BITCOIN TRANSACTION FEES, MINERS' REVENUE, CONCENTRATION AND ELECTRICITY CONSUMPTION: A FAILING ECOSYSTEM

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Abstract
The research and investment community seems to ignore the long-term sustainability of Bitcoin, which is reflected in four flaws: transaction fees, miners' revenue, concentration and electricity consumption. While most of the authors have aimed to examine one topic at a time, with a particular interest in electricity consumption and carbon footprint, the aim of this paper is to examine all these issues simultaneously to provide a more comprehensive view on long-term sustainability of Bitcoin. This paper looks at these flaws and reveals why Bitcoin is not sustainable in the long run, how decentralization is being lost, how the design is putting artificial and unrealistic pressure on the ecosystem, while all being powered by an unjustifiable amount of dirty electricity sources. Our main findings are as follows. Firstly, transaction fees are already high and set to increase in time, further discriminating small transactions against big ones. Secondly, miners' revenue comes mostly from the block reward. The block reward is the main income source for miners, but is set to be cut on a regular basis, making miners' revenue not sustainable in the long run. Thirdly, miner concentration is already an issue, with a possibility of deepening even more and diminishing the idea of decentralization. Fourthly, the high electricity demand and the associated carbon footprint thus cannot be justified by any means. We deem our results useful for overall policy and regulatory implications.

Keywords: Bitcoin, transaction fees, miners' revenue, miner concentration, Electricity consumption
JEL Classification: E14, G19, F39

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1. Introduction

Bitcoin was first mentioned in a cryptography mailing list in 2008 titled: “Bitcoin: A Peer--to-Peer ElectronicCash System” (Nakamoto, 2008). Satoshi Nakamoto, the anonymous mastermind behind Bitcoin had probably been working on this project for some time and decided to release it in 2009, at the point when the world was hit by a financial crisis. This was no mere coincidence, as can be seen from the genesis block, which carries a message from an article published in The Times stating: “Chancellor on a brink of second bailout for banks” (Elliott and Duncan, 2009). In 2009, Bitcoin was more of a proactive protest against the financial and political system and, more specifically, against the current banking system (Fantacci, 2019).

A “system for electronic transactions without relying on trust” (Nakamoto, 2008) was and still is groundbreaking. Nevertheless, during the past 12 years, Bitcoin has uncovered many inefficiencies within the ecosystem, which could potentially cause Bitcoin’s downfall. The research and investment community seems to ignore the long-term sustainability of Bitcoin. Our concept of sustainability should not be only limited to electricity consumption and carbon footprint, but rather viewed as a broad concept considering all the major issues of Bitcoin, which are: transaction fees, miners’ revenue, miner concentration and electricity consumption. While there are research papers addressing one of these issues at a time, with a particular interest in electricity consumption and carbon footprint, up to date there is no paper addressing Bitcoin shortcomings from a more comprehensive point of view. Our objective is to fill this gap by grouping all the relevant evidence and provide a comprehensive view on the long-term sustainability of Bitcoin. Specifically, thisresearch paper aims to examine those four major inefficiencies related to mining and their possible future implications for Bitcoin’s future perspective.

The first research question examines the sustainability of transaction fees. We conclude that transaction fees are becoming high and unsustainable with very little or no chance of adjusting downwards. Furthermore, they discriminate smaller transactions against bigger ones as the transaction fee is the same for all transactions. Halving is putting artificial pressure on increasing the fees and further disproportionally discriminating against smaller transactions.

The second research question focuses on the sustainability of miners’ revenue. According to Das and Dutta (2019), Bitcoin mining is not sustainable unless efficient mining and cheap electricity sources are relied upon. Miners initially enjoyed increasing revenues because of Bitcoin’s increasing price, cheap electricity sources and high mining rewards. The whole mining business is based on a belief that the price of Bitcoin can keep increasing to ensure miners’ revenue even after halving, completely ignoring the high reliability of the mining reward.

The third research question examines the concentration of miners and decreasing decentralization. Miner concentration is a good example of how Bitcoin is becoming less and less decentralized. At this stage, small miners are completely forced out of mining as bigger miners have access to industrial pricing for electricity, can obtain mining equipment at a more competitive price and because the high mining difficulty has increased entry-level costs. In addition, as the mining equipment production is concentrated in China, Chinese miners can obtain it at a more competitive price. Cheap mining hardware together with cheap electricity costs have resulted in most miners being concentrated in China. The recent crackdown on Chinese miners is thus far more serious than it would be if they had been dispersed around the globe.

Another issue with miner concentration is the rise of mining pools. As mining became more difficult, individual miners agreed to pool their hash power to increase their chances of finding new blocks.While the idea is good, one-third of mining pools have acknowledged that decision-making is prerogative to pool administrators (Rauchs *et al*., 2018). These pool administrators have stripped away the decision-making powers from miners and can retain leverage over miners. If incentivized to, they could choose to act dishonestly.

Lastly, Bitcoin's electricity consumption is becoming comparable with country-level outputs for a mere "decentralized" transaction validation, which has so many flaws. In addition, most of the electricity used for mining comes from dirty electricity sources; thus, Bitcoin's carbon footprint is also comparable to a country level. With such a high electricity consumption, a transition to clean energy sources cannot be justified as it would divert scarce electricity from other projects. As the world is battling to transition to clean energy sources, Bitcoin's high electricity demand with all the inefficiencies is not justifiable.

