

# Sustainability Analysis of Blockchain Technology: Bitcoin Energy Usage Case Study

A Master's Thesis submitted for the degree of  
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Univ. Prof. Dr. Davor Svetinovic

Maximilian Hubert Pieringer, BSc (WU)

01401742

## Affidavit

I, **MAXIMILIAN HUBERT PIERINGER, BSC (WU)**, hereby declare

1. that I am the sole author of the present Master's Thesis, "SUSTAINABILITY ANALYSIS OF BLOCKCHAIN TECHNOLOGY: BITCOIN ENERGY USAGE CASE STUDY", 78 pages, bound, and that I have not used any source or tool other than those referenced or any other illicit aid or tool, and
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## Abstract

The aim of this work was to gain insight and knowledge with the basic concepts of the Bitcoin network and its relation to energy consumption. Precisely, the ambition of this literature-based research was to identify key determinants of the network's energy intensiveness. After an extensive review of the relevant literature on the topic, key principles of Bitcoin's electricity consumption were derived.

With regards to environmental sustainability concerns, it was found that the network's properties, in theory, allow for improvements of the unit economics of renewable energy production facilities and renewable intensive energy grids. Such applications, however, are dependent on the unforecastable market dynamics of the Bitcoin price.

In a contextualization approach it was attempted to categorize the electricity consumption levels of the Bitcoin network based on the services offered with similar but not comparable entities. This approach finds that energy consumption does not provide a conclusive and instructive comparative parameter to determine whether energy consumption levels of the Bitcoin network. The paper concludes with advocating for location dependent policy approaches that encourage the strategic deployment of Bitcoin mining hardware to minimize environmental and economic opportunity cost.

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## List of abbreviations

Abbreviation	Definition
ASIC	Application-specific integrated circuit
BECI	Bitcoin Energy Consumption Index
BIP	Bitcoin Improvement Proposal
BMC	Bitcoin Mining Council
BTC	Bitcoin
CAISO	California Independent System Operator
CBECI	Cambridge Bitcoin Energy Consumption Index
CCAF	Cambridge Center for Alternative Finance
CPU	Central Processing Unit
EH/s	Exa-hash per second
EUR	Euro
ERCOT	Electric Reliability Council Texas
FPGA	Field Programmable Gate Array
GPU	Graphics Processing Unit
GW	Gigawatt
J/Gh	Joule per Giga-hash
kWh	Kilowatt-hour
PUE	Power Usage Effectiveness
RTGS	Real Time Gross Settlement
SDG	Sustainable Development Goal
TWh	Terawatt-hour
UN	United Nations
USD	United States Dollar

## 1. Introduction

Blockchain technology has experienced growing interest since its advent more than a decade ago. From business applications to private applications, blockchain technology conveys the promise that it has the potential to improve business and human life around the globe. However, one application of blockchain technology so-called cryptocurrencies, have received a growing amount of recognition not only from the financial world, but also from the public. Some degree of recognition might result from spectacular investment returns in the past. Apart from the fact that cryptocurrencies present a counterintuitive paradigm of “assets”, concerns have been voiced that cryptocurrencies could provide vessels for criminals to circumvent the law. Furthermore, due to the distinct architecture of cryptocurrencies and resulting elevated levels of energy consumption<sup>1</sup>, compatibility of cryptocurrencies with ambitious climate and energy reformation policies has increasingly been questioned and criticized. One application of blockchain technology that appears in the limelight of such criticism is the Bitcoin network and its native cryptocurrency Bitcoin. Projections of extraordinarily high energy consumption levels often have led to conclusions that the Bitcoin network constitutes a problem due to wasteful and vast energy consumption. In addition, environmental concerns have been expressed that the energy demand could incentivize the use of fossil fuels resulting in negative impacts for the climate.

The purpose of the following work is to explore the debate around the energy consumption of the Bitcoin network and determine its most crucial parameters. The ambition is to investigate the following: **suitability of energy consumption as a comparative parameter for the sustainability of the Bitcoin network and associated regulatory policy implications.**

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<sup>1</sup> Energy consumption is a misnomer as energy is merely transformed from one state of energy into another state of energy i.e., electrical energy into thermal energy in the case of Bitcoin mining. Since the literature around the topic often refers to energy consumption of the Bitcoin network, the same terminology will henceforth be applied. Moreover, the terms energy consumption and electricity consumption are used interchangeably throughout this work.

## 1.1. Methodology

The following work will be theory and literature based. As will be shown, the Bitcoin network's energy consumption levels are determined by market conditions. Therefore, a focus will be placed on Bitcoin mining and its associated industry, particularly on the economic conditions that it operates in.

An attempt will be made to contextualize the order of magnitude energy consumption levels of the Bitcoin network. Moreover, to determine the viability of energy consumption as a sustainability parameter, a comparison with similar entities based on functionalities as well as different security models will be made.

Lastly, after having gained some insight into the subject matter, policy implications and recommendations will be discussed with a view on existing frameworks around environmental sustainability.

This work is based upon both scientific and professional literature. With regards to scientific literature, frequently cited peer reviewed as well as non-peer reviewed articles in form of scholar commentaries have been utilized. Professional literature entails research various institutions that are involved in research around the Bitcoin network. Inter alia this includes CoinShares Research, Nydig Research and Arcane Research. Moreover, public reports by institutions like the World Bank, the United Nations, and the Bank of International Settlements, the Dutch Central Bank, IRENA etc., have been consulted. Quantitative data and statistics of the Bitcoin network has been sourced from research platforms like Blockchain.com, CoinMarketCap.com and Coingecko.com. Data around the energy consumption of the Bitcoin network has been sourced from the *Bitcoin Energy Consumption Index* by Digiconomist.com and the *Cambridge Bitcoin Electricity Consumption Index* by the Cambridge Center for Alternative Finance. Lastly, in areas where no credible research is available yet, website data of enterprises pursuing a particular mining strategy has been used.

