendly a blockchain is, we start from the root and dive deep into the consensus algorithms as they essentially determine how much computing power and what kind of hardware will be needed when designing and building a blockchain. Specifically, we analyze and compare different consensus algorithms in detail, including the essential mechanisms, characteristics and core differences with others, performance on energy consumption, and their current applications.

Second, we've made a significant amount of work on grabbing the specific energy consumption data including the annual total electrical energy, annual carbon footprint, and energy cost per transaction of the two most popular cryptocurrencies in the world: Bitcoin and Ethereum. We built a web application called Cryptocurrencies Energy Consumption Visualization (CECV) that converts cryptocurrency energy consumption data into straightforward graphs and visualizes the data in an intuitive and interactive way. Following CECV, we will give a comprehensive analysis of the data as well as analyzing the possible change of their energy consumption in the future.

Finally, we'll give our own conclusions and solutions to build an environmentally friendly blockchain and try to answer two questions: what factors to consider when building a blockchain, and how to build an environmentally friendly blockchain? We'll discuss possible solutions from different perspectives such as clean energy, locations and actual commercial needs, combined with our research on different consensus algorithms.

III. Consensus Algorithms Overview

The energy cost of blockchain with different consensus algorithms is different due to their different approaches to reach a consensus. In this section, we are going to present three major consensus algorithms in blockchain, namely, PoW, PoS, and PBFT. We'll also briefly discuss some other non-PoW consensus algorithms such as Raft and Proof of Authority.

As stated in [1], the blockchain algorithms can be divided into two groups: The first group of consensus algorithms is proof-based consensus, which requires the nodes joining the verifying network to show that they are more qualified than the others to do the appending work. The second group is voting-based consensus, which requires nodes in the network to exchange their results of verifying a new block or transaction, before making the final decision. For proof-based algorithms, we present PoW, PoS, and DPoS. For voting-based algorithms, we present PBFT, as an example.

For each algorithm, we present the basic idea of how to reach a consensus with that algorithm and analyze its corresponding energy cost, especially compared with PoW. Furthermore, we provide some real-world blockchain applications or cryptocurrencies using such algorithms that make the most of the market capitalization.

A. Proof-of-Work

Proof-of-Work (PoW) is the consensus algorithm applied by Bitcoin and many other famous cryptocurrencies such as Ethereum, Litecoin, and Zcash. In PoW, all the nodes in the network are required to solve a "puzzle" with a brute-force approach until one of them first manages to find a hash that is less than a specific hash target number. Note that although there is only one final winner for each puzzle, all of the nodes participating in solving the puzzle have to keep performing the complex computation, which means not only the final winner but also all the other nodes will consume a huge amount of energy. The difficulty of finding such a hash increases as the hash target number becomes smaller, and because of the extremely time-consuming process and rare chance to find a value, it is a proof of "work" as the miner has to spend a colossal amount of time and energy to "mine" it. Therefore, the mining process is the essential reason for the energy consumption issue.

Moreover, with the difficulty increasing, more and more complex puzzles need to be solved and the electricity consumption that comes from relentless, complex computing is bound to increase. We'll give detailed data analysis of the energy consumption of Bitcoin and Ethereum, both of which are based on PoW and have the largest market capitalization currently, in the later section.

B. Proof-of-Stake

Proof-of-Stake (PoS) is a type of consensus mechanism by which a cryptocurrency blockchain network achieves distributed consensus. In PoS-based cryptocurrencies, the creator of the next block is chosen via various combinations of random selection and wealth or age (i.e., the stake) [2].

The main differences between PoS and PoW can be listed as follows: For PoW, to add each block to the chain, miners compete to solve a difficult puzzle using their computers' processing power. For PoS, however, there is no competition on computing power as the block creator is chosen by an algorithm based on the user's stake. In terms of attack, to add a malicious block in PoW, the attacker has to own more than 51% computation power of the network. While in PoS, the attacker has to own 51% of all the cryptocurrency on the network. Another major difference is the reward. In PoW, people get a reward for mining a block while in PoS people do not need to solve puzzles to mine blocks, so there is no reward for making a block. However, in both systems, they take the transaction fee [3].

Particularly, in terms of the energy consumption difference, in PoS, the miners do not need to solve puzzles to mine new blocks, the energy consumption and electronic waste are low compared to PoW. There has been news that Ethereum plans to cut its energy consumption by 99 percent by replacing PoW with PoS [4].