2. Background

There is a growing number of articles regarding Bitcoin, mining economics and mechanics. Blandin *et al*. (2020) and Rauchs *et al*. (2018) examined the significant developments in the global crypto asset ecosystem. Auer *et al*. (2019) focused on the economic viability and future of the Proof-of-Work algorithm. In their work, they concluded that (1) the payment finality based on Proof-of-Work is extremely expensive, and (2) transaction fees cannot be generated on a scale to satisfy the transaction market without block rewards. Easley *et al*. (2019) and Tsang and Yang (2021) examined the economics of transaction fees and concluded that transaction fees increase when transaction congestion occurs. The rest of the articles used in this paper have focused on Bitcoin mining energy consumption (Das and Dutta, 2019; de Vries, 2020; Corbet *et al*., 2021; Huynh *et al*., 2022), carbon footprint

(Stoll *et al.*, 2019; Polemis and Tsionas, 2021; Di Febo *et al.*, 2021) and sustainable mining (Truby, 2018; de Vries, 2019). Das and Dutta (2019) concluded that the Bitcoin mining business is not sustainable unless efficient mining and cheap electricity sources are relied upon. De Vries (2020) found that the energy consumption of Bitcoin is underestimated and proposed a new model to better capture Bitcoin energy consumption. Corbet *et al.* (2021) and Huynh *et al.* (2022) investigated the relationship between Bitcoin price and electricity consumption using different approaches. Nevertheless, they found a positive relationship between Bitcoin price and electricity consumption, suggesting no financial incentives for miners to switch to sustainable electricity sources. Stoll *et al.* (2019), Polemis and Tsionas (2021) and Di Febo *et al.* (2021) examined the externalities related to Bitcoin mining such as carbon emissions to gauge further discussion on the costs and benefits of Bitcoin. Truby (2018) explored ways of promoting environmentally sustainable development of blockchain applications. De Vries (2020) concluded that renewable energy is not able to solve Bitcoin's sustainability problem. Instead, he proposed using a different mining algorithm such as Proof-of-Stake.

3. Bitcoin Mining and Inefficiencies

Bitcoin decentralization is achieved using the Proof-of-Work algorithm, which is Nakamoto's (2008) solution to the double-spending problem without a need for a central clearinghouse. The Bitcoin blockchain is composed of nodes each individually containing a complete copy of the ledger. Miners are responsible for running the nodes, *i.e.*, validate transactions while providing security for the blockchain. They run the nodes using dedicated hardware and software to find a specific hash function (Easley *et al.*, 2019). In more technical details, each transaction is augmented with a random number, which is passed through a cryptographic hashing function such as SHA-256, to generate hashes.

A hash is a long string of numbers of zero bits serving as a Proof-of-Work. A given set of data put through SHA-256 can generate only one hash. Any small change of the original data will completely change the hash. In addition, a hash is only a one-way function, meaning it can only check that the original data match with the data that generated the hash, and it is not possible to obtain the original data from the hash. After the data are hashed, miners are required to find the specific string of numbers of zero bits. The first miner to find a match is then allowed to post a block of pending bitcoin transactions to the ledger and is rewarded by a block reward and all the transaction fees within the posted block (Easley *et al.*, 2019).

This process is repeated roughly every 10 minutes and it requires all the miners to update their ledger with the newly added block. The 10-minute interval as well as the size of the block, which according to Easley *et al*. (2019) has a theoretical upper bound of 4 MB, but the actual block sizes are on average 1.5 MB to 2 MB, limits the speed of transactions. The block size is fixed by an agreed consensus of miners and the 10-minute average interval is maintained by an automatic difficulty adjustment implemented by Nakamoto (2008). By default, the adjustment takes 2016 blocks to recalibrate the difficulty of the algorithm on the basis of the average mining time in the past 2016 blocks (Tsang and Yang, 2021).

The difficulty recalibration is an important feature of the Proof-of-Work algorithm. As long as honest nodes are in control of the network, the verification is reliable. The blockchain becomes vulnerable if the majority of nodes are overpowered by one single node, *i.e.*, by a potential attacker. The attacker can fabricate transactions and post this block with the false transactions if he controls 51% of the total computational power of the blockchain at any given time. The difficulty recalibration prevents any miner from getting ahead of the network simply by increasing his computational power through buying more mining hardware. Mining hardware efficiency improvement is another threat solved by the difficulty recalibration. If the mining difficulty remained stable while the mining hardware became more efficient, all nodes would be able to attack the network at any given time. The difficulty recalibration is then set to secure the network against mining hardware efficiency improvements and also against an increase in mining hardware usage.

3.1 Transaction fees

Transaction fees serve two essential roles in the Bitcoin network (Tsang and Yang, 2021):

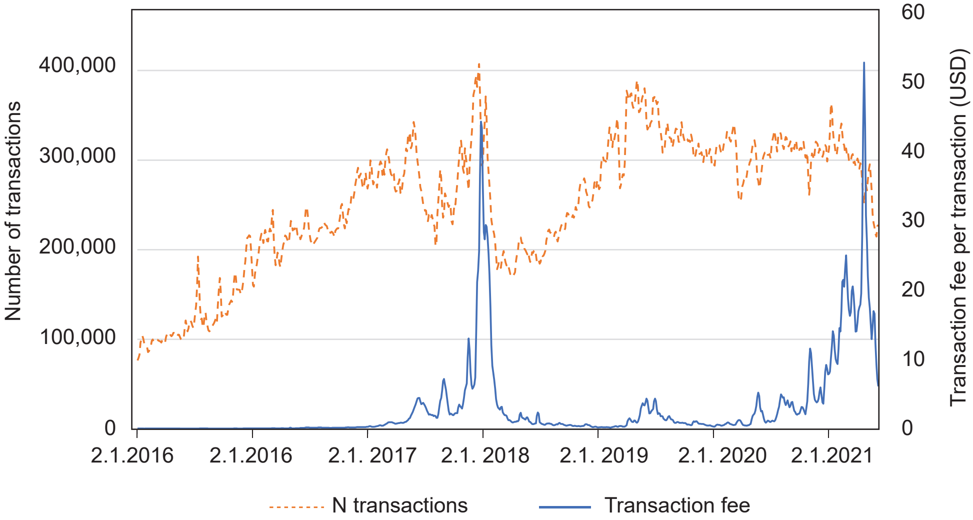
1) Security – transaction fees incentivize miners to not fake transactions on one hand; and
2) Motivation – motivate existing miners to stay in the network and prevent their concentration and motivate new miners to join the network.

This was not the case from the very beginning even though Nakamoto (2010) explained the purpose of transaction fees in the future as he stated in BitcoinTalk Forum: “In a few decades when the reward gets too small, the transaction fee will become the main compensation for nodes.” Until early 2011, few transactions paid fees, as most of the miners’ rewards came from the block rewards themselves. Indeed, there was no financial incentive before 2011 for a block to be filled with transactions, thus allowing miners to earn the block rewards by mining empty blocks (Easley *et al*., 2019). From 2011, the transaction fees started to oscillate around the level of 0.1 US dollar until 2016 when a significant increase and variance occurred.