## 1.2. Structure

The remainder of this work will be structured as follows. First, an introduction to the principles of the Bitcoin network will be provided. Precisely, this comprises network properties as the principle of emerging consensus, the proof of work consensus mechanism and maintenance of the Bitcoin blockchain.

Subsequently, a focus will be put on the mining process in an economically competitive environment. Thirdly, the Bitcoin sustainability debate, precisely the relationship of the

Bitcoin network with energy consumption will be introduced. Fourthly, the energy mix of the Bitcoin network and potential implications for renewable energy development will be discussed. Fifthly, Bitcoin energy consumption will be contextualized and put into perspective. Moreover, the difficulty with comparison and categorization of the energy consumption levels of the Bitcoin network will be illustrated on the example of the transaction type as a starting point.

Lastly, policy implications and recommendations will be discussed.

### **1.3. Motivation for research**

Motivation for this work stems from a general interest in technological innovation. Articles on high energy requirements of the Bitcoin network and the claimed inefficiency of the consensus algorithm employed, has aroused the interest to do more research around the topic. It was found that existing literature around Bitcoin and energy consumption often seemed to associate the energy requirements of the network with negative implications for energy markets in and the environment. Little contextualization of network functions often presented electricity consumption in an isolated way comparing it to electricity consumption of nation states. The fact that, among the only recommendations proposed to solve the perceived problem was a change the Bitcoin protocol's fundamental principles also encouraged interest in the topic.

Therefore, when it comes to regulation, policy makers should have a comprehensive understanding of the technology, its basic functions and most importantly its relationship with energy consumption. Studies often appeared to provide insufficient explanation of influencing factors of electricity usage and appear to refrain from explanation of physical limits to energy consumption. Policy makers might therefore get the impression that the Bitcoin network might threaten the energy security of their constituents with runaway spikes of electricity consumption. However, new emerging research highlights potential application areas that could provide societal net benefits and alignment with energy policy. It is strongly believed that policy decisions based on potential misconceptions about the Bitcoin network and its energy consumption could bear societal opportunity costs regarding inefficient energy usage and forgone innovation. As a result, it is believed that research in this area is relevant. Lastly, the topic has been selected due to personal interest and personal ambitions regarding potential future professional career paths.

## 2. Basic concepts of the Bitcoin network

The Bitcoin network, as a medium for value transaction, has gained considerable recognition in the public eye during the past years. Since the development of internet payment services, the transfer of value has gained a digital dimension as digital payments have increasingly been substituting physical cash transactions. Regardless of the means of payment that are used, there is one central element that all processes of transactions have in common, which is the element of trust. Contrary to the physical world, where transacting parties physically engage in barter or exchange goods and services for cash in a physical setting, transactions in the digital realm have a key constraint. This is that transactions must be channeled through a third party to audit and verify that transacting parties are truly in possession of funds they wish to transfer (Ammous, 2018). Precisely, one of the key tasks of third parties is to prevent double spending of funds by potentially fraudulent actors. However, in 2008, an anonymous individual or anonymous group of individuals by the name of Satoshi Nakamoto, presented a concept for a value transaction network that would replicate physical cash transactions in the digital realm. Precisely, the academic-style whitepaper with the title “*Bitcoin: A Peer-to-Peer Electronic Cash System*” proposed a solution to eliminate double spending without the presence of a third party (Nakamoto, 2008).

### 2.1. Network architecture

In his proposal Nakamoto introduced several mechanisms, upon which the network was founded to effect value transfer between network participants. The Bitcoin network was conceptualized as a peer-to-peer network, which means that the network’s functions are distributed among network participants, so-called nodes, which share various functions and are all endowed with the same rights to contribute to the network’s functioning. There exists a symbiosis between nodes as they all provide and use certain services of other nodes. However, even though nodes are independent of each other and interact somewhat asynchronously, they follow a certain set of pre-established rules to achieve consensus among each other (Antonopoulos, 2018).

Compared to systems where a central server is responsible for information processing, in a peer-to-peer network this happens between nodes. Peer to peer networks are distributed and decentralized, with the objective to reduce potential attack surfaces and increase resilience. While such networks optimize for these attributes, information processing

requires more time. With respect to the Bitcoin network, the key purpose of this peer-to-peer network is to provide a medium for the exchange of digital values (Steinmetz et al., 2020).

## 2.2. Components

The Bitcoin network is based upon several key principles such as cryptography, hashes, and computational algorithms (Steinmetz et al., 2020). Conversely to what one might imagine under the term coin, units of Bitcoin are merely a consecutive list of digital signatures that provide information about the current owner of the respective data (Nakamoto, 2008). Units of Bitcoin can be transferred between network participants and are held by digital addresses that consist of a so-called public key and a private key. Private keys enable the holder Bitcoin to initiate a transaction by signature that is protected by cryptography for purposes of security (Kroll et al., 2013). The public key on the other hand is a publicly visible address network participants utilize to receive units of Bitcoin (Alqassem and Svetinovic, 2014).

Within traditional payment networks that rely on third parties for maintenance, network participants currently not involved in transactions do not have access to information regarding transacting parties and the value exchange. Conversely, the Bitcoin network is an open network that discloses information about every single transaction that has been occurring. For users to still retain anonymity, the utilization of cryptographic public keys that are visible to everyone in the network, but do not disclose any information regarding the identity of the individual behind an public key was implemented (Nakamoto, 2008).