There have been many PoS based currencies since PoS was proposed. The first PoS based currency was PeerCoin [5] which kept Proof-of-Work as part of the minting process to facilitate initial minting. With the development of PoS protocol, we have NovaCoin which uses a hybrid PoS / PoW system [6]. Nowadays, some of the PoS-based cryptocurrencies that take up the most market capitalization are Binance Coin, Polkadot, Cardano, Stellar, etc [7].

A modification of PoS is the Delegated Proof-of-Stake protocol commonly known as DPoS. Unlike the Proof-of-Stake protocol where a user puts his coins on stake for acquiring the right to validate a transaction, forge blocks, and earn associated rewards, DPoS protocol allows users to vote a witness and the witness who gets the maximum vote will get the right to validate a transaction, forge blocks, and earn associated rewards. This protocol is also found to consume less energy as compared to Proof-of-Work and is also better than Proof-of-Stake [8]. Some of the PoS-based cryptocurrencies that take up the most market capitalization are EOS, TRON, Tezos, etc [7].

C. Practical Byzantine Fault Tolerance

The Byzantine Fault Tolerant Algorithm (BFT) is a fault-tolerant algorithm for Byzantine problems. The BFT solution allows nodes in a network to reach a consensus when the communication is reliable but the node may be down or evil. The Practical Byzantine Fault Tolerant (PBFT) [**?**] is the first widely used BFT algorithm. In PBFT, if more than two-thirds of the nodes are working normally, the entire system can work well.

Specifically, one node in the system will be regarded as the master node, and the other nodes are child nodes. All nodes in the system will communicate with each other and reach a consensus on data based on the principle that the minority obeys the majority. There are four steps of establishing the consensus via PBFT. First, the client sends a request to the master node to perform an operation. Second, the master node communicates with each child node. Third, all nodes perform the algorithm and return the result to the client. Fourth, the client receives the result from nodes.

There are two main advantages of the PBFT algorithm. First, PBFT is highly efficient compared with PoW, as it does not need to wait for block confirmation and the consensus will be established instantly once the verification process of a new block is finished. Second, it is energy saving and environmentally friendly as mining is not required — no hash puzzle needs to be solved in PBFT. Energy consumption and electronic waste are low compared to PoW. However, PBFT cannot be used in public blockchain since the communication cost will be extremely huge. In PBFT, the number of nodes is limited due to the needs of frequent communication between each node. What's more, the PBFT cannot prevent a malicious user from using multiple accounts to conduct consensus fraud. Consequently, User authority control should be applied to the PBFT system.

The PBFT have been widely used in blockchain applications and one of the most famous is Hyperledger Fabric. Hyperledger Fabric introduces a new blockchain architecture with elasticity, flexibility, scalability and confidentiality. Hyperledger Fabric Blockchain is a modular, extensible blockchain with access control, which supports the execution of distributed applications.

D. Other non-PoW algorithms

We also looked into some other consensus algorithms such as Raft, Proof-of-Authority and Proof-of-Importance, all of which are more environmentally friendly compared with PoW.

Raft is designed as an alternative to the Paxos family of algorithms. In Raft, a node can be in three states: the follower state, the candidate state or the leader state. Briefly speaking, the nodes will first go through a leader election, after this, all changes to the system go through the leader. The leader will not commit a change until a majority of followers acknowledge it. If the leader node is no longer valid, the nodes will go through another election. Raft also works with network partition and multiple leaders. One recent application of this algorithm will be in the recent release of the Oracle Blockchain Platform.

Proof-of-Authority (PoA) is proposed by Gavin Wood, co-founder of Ethereum and Parity Technologies [15]. In proof of authority, people's reputation are attached to their identity. People vote for a validator to perform as an authority to validate all the transactions. Therefore, nodes do not send transactions to each other. Instead, they send a transaction to the authority once it happens and every node updates its ledger from the authority. So proof of authority is pretty much centralized. By attaching a reputation to identity, validators are incentivized to uphold the transaction process, as they do not wish to have their identities attached to a negative reputation. This is considered more robust than PoS [16].

The Proof-of-Importance algorithm prioritizes miners based on the number of transactions in the corresponding cryptocurrency that they perform. The more transactions are made to and from an entity's cryptocurrency wallet, the higher that entity's chances of being given mining projects are. This algorithm is adopted by New Economy Movement, attempting to restructure the current economic system.

With no need to solve puzzles, the energy consumption of the three consensus algorithms mentioned is low compared with PoW.