Bitcoin transaction fees are not as straightforward and fair as one would expect. The transaction fee, in theory, is decided by both the demand (users) and supply (miners), at least under normal circumstances. There are various endogenous and exogenous variables possibly affecting the transaction fee. The exogenous variables include the increase in the number of transactions, entry and production costs of miners, mining difficulty and the price of Bitcoin. Under the basic demand and supply model, an increase in the number of transactions should increase their fees. As we can see in Figure 1, this is not the case, and the transaction fees are more puzzling. Data for entry and production costs of miners are difficult to obtain; thus, no figure is plotted. However, we can assume that high entry and production costs could discourage miners from confirming low-fee transactions. The situation may become more serious in the future when miners will rely solely on transaction fees, approximately in the year 2140, or even sooner if the Bitcoin price does not continue to increase. With the inflow of new miners, mining difficulty is increasing and thus it makes it more costly for miners to mine blocks. Interestingly, the relationship between mining difficulty and the transaction fee is completely disconnected (see Figure 2). Lastly, the price of Bitcoin should also affect the transaction fee as it is paid in Bitcoins and not US dollars. An increased price of Bitcoin, *ceteris paribus*, should push down the transaction fee. Figure 5 shows that this is not the case as other variables impact the transaction fee setting mechanism.

Endogenous variables include the block time and block size, which are set as they are for the maximum security of the blockchain. They are also responsible for limiting the transaction speed; thus, congestion can result in transaction queuing, effectively increasing the transaction fee (Easly *et al*., 2019). Tsang and Yang (2021) also provide evidence of increased transaction fees when a demand shock occurs. As they further note, the relationship is even stronger during times with volatile markets. This can be also observed in Figure 3.

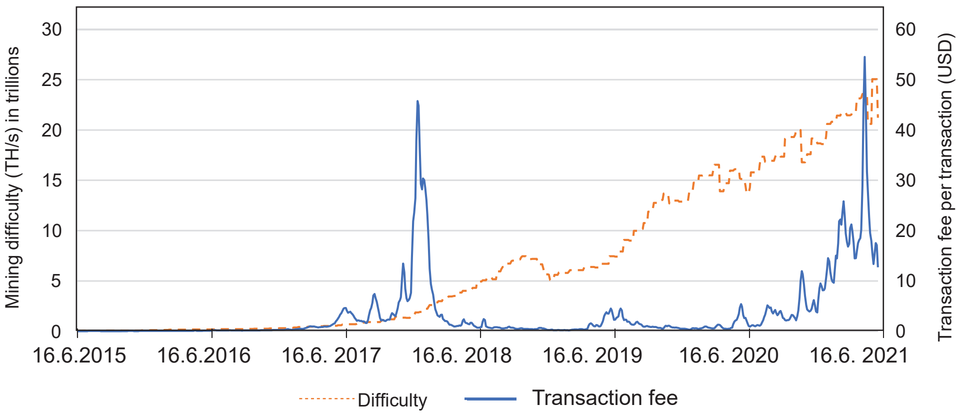
Figure 1: Number of transactions and the average transaction fee



Note: This figure shows the relationship between confirmed transactions and the average transaction fee in US dollars. If the mechanism was purely based on supply and demand, an increased number of transactions should influence transaction fees.

Source: Data obtained from blockchain.com

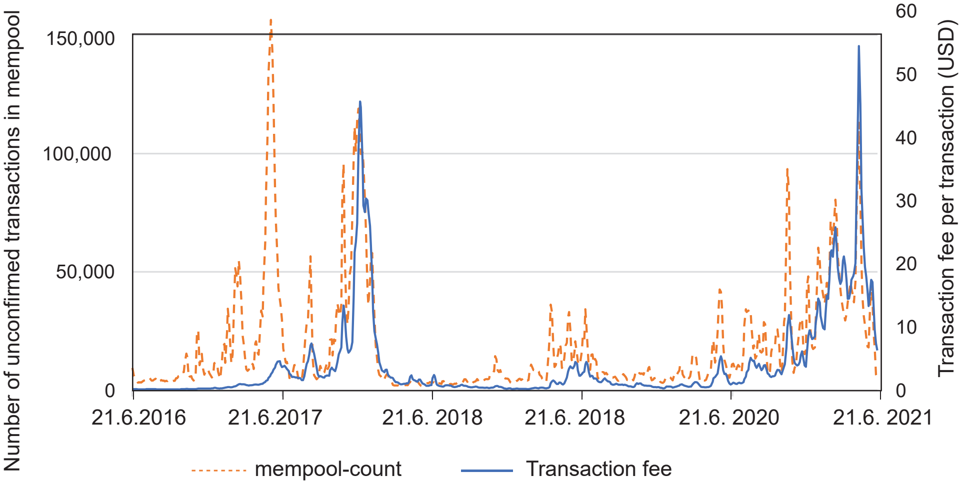
Figure 2: Mining difficulty (TH/s) in trillions and Transaction fee per transaction



Note: For the bitcoin network to remain secure as well as the block size remain 10 minutes, the difficulty is adjusted every 2016 block or approximately every 2 weeks. Increased difficulty could theoretically lead to an increase in transaction fees as the cost of mining could discourage new as well as old miners, and vice versa. The figure showcase that is not the case.

Source: Data obtained from blockchain.com

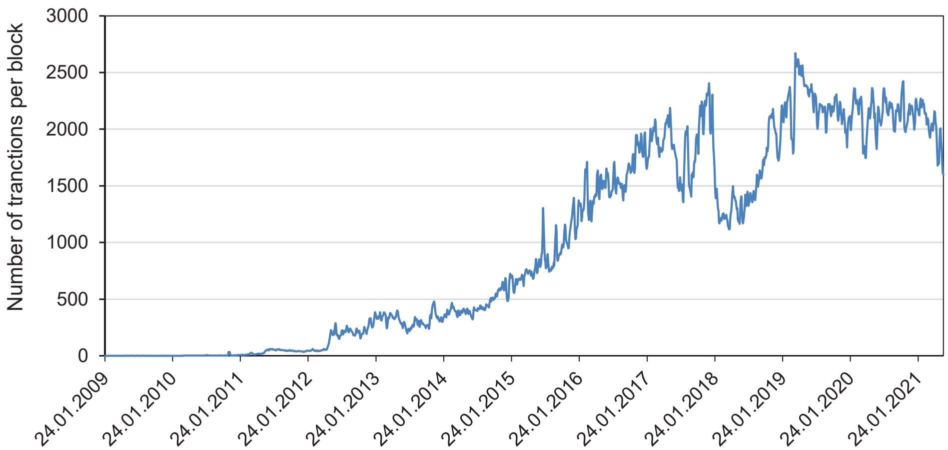
Figure 3: Number of unconfirmed transactions in mempool and transaction fee per transaction



Note: It can be observed that during a time of congestion an increased number of unconfirmed transactions may lead to an increase in transaction fees. Economically it makes sense, as miners have a capacity of possible transaction confirmation within one block thus transactions with higher fees will be dealt with first and transactions with lower fees may remain left out.