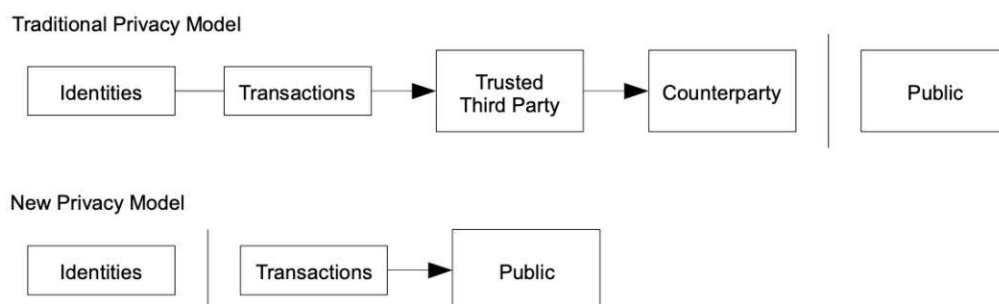


Figure 1. Bitcoin network privacy model (Nakamoto, 2008)

### 2.3. The Bitcoin Blockchain

The blockchain can be compared to a public accounting ledger that displays and records all transactions that have ever taken place on the Bitcoin network, as well as all addresses that have ever transacted and all account balances of every address (Alqassem and Svetinovic, 2014). This ledger is distributed among nodes so that all network participants dispose of an identical version of the blockchain and thus also of the entire transaction history. Storage capacity of blocks that contain transactions has been kept limited on purpose, in order for nodes to remain compatible with conventional IT infrastructure so that the network can maintain a high degree of decentralization (Sedlmeir et al., 2020). Transactions are recorded in a block format, that are then chained together to keep displaying new ownership of Bitcoins. Each block has a reference value, a cryptographic hash, to the block that precedes it in its “*block-header*” (Kroll et al., 2013). That way every block is connected backwards to its “*parent block*” i.e., the previous block, which in turn is linked to its previous block and so on. This chain of data can thus be traced back to the very first block ever added to the chain, the so-called “*genesis block*” (Kroll et al., 2013).

This specific architecture via hashes connected to parent blocks has got some important implications for the security of the Bitcoin blockchain. The further back on the blockchain a particular transaction is, a modification by malicious actors would require an extensive amount of computational capacity and electrical power to such a degree as it would be non-economical. This implies that the further back a block is in the transaction list of the blockchain, the increasingly difficult and less likely it becomes for a malicious actor it becomes to change the transactions of that block. (Antonopoulos, 2018). This will be discussed in more detail below.

In general, the key features of the Bitcoin blockchain can be summarized in a few key points:

- 1) “*Decentralization*”

Due to the design of the Bitcoin blockchain, there is no need for validation of transactions via a trusted third party, but via computational algorithms that fulfill the function of a so called consensus mechanism nodes have to follow.

## 2) *Persistency*

The structure of chained blocks that build on each other allows the display of an increasingly robust transaction history, whereby past transactions become increasingly unforgeable. This circumstance implies that transactions cannot be reversed and are final (Meiklejohn et al., 2013)

## 3) *Anonymity*

Network participants, who wish to transact via the Bitcoin network must generate a public and a private key, which does not require a user to reveal their personal identity. Nevertheless, re-usage of public does jeopardize anonymity in the network and can be traced back to the individual owner of a particular address (Meiklejohn et al., 2013).

## 4) *Auditability*

Due to the publicity of the Bitcoin blockchain, every transaction and ownership of Bitcoin units can be audited. This both true for network participants and non-network participants.

Zheng et al. (2017)

### **2.4. Network rules and consensus mechanism**

Because the Bitcoin network is not presided by a central authority that is responsible for maintenance and payment authorization, other mechanisms are implemented to ensure cooperation between nodes. In this regard, another important property of the Bitcoin network is the concept of so-called “*emerging consensus*” (Antonopoulos, 2018).

This concept can be envisioned as a set of participation rules that nodes must follow:

- 1) Nakamoto’s rules require network nodes, which possess a complete copy of the entire history of the blockchain, i.e., full nodes, to verify each transaction independently pursuant to an extensive list of criteria, that, for instance, require transactions to follow a predefined syntax and structure (Antonopoulos, 2018).
- 2) Each transaction will be checked for certain parameters, for instance structure and unspent character. Transactions that do not meet the requirements of the network

are filtered. Transactions that do meet the criteria are then stored in the so-called memory pool of each node from where they will be collected into blocks by mining nodes. Each node's memory pool is synchronized, so that transactions that have been validated are removed from the memory pool in order not to overload its storage capacity (Alqassem and Svetinovic, 2014).

- 3) Subsequent to step 2), mining nodes that have successfully performed this algorithmic calculation for a certain block, present the solution to all the other network participants that must verify that the mining node has indeed performed the calculation successfully for the specific block, that the transactions contained within the block are correct and unspent and that the block presented fulfills certain formal criteria according to the network's rules. New blocks containing the most recent transactions are added to the blockchain individually in a continuous matter with a time interval of 10 minutes between each block on average (Küfeoğlu and Özkuran, 2019).
- 4) As it could happen that two different mining nodes present a correct calculation for a specific block they have been working on at the exact same point in time, Nakamoto's rules require that both blocks be attached to the blockchain in the form of a fork with two continuing streams of blocks forward. However, as one of the two chains will eventually become longer than the other this implies a higher degree of cumulative computing power, spent on the longer chain. This will then be treated as the correct version of the blockchain by nodes (Nakamoto, 2008; Antonopoulos, 2018)

## 2.5. Blockchain maintenance

The maintenance of the blockchain is commonly referred to as “mining” and is one of the most crucial concepts of the Bitcoin network. Since the mining process and network properties such as proof of work are in the limelight of the sustainability debate regarding the energy consumption of the Bitcoin network, this section will discuss them in some detail.

The term “mining” is reminiscent of the mining of precious metals and may sound somewhat misleading in the context of information technology. However, similar to the physical world, the term mining in the Bitcoin network is also associated with the expansion of scarce and costly resources (Sedlmeir et al., 2020).

As mentioned, the main task of the mining process is to provide security for the blockchain, collect verified transactions into blocks and add new blocks of to the blockchain. Nakamoto (2008) has emphasized on the importance of this process and conceptualized an incentive mechanism that would reward miners monetarily to ensure that miners would participate in the network and perform the energy intensive task that is mining.