IV. Energy Consumption Data Analysis

In order to better conduct the data analysis of the energy consumption of blockchains, we focused on Bitcoin and Ethereum, the largest Proof-of-Work based coins and also the most popular cryptocurrencies currently in the world. We grabbed relevant energy consumption data from Cambridge Bitcoin Electricity Consumption Index (CBECI) [12], Bitcoin Energy Consumption Index (BECI) [10] and Ethereum Energy Consumption Index [11]. Furthermore, we built a web application called Cryptocurrencies Energy Consumption Visualization (CECV) that converts cryptocurrency energy consumption data into straightforward graphs and visualizes the data in an intuitive and interactive way.

CBECI provides a real-time estimate of the total electricity load and consumption of the Bitcoin network. Since it's impossible to determine the exact electricity consumption, CBECI provides a range of estimates with a lower bound estimate and an upper bound estimate. Among the two boundaries, there is a best estimated energy consumption that is believed to be most closest to Bitcoin's real annual electricity consumption. From the blue line in Fig. 2, we can observe the trend of the best estimated energy consumption of Bitcoin over the past five years. Overall, the energy consumption keeps growing fast, from approximately 2.155 TWh per year in 2015 to 96.686 TWh per year in 2020.

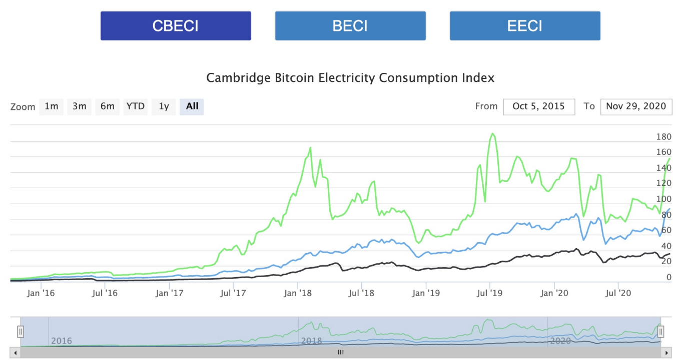

Fig. 2. Cambridge Bitcoin Electricity Consumption Index (CBECI)

The Bitcoin Energy Consumption Index (BECI) provides the latest estimate of the total energy consumption of the Bitcoin network. According to the Bitcoin Energy Consumption Index, the peak value of the annual electricity consumption reached 77.782TWh, which is comparable to the power consumption of Chile, as shown in Fig. 3.

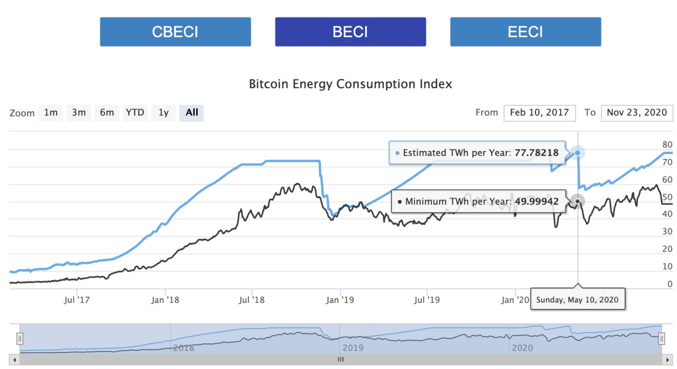

Fig. 3. Bitcoin Energy Consumption Index (BECI)

Moreover, from [10], the generated annual carbon footprint is nearly 36.95 Mt of carbon dioxide, comparable to the carbon footprint of New Zealand. Moreover, the electricity consumption of a single transaction is 761.93 kWh, which is close to the energy consumption of 718,766 VISA payments and is equivalent to the 23.4-day average electricity consumption of American households, and the e-waste generated by each transaction is 90.60 grams, as shown in Fig. 4.

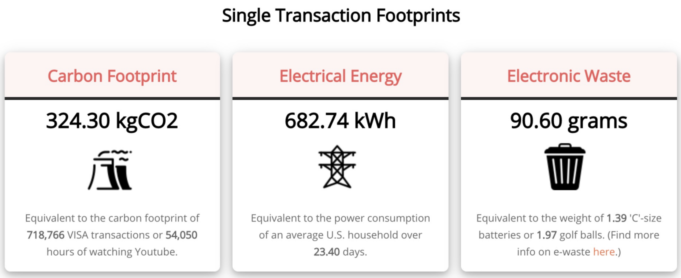

Fig. 4. Single Transaction Footprints of Bitcoin

The Ethereum Energy Consumption Index (EECI) [11] provides the latest estimate of the total energy consumption of the Ethereum network. As for the energy consumption of Ethereum, we can observe from the Ethereum Energy Consumption Index shown in Fig. 5 that, the energy consumption keeps growing in the past year, and the peak value of the annual total electrical energy consumption is 12.63 TWh, which is comparable to the power consumption of Uruguay, and the footprint per single transaction is 29.44 kWh, equivalent to the power consumption of an average U.S. household over 0.99 days.