Source: Data obtained from blockchain.com

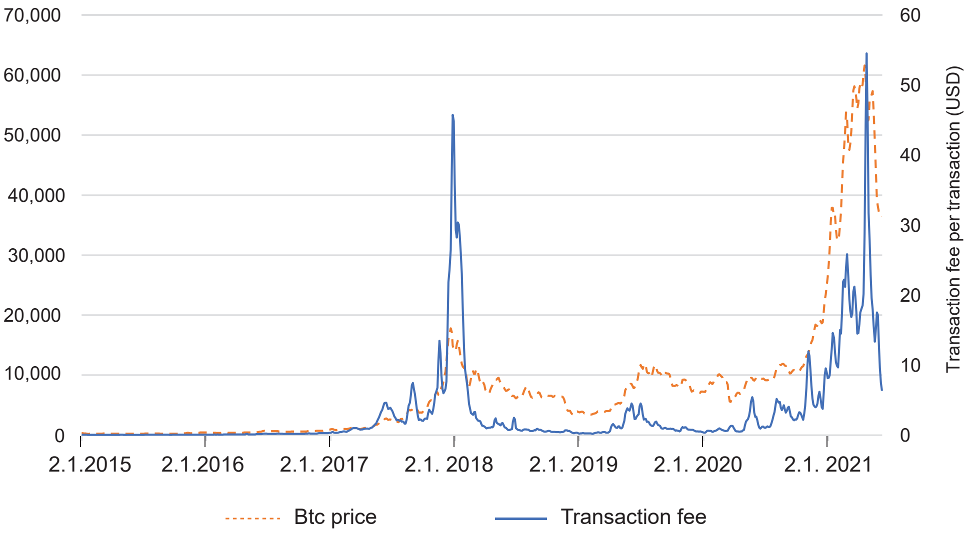
Figure 4: Number of transactions per block



Note: The Bitcoin community suggests that Bitcoin's blockchain may support 7 transactions per second. This is still very hypothetical as even at the peak in 2019 Bitcoin's blockchain processed 2,671 transactions within one block, meaning 4.45 transactions per second.

Source: Data obtained from blockchain.com

Figure 5: Bitcoin price and transaction fees per transaction (USD)



Note: Bitcoin price is affecting, to some extent, the transaction fee. Interestingly the peak in December 2017 and April 2021 in Bitcoin price did not have a similar response in the average transaction fee, which suggests this relationship is not that straightforward. Indeed, an increase in the price of Bitcoin had almost no effect on the transaction fee per transaction.

Source: Data obtained from blockchain.com

As Nakamoto (2008) puts it, Bitcoin is "a purely peer-to-peer version of electronic cash". It is interesting how the narrative within the Bitcoin community changed in the past 12 years from being electronic cash to being purely a store of value. We believe the main reason for this sudden change is transaction fees. At the time of inception, Bitcoin transactions had zero fees, because mining wascomparatively easier, and thus cheaper, and the mining reward was higher. This may have been the case fromthe inception; however, as adoption was rising and mining difficulty increasing while at the same time mining equipment efficiency increasing, mining reward decreasing and Bitcoin price increasing, the transaction fee became more puzzling.

Nakamoto's design of transaction fees was created to reflect the market forces while securing the blockchain. The long-term implications are just starting to emerge, and they pose various dangers for Bitcoin. It is questionable if the creator did not think it through or he just did not believe in such a high adoption, thus not addressing this problem. Our views on transaction fees can be divided into three main components: (1) The supply side has a bigger influence over it compared to the demand side. Indeed, evidence provided by Easly *et al*. (2019) and Tsang and Yang (2021) suggests that during times of congestion, the miners are the ones setting the transaction fee. One could argue that congestion times are rare; however, we need to bear in mind that by increasing the adoption of Bitcoin, this problem could occur more often. (2) For the moment, miners are profiting from both mining rewards and transaction fees. As the mining reward will be decreasing in the future until it reaches zero in 2140, miners will have to rely more and more on transaction fees. Auer *et al*. (2019) suggest that Bitcoin cannot be functional by solely relying on transaction fees, as up to date, miners' revenue was mainly reward-denominated. And finally, (3) the setting of transaction fees is disproportional in small and big transactions. While for big transactions, *i.e.*, the rich, the transaction fee is appealing, for small transactions it is outrageous at best as the medium transaction fee for the period from January 2015 to June 2021 was 4.02 US dollars per transaction.

3.2 Miners' revenue

Miners' revenue is predominantly influenced by the price of Bitcoin (see Figure 6). Other determinants of miners' revenue include halving of the reward, transaction fee height and difficulty level adjustment. Up to now, the gross part of the revenue has been generated from block rewards (see Figure 7). In time, miners' revenue from transaction fees should increase as the block reward is halving approximately every 4 years, which is certainly not the case at the moment. This is dueto the limited number of transactions within one block. As Bitcoin's blockchain is approaching the limit for the number of transactions and the reward is halving at the same time, there are only three ways for Bitcoin miners to increase or maintain their revenues: (1) the price of Bitcoin must consistently increase, (2) transaction fees must increase, or (3) the mining industry will become either more concentrated or completely monopolized.

The first two options are unrealistic. It is certainly remarkable that the Bitcoin price has surpassed the threshold of 1 trillion US dollars in market capitalization; however, any further increase will be very difficult. Bitcoin's price action has proved in the past 12 years that it is speculative. No speculative asset in the history of capital markets has surpassed the 1 trillion USD market capitalization and continued to increase in value for a substantial time. Revenue from transaction fees also depends on Bitcoin's price; however, the same logic applies. The other option is for transaction fees to increase and maintain that higher level. This would result in an outflow of users as it would disproportionately increase the transaction fee for small transactions against big ones. Paying a 60 USD transaction fee for a short period during transaction congestion is different from paying it casually.