Before a block can be added to the blockchain and thereby become valid, mining nodes (henceforth miners) must complete an additional set of verification mechanisms. Precisely, a mining node must perform the so-called proof of work, by means of the “secure hash algorithm 256” (SHA256). A hash constitutes a predetermined set of characters, regardless of the length of the data stream that goes into it. In the case of the SHA256 the length is 256 bits (Antonopoulos, 2018).

To describe the process in a more simplified way, the SHA256 can be envisioned as a grinder that creates a hash from different inputs of data. In the mining process of the Bitcoin network, there are three inputs that are double hashed (Alqassem and Svetinovic, 2014). Firstly, the hash of the previous block. This ensures the sequential structure of the blockchain, with each block having a reference to its parent block. Secondly, a hash representing all transactions in the current block. Thirdly, a nonce variable to be able to vary the hash accordingly since the hash of the previous block and the hash of a current block would always result in the same hash (Küfeoğlu and Özkuran, 2019).

The only possibility for miners to find a hash that fulfills these requirements is by repeatedly trying the process and modifying the nonce value. As a result, this trial-and-error process to find a correct nonce requires repeated computations by miners that require electricity as an input. This procedure needs to be complied with, if a miner intends to add a block onto the blockchain and hence requires the proof of work to be completed (Küfeoğlu and Özkuran, 2019).

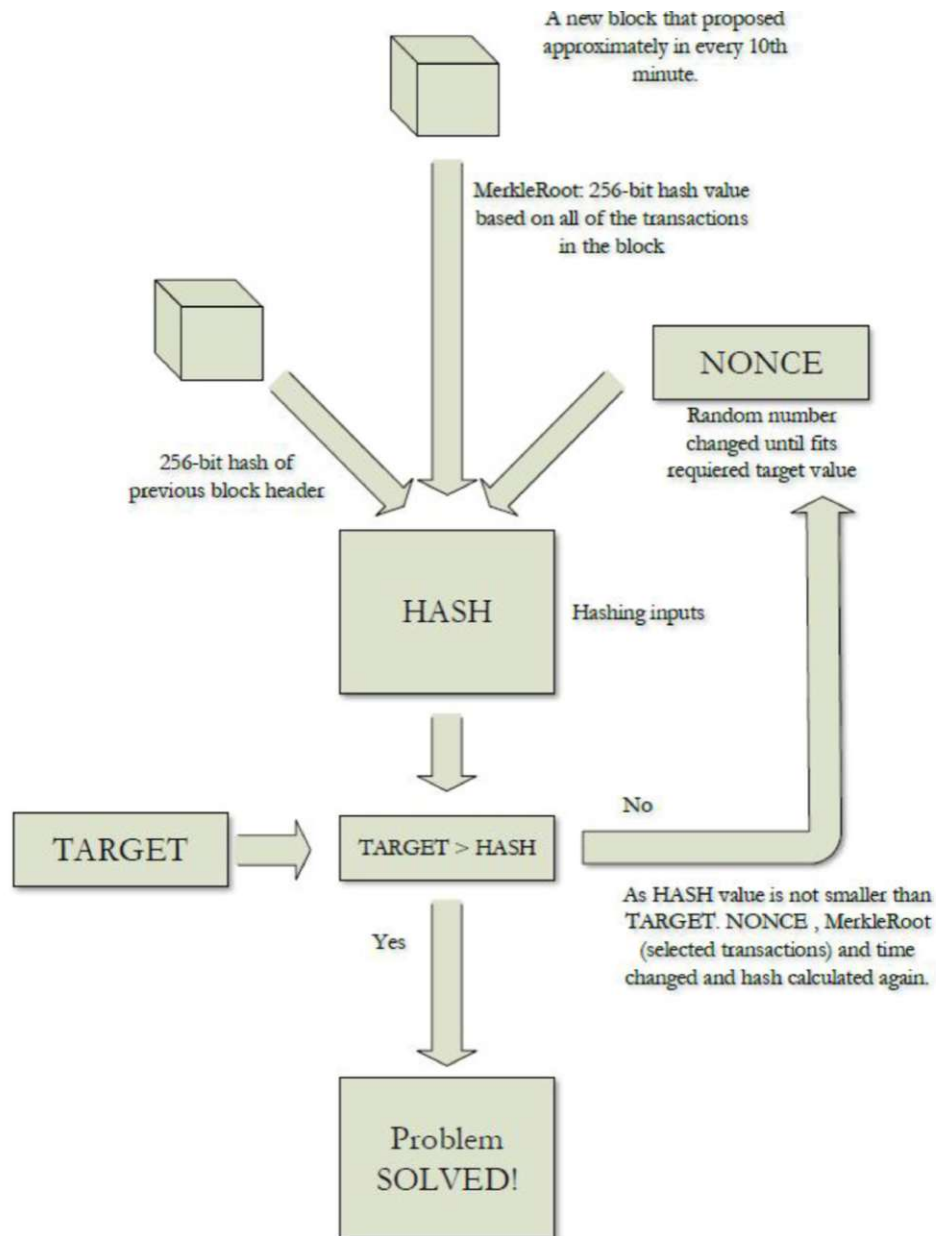


Figure 2. Bitcoin mining process (Küfeoğlu and Özkuran, 2019).

A successful miner presents his solution for a hash below a certain threshold with a certain nonce value to all network participants that are known to him. Subsequently, these nodes distribute the miner's propagated solution to all their known nodes. As nodes confirm the block as valid, they disseminate it further within the network, thereby initiating a cascade to reach as many nodes as possible. To confirm newly propagated blocks, all nodes examine the block for certain formal parameters, which include a check if the miner, who presented the block as a new addition to the blockchain, has veritably expended

computational capacity and electricity to complete the proof of work (Antonopolous, 2018).