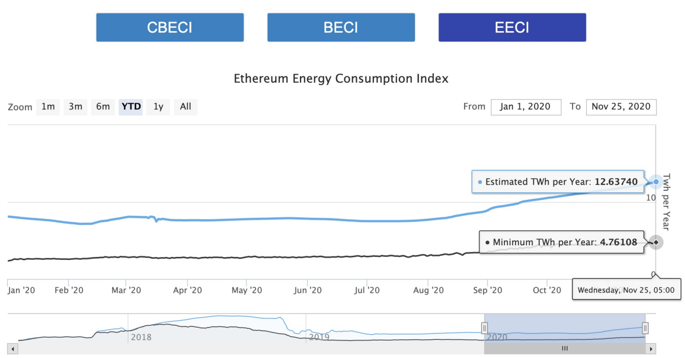

Fig. 5. Ethereum Energy Consumption Index (EECI)

V. Solutions

In this section, we will discuss the possible solutions to two essential questions of our project: What factors should we consider when building a blockchain, and how to build an environmentally friendly blockchain?

As for the first question, just as we've discussed above in detail, energy consumption is no doubt an essential factor we need to consider when we choose the consensus algorithm to build a blockchain. For example, Ethereum plans to cut its energy consumption by 99 percent by replacing Proof-of-Work with Proof-of-Stake.

As for the second question, there are five key points we want to discuss and propose.

First, the government should encourage the cryptocurrency miner to use renewable and clean energy such as hydropower, wind power and solar power as their mining power source, and miners should also take this factor into serious consideration when selecting places to build mining farms. The increasing consumption of the renewable energy will also greatly benefit the development of the clean energy in the long run. For example, in 2017, 80% of Chinese bitcoin mining operations were located in Sichuan Province [17]. About 90% of the energy consumtopn in Sichuan Province comes from renewable resources. A report from CoinShares Research estimates that approximately 77.6% of cryptocurrency miner are consuming electricity generated from renewable resources [18].

Second, miners should consider build mining farms on places where there are excess electricity. There are mainly three benefits. Firstly, the profitability of cryptocurrency mining depends on the market price of currency and the price of electricity. If the value of cryptocurrency depreciates below its mining electricity cost, mining will become unprofitable. Thus, it's obvious that if miners want to achieve the highest profit, they should be able to obtain the cheapest electricity. For example, there are excess electricity in Erdos and the electricity price is much low. There are also rich water resources in Thailand or Sichuan and Yunnan Province in China. In previous years, these excess water and electricity were wasted or dumped as excess milk. However, with the development of Bitcoin, more and more crytocurrency miners built their mining farms there because of the low local electricity price. Secondly, The arrival of Bitcoin mining farms can increase the income of hydropower stations by millions each year and greatly stimulate local economic development. Thirdly and most importantly, those wasted electricity is well utilized, which is truly environmentally friendly as those mining farms essentially do not produce carbon footprints.

Third, we should develop more efficient mining machines. In Fig. 6, we can see the comparison of different versions of AntMiner machines. With the development of the mining machine technology, the mining power efficiency is greatly improved. For example, the AntMiner 4+ has a power efficiency of 0.58 J/GH, while the power efficiency of its higher version — AntMiner S7 is only 0.25 J/GH. Developing and using the higher efficient mining machine can be much helpful to save energy and protect the environment.

Fourth, we propose the principle that blockchains are built based on specific and real commercial needs, and we should better choose the plan which has lower energy consumption. We should also consider hybrid blockchains, which combines the advantages of PoW, PoS, and PBFT, with relatively low energy consumption, high scalability, high throughput, and low latency. More specifically, in Fig. 7 we list the evaluation and comparison of different consensus algorithms discussed in our project. For each consensus algorithm, we evaluated its advantages and disadvantages with several metrics including scalability, decentralization, throughput, latency, and so on. Note that in order to build an environmentally friendly blockchain, we pay extra attention to the energy consumption