The issue gets even more serious considering halving events. Halving effectively cuts profits of miners in half, which must be either compensated by mining equipment efficacy (hashing power and electricity consumption), decreased electricity costs, or increased transaction fees. Those variables each have a different level of improvement/price elasticity, and they cannot effectively and sustainably readjust every 4 years by the same token as halving. Halving thus relies mostly on a price increase of Bitcoin.

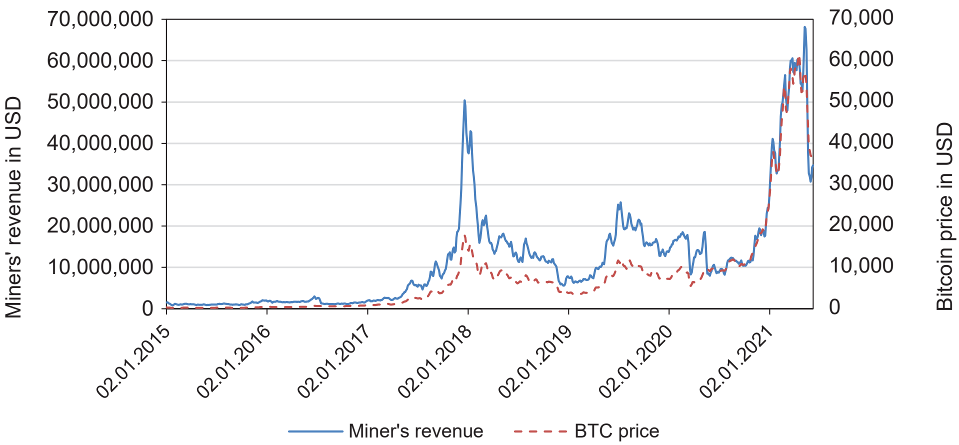
There is a reason why we have not mentioned difficulty readjustment. The purpose of it is to readjust on a moving average, targeting an average number of blocks per hour as a security measure of increasing hardware speed and varying interest in running nodes (Nakamoto, 2008). Difficulty readjustment is the only possible variable that could effectively and sustainably readjust in the long run, theoretically. Practically, it has close to zero chance to substantially adjust downwards on such a competitive market. If done on an individual level, loss of revenue is inevitable without an effect on difficulty. If done as a coordinated agreement, it would:

(1) Lead to an immediate inflow of new miners, increase in difficulty and result in a loss of revenue to old miners;

(2) The miners would have to decrease the speed of mining blocks, thus decreasing the transaction validation speed and a potential increase in transaction fees could occur;

(3) As transaction fees would increase artificially for the sole purpose of miners' greed, more individuals would leave the network for good.

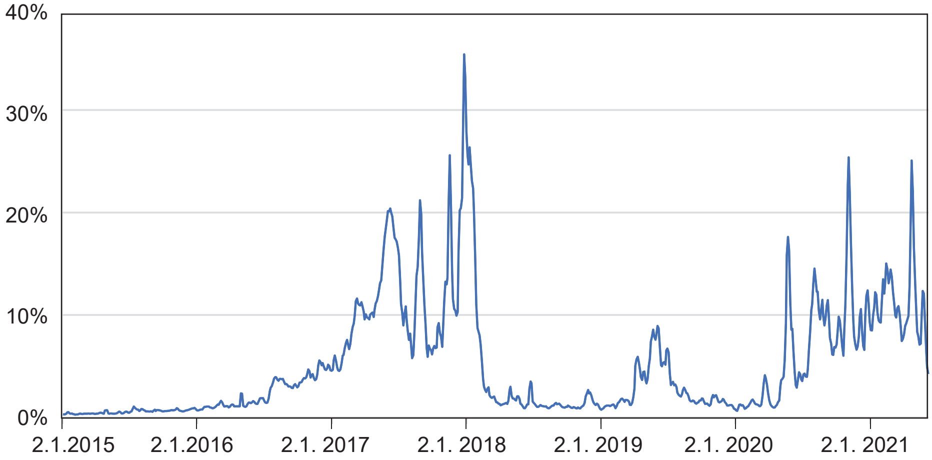
Figure 6: Miners' revenue and Bitcoin price



Note: The relationship between Bitcoin's price and miners' revenue is obvious as both the block reward and transaction fee reward are denominated in Bitcoins. The highest revenue generated is concentrated around the peak.

Source: Data obtained from blockchain.com

Figure 7: Transaction fees as a % of miners' total revenue



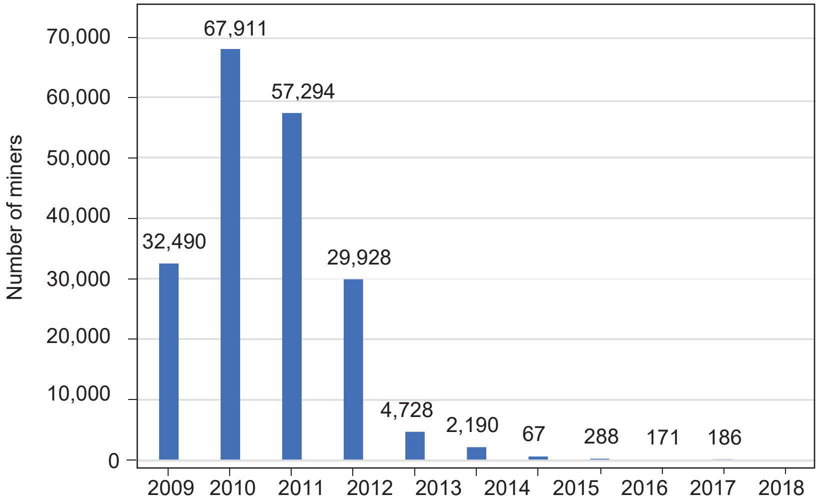
Note: Revenues generated from transaction fees are still just a small portion of total miners' revenues except for times of transaction congestion and increased transaction fees. Interestingly, miners' revenue from transaction fees peaked in 2017 even though the height of transaction fees increased in 2021 clustering and the reward block halved.