As a result, the proof of work consensus mechanism can be interpreted as a verification mechanism that requires miners to invest a considerable amount of computational power before they can present a block, since it is statistically very unlikely that a correct nonce value will be encountered after only a few hashes (Antonopolous, 2018). Precisely, this process is applied to prove that a miner who found the hash smaller than a certain threshold value, must have tried the process for a certain number of nonce values. Regarding the characteristics of the correct nonce value, it is important to note that such a value is only used one time and for the correct block only, which constitutes an additional security feature and implies a huge degree of immutability for the blockchain (Brühl, 2017).

As a result, despite this mechanism resulting in a large amount of superfluous computations, it is necessary for network participants to agree on the validity of transactions and be resilient against attacks (Lei et al., 2021).

## **2.6. The difficulty adjustment**

For any given hash and subsequently block to be valid and accepted by the network, the condition that needs to hold for the proof of work mechanism is that the hash must be numerically smaller or equal compared a given target value determined by the network (Antonopoulos, 2018).

Because the network's rules prohibit arbitrary addition of blocks to the blockchain, the target value establishes the difficulty rate of new block discovery i.e. the amount of computations miners will have to perform, such that a new block will be added to the blockchain every ten minutes on average by miners regardless of how many hashes are computed in the entire network (Küfeoğlu and Özkuran, 2019).

For this condition to be always fulfilled, the network's rules demand that nodes autonomously reevaluate the time intervals between new blocks added to the Bitcoin blockchain. If the network operates as intended, an interval of approximately two weeks equals 20,160 minutes ( $20,160 / 60 \times 24$ ), which in turn, with an interval of 10 minutes between added blocks, implies that a total of 2,016 should have been added to the blockchain. This number of blocks represents a comparative value for nodes, which is used as a guide to adjust the difficulty of the target value upwards if more than 2,106

blocks are found, or downwards to make it easier to find correct nonce values for a block (Antonopoulos, 2018).

If a new target has been calculated, it is subsequently distributed among all network participants who then reset it. The formula applied to get the new target is as follows: “*New target = Current target \* Actual time it took to create the last 2016 blocks / 2 weeks*” (Alqassem and Svetinovic, 2014).

The target value has some peculiarities. According to O’Dwyer and Malone (2014), the largest possible value for the target in the network is  $(2^{16} - 1)2^{208}$  and the SHA256 occupies a value between 0 and  $2^{256} - 1$ . (O’Dwyer and Malone, 2014).

As a result, it is concluded that the probability to find a correct nonce value at a given difficulty can be depicted follows:

$$p = \frac{T}{2^{256}} = \frac{T_{\max}}{D2^{256}} \approx \frac{1}{D2^{32}}.$$

*Figure 3. Nonce value probability (O’Dwyer and Malone, 2014).*

Hashes for different nonce values are independent form each other, however, it is assumed that attempts will behave in accordance with geometrical distribution. Hence the expected number of hashes to be tried at a given difficulty can be represented as difficulty times  $2^{32}$ . At a given rate of hashes computed “*R*” and difficulty “*D*”, a miner can thus get an estimation of the expected time to find a block by applying “ $D2^{32} / R$ ” (O’Dwyer and Malone, 2014).

### **2.7. Incentives and disincentives of the proof of work mechanism**

Repeated hashes to find the correct nonce within the boundaries of the proof of work mechanism require considerable power and energy expansions. Naturally, the question arises why miners should go to such lengths for the mere validation of transactions and be incentivized to behave honestly towards the other network participants.

The answer to this question is a monetary incentive implemented in network, which is called “*Coinbase transaction*” (Antonopoulos, 2018).

In every new block that is presented to the network nodes, the first transaction in every block is the so-called Coinbase transaction and represents a miner’s claim on the reward

of a predefined amount of Bitcoin units. The Coinbase transaction has got fundamentally different characteristics compared to regular transactions because the number of Bitcoins rewarded do not have a prior transaction history (Alqassem and Svetinovic, 2014).

The amount of this reward depends on the number of blocks mined since the beginning of the Bitcoin network. Currently the amount of Bitcoin units distributed to a successful miner via the Coinbase transaction is 6.25 (CoinMarketCap.com, 2022). To provide some context, at the time of writing the Bitcoin price equals 19,087.14 USD. In fiat currency numbers the total reward for a miner who successfully solves a block corresponds to total revenues of 119,294.62 USD, transaction fees excluded, to cover a miner’s expenses (CoinMarketCap.com, 2022)

However, the issuance of new Bitcoin units is not only constrained by ten-minute intervals. More importantly, it is halved in intervals of 210,000 blocks, which corresponds to a period of approximately 4 years (Antonopoulos, 2018). The next such halving is expected to occur in 2024, which means that the reward will then be adjusted to 3,125 units. For comparison, the first four-year period of the Bitcoin network from 2009 to 2013, the reward was 50 bitcoin units (CoinMarketCap, 2022).

The bisection of block rewards is going to continue until approximately 2140, when no new Bitcoin units will be issued, and the total number of Bitcoin will be at 21 million. As Böhme et al. (2015) have stated in this regard: “*Bitcoin can be understood as the first widely adopted mechanism to provide absolute scarcity of a money supply.*” (Böhme et al., 2015). The following graph provides an overview of the issuance scheme and decreasing growth rate of newly distributed units of bitcoin.

*Table 1. Bitcoin supply and growth rate (Ammous, 2018).*

Year	2009	2010	2011	2012	2013	2014	2015	2016	2017
Total BTC Supply, millions	1.623	5.018	8.000	10.613	12.199	13.671	15.029	16.075	16.775
Annual growth rate, %		209.13	59.42	32.66	14.94	12.06	9.93	6.80	4.35
Year	2018	2019	2020	2021	2022	2023	2024	2025	2026
Total BTC Supply, millions	17.415	18.055	18.527	18.855	19.184	19.512	19.758	19.923	20.087
Annual growth rate, %	3.82	3.68	2.61	1.77	1.74	1.71	1.26	0.83	0.82

A maximum number of Bitcoin units implies that Coinbase transactions constitute a decreasing and finite form of remuneration for miners. To keep miners engaged in the network after this point has been reached, transaction fees, whose importance is comparatively negligible now, will have to increase so that miners are rewarded and continue to have a monetary incentive to continue maintaining the Bitcoin blockchain.