	AntMiner S4+	AntMiner S5	AntMiner S5+	AntMiner S7
Chip	204x BM1382	60x BM1384	432x BM1384	162x BM1385
Hashrate	2570 GH/s	1155 GH/s	7722 GH/s	4860 GH/s
Power Draw	1500W	590W	3436W	1210W
Power Efficiency	0.58J/GH	0.51J/GH	0.445J/GH	0.25 J/GH
Dimensions(mm)	432*442*133	298*137*155	275*372*155	301*123*155
Weight (boxed)	14.4kg	4.2kg	11kg	4kg

Fig. 6. Mining Machines Comparison

of each algorithm. For example, we consider PoW a consensus algorithm with very high energy consumption and high latency, low efficiency, and low throughput. However, it still obtains some advantages such as high scalability and decentralization. As the most widely applied consensus algorithm in the blockchain industry nowadays, the cryptocurrencies using this consensus algorithm take a large part of the market capitalization. The representative applications include Bitcoin, Ethereum, Litecoin, Zcash, and so on.

For other consensus algorithms discussed here, since in those algorithms the nodes do not need to solve puzzles to mine new blocks, the energy consumption and electronic waste are low compared to PoW. However, each of them has its own advantages and disadvantages. For example, PoS consumes much less energy than PoW and is of high scalability while it suffers from high latency, low throughput, and low-level decentralization. PBFT also consumes much less energy and the throughput is high, however, it cannot support too many nodes and the scalability is low.

Consensus algorithms/ Metrics	Energy consumption	Advantages	Disadvantages	Representative application
PoW	Very High	High scalability, decentralization	High latency, low efficiency, low throughput	Bitcoin, Ethereum, Litecoin, Zcash
PoS	Low	High scalability	High latency, low throughput, low-level decentralization	Cardano
DPoS	Low	High throughput, low latency	low-level decentralization	EOS, Tron, Tezos
PBFT	Low	High throughput, low latency	Low scalability, low-level decentralization	Fabric
RAFT	Low	High throughput, low latency	No Byzantine fault tolerance	Etcd

Fig. 7. Evaluation and Comparison of Different Consensus Algorithms

Through the evaluation of different consensus algorithms within different metrics and a comparison of their advantages and disadvantages, we deem it necessary to take the actual situation into consideration especially the energy consumption when deciding which consensus algorithm to use. For example, imagine a case where a bank wants to launch some cryptocurrency business. Here we want high throughput, low latency and are sensitive with energy consumption and tolerable with low decentralization. Then we prefer DPoS, PBFT, or Raft rather than PoW. Many DeFi applications use Ethereum's products, and Ethereum is also moving to PoS, which doesn't require huge investments in hardware or energy.

Fifth, it's crucial to take careful investigations and make detailed analysis of energy consumption before building a blockchain, and carefully evaluate the trade-off between the environmental effect and business profits. In terms of what we can do immediately, one possible action we can take is to advertise our Cryptocurrency Energy Consumption Visualization (CECV) to the public. By doing this, we aim to make more people be aware of the blockchain environment issue. Thus, not only the business entities who consider this a trade-off between profits and its social image but also the normal people in public will take this seriously since it is a matter of the environment where we live every day and also concerning the future of human beings.

VI. Conclusions

In conclusion, in this project we achieved three main goals. First, we did a lot of research on analyzing and comparing different consensus algorithms in detail as they essentially determine how much computing power and what kind of hardware will be needed. We got to know that the mining process is the essential reason for the energy consumption issue of PoW. Many other consensus algorithms such as PoW and PBFT are good choices for building blockchains as they're much less energy-intensive compared with PoW.

Second, we made a significant amount of work on analyzing the energy consumption condition of the largest Proof-of-Work based coins and also the most popular cryptocurrencies currently in the world: Bitcoin and Ethereum. We grabbed the specific energy consumption data and implemented a web application called CECV to visualize the data in an interactive way, and we have published the application on a website. We also gave a deep and comprehensive analysis of the data.

Finally, we gave our own conclusions and solutions to build a environmentally friendly blockchain. We discussed and proposed five key points. First, we should consider clean energy as the energy resource for mining. Second, miners should consider build mining farms on places where there are excess electricity. Third, we should develop more efficient mining machines. Fourth, we should consider specific and real commercial needs when building blockchains, and should better choose the plan which has lower energy consumption. Finally, we should take careful investigations and make detailed analysis of energy consumption before building a blockchain, and carefully evaluate the trade-off between the environmental effect and business profits. Advertising CECV to make more people be aware of the blockchain environment issue should be a good way to start.

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