Source: Data obtained from blockchain.com

3.3 Miner concentration

In the early stage of Bitcoin, it was possible to participate in mining activities for anyone as there were almost zero entry barriers. It is also worth noting that, at the beginning, mining was not profit-driven but more of a hobby, which can also be observed from the development of the number of miners in time (Figure 8). At first, the increase in price and low entry and operational levels as well as being able to mine as a solo miner attracted many miners. In 2010, the number of miners peaked at 67 ,911. In the coming years, some individuals recognized a great business opportunity and started to mine for profit, which drastically decreased the number of miners to 144 in 2019. The rise of the cryptocurrency mining industry can be formally recognized since 2013, as computational difficulties made it necessary to utilize specific-purpose hardware (Blandin *et al*., 2020). in effect, this drove up mining entry and operational costs forcing small miners to leave the mining industry.

Figure 8: Evolution of number of miners

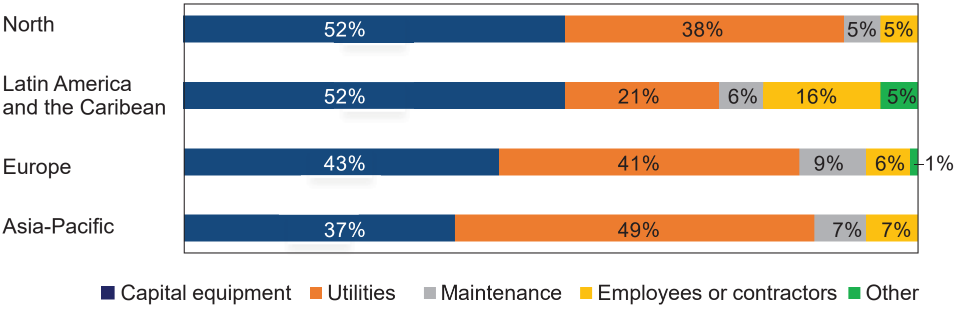


Note: The decreasing number of miners can be associated with the increased competition and overall entry and operational cost increases.

Source: Data obtained from Xu *et al*. (2021)

As reported by Blandin *et al*. (2020), a miner's costs comprise 45% of capital expenditures (purchase of mining equipment, infrastructure development and allied costs) and 55% of operational expenditures (electricity bills, maintenance and workforce). A comprehensive breakdown of mining costs per region can be seen in Figure 9 and Figure 10. Big miners have several competitive advantages compared to small miners. Because of the larger scale, they can obtain mining equipment at a more competitive price. As reported by Blandin *et al*. (2020), the majority of miners no longer pay residential electricity prices, but rather industrial pricing by contractual agreement with power generators. This could lead to a further concentration of miners until either a monopoly or only a handful of miners remains.

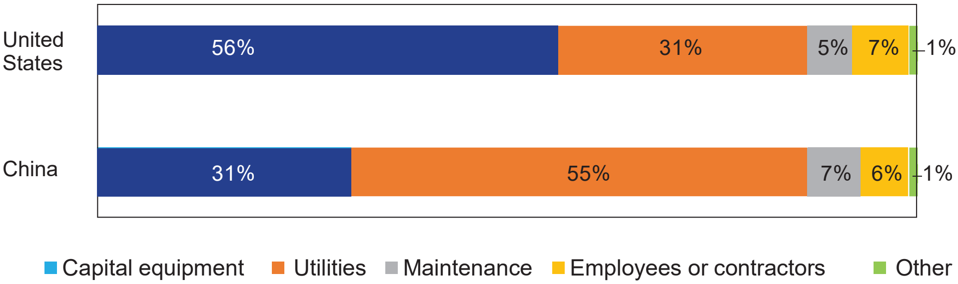
Figure 9: Mining costs per region



Note: As can be observed, the capital equipment and utility costs comprise the majority of the costs, with some variations in certain regions.

Source: Data obtained from Blandin *et al*. (2020)

Figure 10: Mining costs in the United States and China



Note: The disproportionality between mining costs can be best observed in the two major mining regions. The answer to this disparity can be found in the production of mining equipment, which is predominantly done in China, and thus the costs of obtaining it are lower compared to other regions, where it goes through more intermediaries or is more expensive due to tariffs.

Source: Data obtained from Blandin *et al*. (2020)

Rauchs *et al*. (2018) recognize three major types of mining concentration:

(1) Hardware manufacturing concentration,

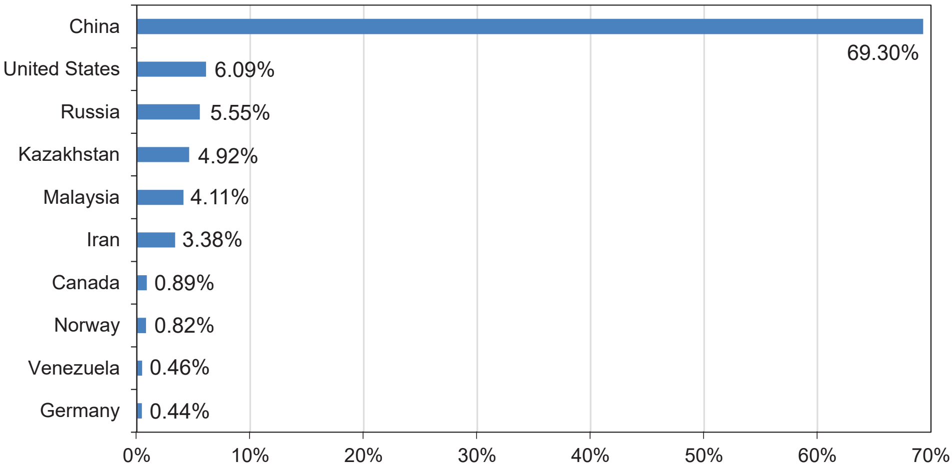
(2) Hashing facility concentration,

(3) Pool concentration.

Hardware manufacturing poses a danger of further concentration of miners in certain regions as miners there can obtain mining equipment at more competitive prices. As reported by Rauchs *et al*. (2018) in 2019, 47% of mining hardware manufacturers were in the Asia-Pacific region, predominantly in China. If looking at specific mining devices, the numbers are even higher. Mining hardware sales are also concentrated in China with a 52% share, compared to a mere 12% share in the United States (Blandin *et al*., 2020). Hashing facility concentration is closely tied with entry and operational costs. Chinese miners can obtain both at comparatively lower prices; thus, hashing facilities are also concentrated in China (see Figure 11).