The bitcoin protocol always ensures that miners are exclusively entitled to the reward according to the Coinbase transaction at a given level of the block reward and not any arbitrary amount. The rules of emerging consensus prevent potentially fraudulent miners from claiming a higher reward. Network nodes check each block presented by miners for certain parameters, which also include the correct bidding of the Coinbase transaction. Should the Coinbase transaction in a presented block be larger than required by the protocol, this block would not satisfy the criteria applied by the nodes and would thus be rejected. The same would be true if a miner would present a fraudulent block to the network, that did not comply with the criteria of the proof of work mechanism (Antonopoulos, 2018).

This condition has an important security feature, as it constitutes a cost disequilibrium between miners who try to compute valid blocks and nodes that examine their validity. Fraudulent miners who presented an invalid block would still have to expand some computational power and electricity. On the other hand, nodes can check the validity of blocks at marginal cost. This condition implies that miners, who intentionally present blocks incompatible with the network’s requirements, will have wasted their resources as the network’s nodes will reject the block during examination and not deem it compatible with the network (Ammous, 2019).

The table below provides a comprehensive overview of the most important features the proof of work consensus mechanism fulfills in the bitcoin network.

*Table 2. The proof of work algorithm requirements (Alqassem and Svetinovic, 2014).*

Feature	Description
Scalable difficulty	The ability to adjust proof-of-work difficulty must not be fixed. In other words, if the block generation rate is high the difficulty should increase and it should decrease otherwise.
Fair distribution of wealth	All miners are equally likely to get the mining rewards. In Bitcoin, the SHA-256 hashcash function along with the difficulty adjustment algorithm guarantee this.
Easily verifiable results	The ability to verify proof-of-work values by network nodes promptly and without delaying or relying on a central authority. SHA-256 by its nature is a one-way, fast and easy to verify function.
Sensitivity to tempering block data	This is essential to strengthen blockchain’s connectivity and to maintain the network’s security by preventing malicious attackers from modifying transactions within blocks.

In general, consensus algorithms are one of the most important aspects of blockchain technology. Since there is no central authority, consensus rules and mechanisms are necessary for network participants to agree on the validity of transactions and be resilient against attacks. Different consensus mechanisms differ with regards to “their

*computational intensity*. “, which is an indicator for energy consumption (Lei et al., 2021).

Because the Bitcoin network is a distributed system, a problem of coordination arises since all nodes must agree on the same version of the blockchain. This problem is solved by Nakamoto’s implementation of emerging consensus and the proof of work that must be completed for each new block. This in turn implies that the correct version of the blockchain is the one with the highest degree of contained proof of work, thus identifying it as the correct one for all network participants (Zheng et al., 2017). As a result, the implementation of the proof of work mechanism ensures that only one valid version of the Bitcoin blockchain exists, upon which on which all network participants can agree and hence achieve consensus. On the other hand, this also implies that the Bitcoin blockchain will expand and increase data storage requirements.

### 3. The current state of Bitcoin mining

As described above, the mining process performs crucial tasks in the Bitcoin network. Essentially the process is characterized by fierce competition between different miners, who are all competing for rewards in from of the Coinbase transaction. The appreciation of the price of Bitcoin since 2009 has resulted in exponential growth of the computational power applied to the network. One of the most important metrics to observe with regards to mining is the so-called hash rate i.e., the total amount hashes that is computed per second in the Bitcoin network to find a hash below a given target value at a certain difficulty (Antonopoulos, 2018).

The total hash rate also provides an important security indicator. Since the Bitcoin network has been envisioned as a decentralized network, the hash rate ought to be distributed sufficiently as to prevent single entities from gaining a larger share and thereby control enough computational capacity to fraudulently amend the blockchain. However, such attacks involve significant cost and are mitigated if the overall hash rate increases in a distributed manner (Antonopoulos, 2018).

The total hash rate for the Bitcoin network is expressed in units of exa-hashes per second (EH/s), which corresponds to one quintillion hashes being computed per second (Kavanagh, 2022). Moreover, the more miners and hence hash power is being applied to the network with the aim to capture the block reward, the more difficult it will become for miners to be claim this reward. As mentioned, an increased number of hashes will result in less than ten-minute time intervals between blocks. However, the difficulty adjustment will recalibrate the target for nonce value in accordance with the overall hash rate. As a result, despite hash power and difficulty levels having increased exponentially, the supply of Bitcoin remains inelastic in response to how much effort is being applied by miners to get rewards in the form of Bitcoin. This is a fundamental principle as it implies that there is a maximum amount of profit to be extracted from each block.

Hash Rate  
227.8 EH/s

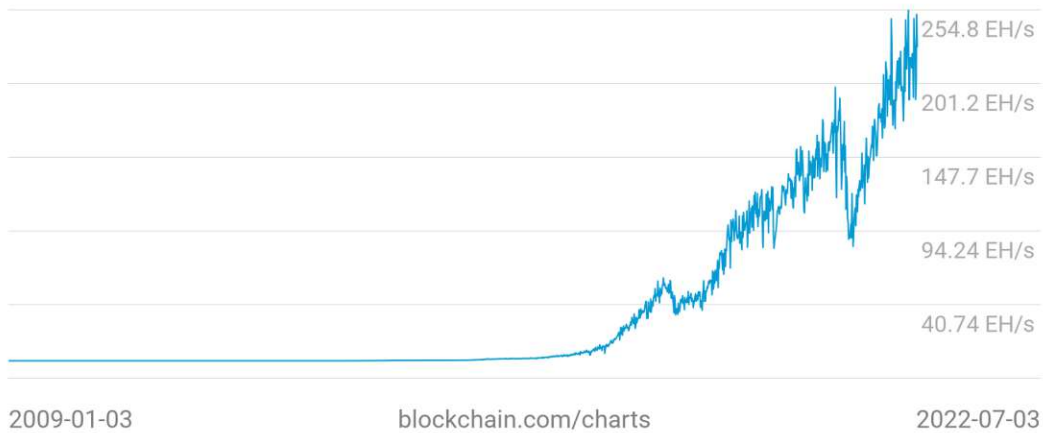


Figure 4. Bitcoin network hash rate (Blockchain.com, 2022).