High mining concentration makes Bitcoin vulnerable to political and regulatory uncertainty of a certain region, far from the promise of decentralization. The high mining difficulty makes it impossible for individual miners to produce new blocks; thus, mining pools have been created to combine computational power and individual miners higher efficiency. The most disturbing thing about mining pools is their censorship power. One-third of mining administrators acknowledged that decision-making is a prerogative to administrators. A Mining pool can retain leverage over miners and if incentivized to, they could choose to act dishonestly, *e.g.*, mine dishonestly, blacklist transactions or addresses, and redirect miners' hash power (Rauchs *et al*., 2018).

Figure 11: Hash rate global distribution for 2020



Note: The vast majority of miners in 2020 were located in China. Recently China announced a crackdown on Bitcoin mining, which could lead to a massive outflow of miners from this region.

Source: Cambridge Bitcoin Electricity Consumption Index (CBECI) from (2021)

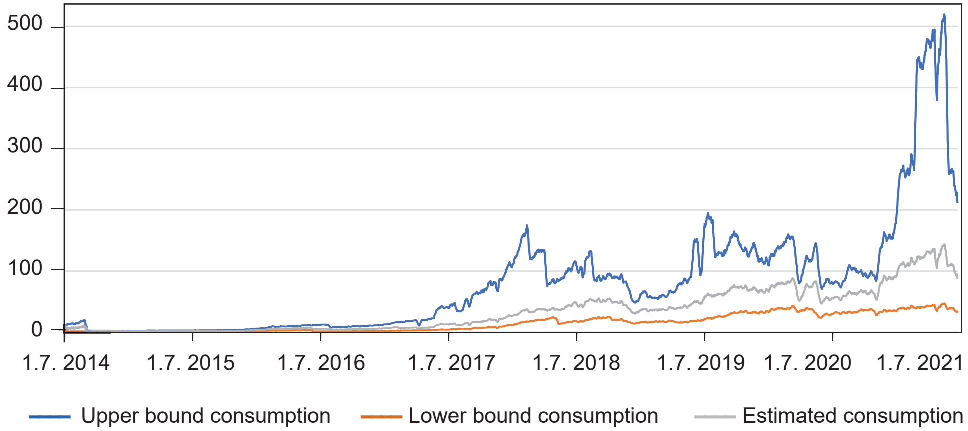
3.4 Electricity consumption

The electricity consumption of Bitcoin is just too high to be justified by any means. The exact electricity consumption cannot be determined; thus, some authors have come up with different approaches to estimate it. To date, only two indexes track real-time data. In Figure 12, we can see the Cambridge Bitcoin Electricity Consumption Index (or CBECI) with the lower and upper -bound estimations and the estimated consumption. Figure 13 compares the CBECI with an estimation developed by de Vries (2020). As can be seen in both figures, the electricity consumption increased 10-fold in a mere 4-year period. Electricity consumption is dependent on Bitcoin's price, mining difficulty, electricity prices as well as mining equipment efficiency. For Bitcoin to function properly, the price must keep increasing in time, which would lead to an even further increase in electricity consumption.

Many authors tend to compare Bitcoin's electricity consumption to a specific country. While it is good to depict the enormous electricity consumption, the comparison is just not appropriate. A better perspective of Bitcoin's electricity consumption can be obtained by a comparison with traditional financial institutions. The entire banking sector is estimated to consume as much as 650 TWh of electricity annually. This estimation includes not only the data centres processing transactions but also branches and ATMs. All estimations of Bitcoin focus only on mining-related consumption while ignoring Bitcoin ATMs and a variety of third parties (de Vries, 2019).

De Vries (2020) also gives other comparisons. A single Bitcoin transaction consumes on average 1600.77 kWh. With the same electricity consumption, Visa could process 1,077,016 transactions. The annual costs of electricity consumption are estimated to be 6,555,787,630 US dollars, an outrageous number for the sake of promised "decentralization" and security. This estimation is based on an electricity price of 5 cents per kW/h, which is approximately the average rate paid globally (Blandin *et al*., 2020). Nakamoto (2008) relied on the ever-increasing efficiency of mining hardware to neutralize the impact of such a high electricity consumption, even though it is questionable if he anticipated Bitcoin to reach this level.

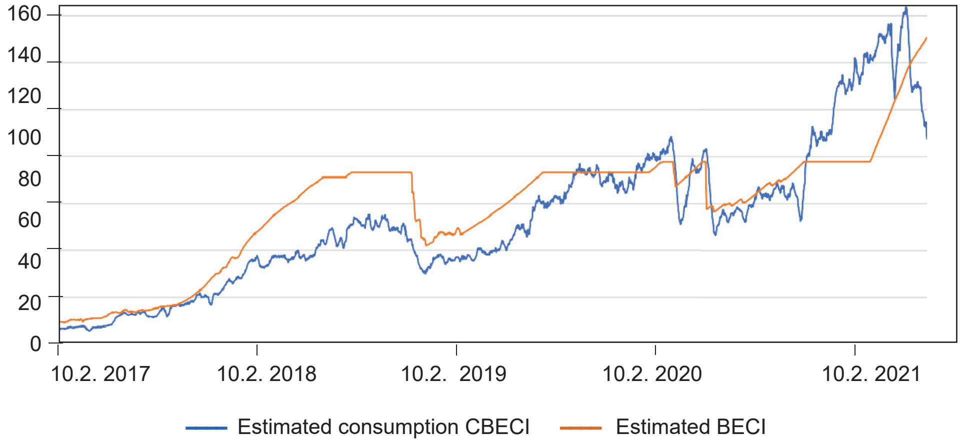
Figure 12: Estimated annual consumption in TWh



Note: Bitcoin mining electricity consumption varies significantly in time due to many factors such as difficulty, mining hardware, electricity cost, Bitcoins' price, and others. The electricity consumption of Bitcoin is gradually increasing in time to a point where it reached 141.28 TWh (annualized) at the peak on the 10th of May 2020 or an equivalent to the annual electricity consumption of Sweden.

Source: Data obtained from Cambridge Bitcoin Electricity Consumption Index (CBECI) from (2021)

Figure 13: Cambridge Bitcoin Electricity Consumption Index (CBECI) vs Bitcoin Energy Consumption Index (BECI)



Note: The methodological difference in their estimation is that the CBECI is estimated bottom-up from the usage, efficiency and profitability of mining hardware, while the BECI uses a top-down approach, *i.e.*, using miners' revenues as the main point and breaking it down according to the share of electricity consumption in total expenses and the price of electricity.

Source: Cambridge Bitcoin Electricity Consumption Index (CBECI) (2021) and de Vries (2020)

With such a high consumption, another issue is being discussed recently. What source of electricity is used for mining and is it sustainable? Blandin *et al*. (2020) report that 39% of total energy consumption of hashing comes from renewables. The proportion varies regionally and if looking at Asia, which accounts for 77% of the total hash power, the number of renewables will be only 26%. As of November 2018, Stoll *et al*. (2019) estimated Bitcoin's annual carbon footprint to be in a range from 22 to 22.9 MtCO_2. For 2021, the estimation made by Alex de Vries (2019) stood at 62.28 Mt CO_2, an increase of 3 times and an equivalent of the annual carbon footprint of Belarus. The staggering increase inthe carbon footprint prompted talks of using more renewable electricity sources for mining, but the transition may not be that easy.

Firstly, it appears that there is a mutually beneficial process present between the electricity sector and Bitcoin mining. Energy companies tend to benefit from a high Bitcoin price and increased difficulty (Corbet *et al*., 2021), while the Bitcoin mining industry enjoys low electricity prices. Low electricity prices and an increasing Bitcoin price attract more miners, prompting an increase in mining difficulty and increased electricity consumption. The mutually beneficial relationship presents no financial motivation for either party to switch to sustainable electricity sources. Huynh *et al*. (2022) also confirmed this connectedness using data on electricity consumption, Bitcoin returns and volume. They found that there is a positive correlation between electricity consumption and Bitcoin returns and volume, which is particularly strong during crash periods. The strongest relationship was found between trading volume and energy consumption, suggesting that liquidity leads to more demand in Bitcoin energy consumption. However, energy consumption has a weak causal effect on Bitcoin returns and volume.

Secondly, Corbet *et al*. (2021) provide evidence that a growing Bitcoin price made no contribution to the growth of green investment assets, suggesting no evidence of the current carbon footprint being somewhat compensated for. Di Febo *et al*. (2021) found the relation of Bitcoin price and carbon credits to be only in one direction and greater in downside quantiles as compared to the upside, suggesting an extreme carbon market behaviour in times of elevated risk in Bitcoin, *i.e.*, asymmetric reaction patterns with respect to Bitcoin gains and losses. A study from Polemis and Tsionas (2021) focusing on the effects of Bitcoin miners' revenue on carbon dioxide emissions revealed that miners' revenue negatively affects environmental degradation.

Switching to clean energy sources may not be the answer. While it can lower the carbon footprintof Bitcoin, it can also divert scarce clean energy sources from other projects and diminish the overall effect. Some may argue that if mining equipment becomes more efficient and substantially decreases the electricity demand, it can become sustainable. The mining is intentionally designed to be resource-intensive to achieve the trust and security advantages of Bitcoin, which is dwarfed by the electricity-intense demand (Truby, 2018). De Vries (2019) also concluded that energy use is not the only way in which Bitcoin impacts on the environment. Disposing of mining equipment contributes to the annualized e-waste of 10,948 metric tons, or an equivalent of Luxembourg.

4. Conclusion

Bitcoin was and still is a groundbreaking piece of work, which has paved the road for projects addressing its inefficiencies. During the past 12 years, it has been proven that Bitcoin is just not sustainable from many perspectives. The transaction fees are too high, with a very high possibility of keeping increasing and further discriminating small transactions against big ones. Miners' revenue sustainability is built on a belief that Bitcoin prices can keep increasing. Difficulty adjustment could solve this issue; however, it would result in an even higher miner concentration, diminishing the decentralization even further. The high electricity consumption is outrageous if we account for all those inefficiencies and compare it with the traditional banking system. To stress the issue further, Bitcoin mining is associated with a high level of carbon emissions. A transition to clean energy sources would solve nothing as the whole world is battling with transitioning to clean energy and Bitcoin would just divert scarce clean energy with no additional value.

This study provides significant policy and regulatory implications for Bitcoin in particular, and the whole crypto industry in general. Firstly, based on the presented literature and logical arguments, we outlined the inefficiencies of Bitcoin and how its narrative has changed during its lifespan. The rapid rise of Bitcoin was caused by the influx of speculative capital during the time when the stock market was also rallying and heavy advertisement campaigns were calling for decentralization. In our belief, Bitcoin in particular, and the crypto industry in general, are a form of financial hazard and regulatory bodies should regulate it accordingly. Secondly, the electricity consumption of Bitcoin is enormous. Some may argue that is the cost of decentralization, security and the overall innovations that Bitcoin has brought. However, even if we accept this argument, are there enough innovations to justify the high electricity consumption? Electricity scarcity is becoming an issue, especially with the ever-increasing calls for sustainability. Truby (2018) and Di Febo *et al*. (2021) also agree that Bitcoin mining and transactions are an inefficient use of scarce electricity.

Lastly, there is a lot of attention regarding Bitcoin's carbon footprint, with many researchers providing evidence of Bitcoin's negative impact on the environment. Authors such as Di Febo *et al*. (2021) and Polemis and Tsionas (2021) suggest that miners could be incentivized to use clean energy sources. We highly disagree with this proposal as there is clearly not enough justification for it. Bitcoin lacks innovation, it has already failed to deliver what it promised, it is discriminating individuals with lower transaction amounts, its price and transaction fees are highly unstable and speculative, the miners' revenue is not sustainable, its electricity consumption is enormous and has a high carbon footprint. A complete ban on Bitcoin and crypto mining activities would be a very reasonable solution. Some countries have been reluctant to take this stance as they have been afraid of losing out on innovations. However, there is no evidence suggesting that banning Bitcoin and cryptocurrency mining activities would affect innovations. Rather, it would divert the attention from excessive mining activities towards more sustainable solutions. If countries are reluctant to ban crypto mining, the alternative could be incentivization to use carbon credits or offsets.

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