### 3.1. Mining equipment

Miners engaging in the mining process face a crucial constraint regarding the available options of hardware technology to be utilized for the process. Due to exponential increases of the hash rate, more efficient mining equipment constitutes a significant competitive advantage for miners allowing them to compute more hashes in the same period of time than their competitors, thus increasing their probabilities to find a valid block (Antonopoulos, 2018).

Mining technology has been evolving rapidly over the past decade. Early difficulty levels allowed to engage in mining via a Central Processing Unit (CPU) i.e., via conventional computers that employed mining software. Since then, mining technology has evolved from the employment of Graphic Processing Units (GPU) towards Field-Programmable Gate Arrays (FPGA). The last and currently most widespread mining technology are so-called Application Specific Integrated Circuits (ASIC) (Szmigielski, 2016).

ASICs are hardware devices that are built exclusively for the purpose of Bitcoin mining. At the time of writing ASIC miners are the most efficiently performing mining devices available on the market in terms of hashes computed per unit of time and energy efficiency, which is defined as Joules per Giga hash (J/Gh). As a result, for miners to be profitable in today's market environment ASICs need to be employed (CCAF, 2022).

FIGURE 2: TOTAL HARDWARE UNITS IN USE

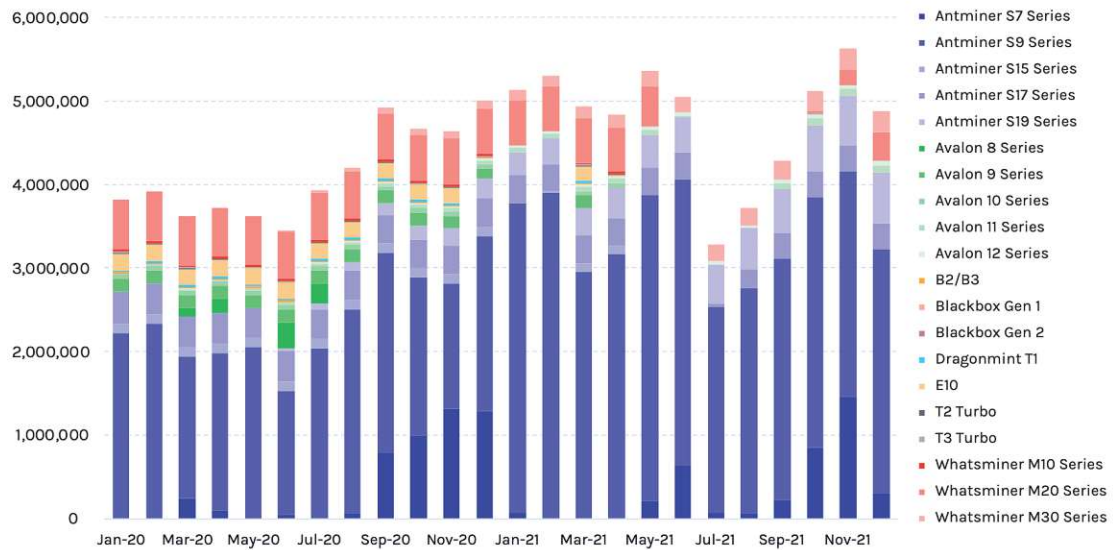


Figure 5. Total hardware units in use (CoinShares Research, 2022).

Increasing Bitcoin prices and thus increasing overall hash rate have led to an “arms race“ in the employment of more efficient ASICs in recent years (Vranken, 2017). Efficiency gains from older to newer ASICs are quite remarkable. For instance, the so-called “Bitmain Antminer S3” released in 2014, had an average energy efficiency of 0.77 J/GH, whereas the “Bitmain Antminer S19 XP” which was introduced to the market in 2022, has an energy efficiency of 0.02 J/GH (CCAF, 2022). Competition is said to reach even so far, as ASIC manufacturers refrain from selling devices on the market, but rather build their own datacenters to use their product themselves before they are released on the market (Magaki et al., 2016).

### 3.2. Types of mining

Whereas mining can be performed on an individual basis, increased hash rate entering the Bitcoin network reduces the likelihood of an individual miner to find a valid block (Szmigielski, 2016). In order to be profitable in the competitive mining environment nowadays, miners need to bundle their hash capacities in so-called mining pools to increase the probabilities to find a valid block. Miners who join such a mining pool via a specialized software protocol are rewarded proportionally to the amount of hash power they contributed to find a block (Antonopoulos, 2018). Depending on the size of a mining pool and miners’ electricity cost, pool mining enables miners to have a continuous stream

of income and thus hedge against Bitcoin price drawdowns compared to solo mining (Szmigielski, 2016).

### 3.3. Economics of bitcoin mining

Nowadays the Bitcoin mining ecosystem is characterized by a large-scale mining industry that has developed in recent years and consists of several large and some publicly listed mining companies. However, in order to operate as efficiently and as profitably as possible, the mining industry is constrained by a few key factors. Firstly, electricity constitutes the most important input factor for the purpose of computing hashes. Secondly, miners are dependent on a nonintermittent and resilient internet connection to maintain connection to the network. Thirdly, miners' economic performance is dependent on the choice of ASICs employed. To apply the highest possible hash rate to the network, the choice for a certain efficiency rate will to some degree be determined by the price of electricity. Fourth, legal conditions and energy markets in a jurisdiction will determine where miners will establish their operations (Szmigielski, 2016). Lastly, miners must hedge their economics against Bitcoin price volatility to be able to withstand periods of diminishing profits.

In view of these circumstances, miners must account for several eventualities which could potentially impact their undertakings and jeopardize their economics. On a more general level, there are certain conditions that need to hold in order for a miner to enter the competition given the dynamics of the mining market. Depending on a miner's individual constraints regarding the factors above, each miner's economic condition can be represented as " $G < PV/C$ ", where " $G$ " is the cost for the number of hashes a miner must compute to find a correct nonce and subsequently a hash for a valid block. " $C$ " represents the overall cost a miner must bear, in this case capital expenditure for ASIC devices and the cost for electricity. Finally, expression " $P$ " constitutes the hash rate determined by " $C$ ", and " $V$ " the amount of Bitcoin gained for a valid block (Kroll et al., 2013).

Because the mining market is a global market, a miner's decision to enter the market is dependent on the total hash rate applied to the network. Moreover, there are exogenous factors determined by the Bitcoin protocol, most importantly the difficulty adjustment " $R$ ", to keep block intervals constant at ten minutes on average. The difficulty adjustment will of course be dependent on the total number of miners contributing hashes in the total market. Expression " $G$ " will be impacted by that. Precisely, on a global scale " $G =$

$P/R$ ” holds. If this global dimension is now introduced into the original equation, the implication and thus the question whether a market entry is economically worthwhile, can be expressed as  $P(global)/R < PV/C(global)$  from which follows that “ $C < RV$ ”. Ultimately, this condition will trend towards, and eventually establish an equilibrium in which mining costs and mining profits are equalized (Kroll et al., 2013).

This condition has important ramifications because mining profits are dependent on the market price of Bitcoin, which is historically volatile and unpredictable. Therefore, for miners to improve the robustness of their economics, the biggest lever is by employing an effective cost minimization strategy based on a mix of efficient ASICs and cheap electricity cost.

With regards to the types of costs, both Kroll et al. (2013) and Delgado-Mohatar et al. (2019) show that a miner’s expenses have both a fixed and a variable cost character. Mining hardware devices constitute sunk costs as a miner cannot recover ASIC expenses retrospectively, based on the notion that ASICs will only be bought for the sole purpose of mining Bitcoin. Therefore, a miner’s decision to engage in mining, continue mining or terminate mining is primarily dependent on their variable cost i.e., the cost for electricity. This implies that the economic condition that at least needs to hold for an economically rational miner to engage in Bitcoin mining and continue to do so is until the financial gains from Bitcoin rewards are above or at the break-even point with electricity costs (Delgado-Mohatar et al., 2019). As can be seen, this is also congruent with Kroll et al.’s (2013) findings.

### 3.4. Profitability

To capture economic value and be profitable, however, the profitability constraint for Bitcoin miners can be understood as the mining reward per hash, which needs to be maximized, over the variable electricity cost per joule (Cambridge Center for Alternative Finance, 2022).

Profitability in the mining market is dependent on three core parts, which are the price of electricity, the efficiency of mining devices and the price of Bitcoin. Firstly, the literature generally assumes that competitive, industry-scale miners will face an electricity price

constraint at a maximum of 0.05 USD per kWh hour to be profitable (Stoll et al., 2019; Delgado-Mohatar et al., 2019; Digiconomist, 2022; CCAF, 2022)

Secondly, as mentioned repeatedly, the efficiency of ASICs and the maximum hash capacity at a given power level is a key profitability constraint for miners. The lifecycle of ASIC devices has been subject to debate, as some scholars assume relatively short lifetime of ASICs in a span of 1.5 to 2 years (de Vries and Stoll, 2021).

Conversely, recent estimates postulate certain devices that have been introduced in 2016 (*Antminer S9*), to still have constituted 20% of the overall hash rate in 2021 (CoinShares Research, 2022). Despite rapid improvements of efficiency rates in recent years, the rate of improvement for efficiency gains is expected to stifle in the future due to dependency

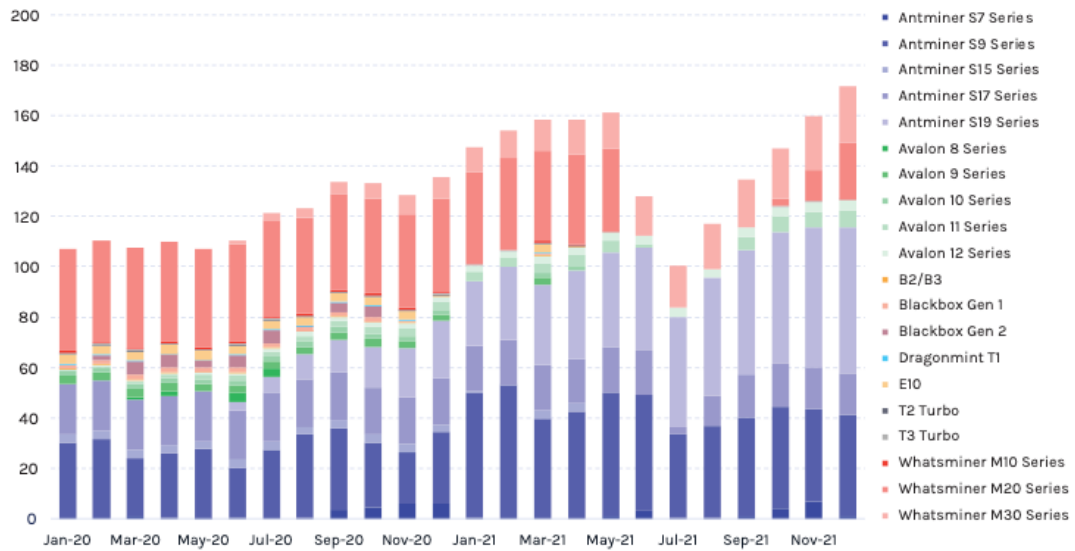


Figure 6. Total hash rate by hardware unit (EH/s) (CoinShares Research, 2022).

on developments in the semiconductor industry (Vranken, 2017; Kristoufek, 2020).

Thirdly, a large driver and hence influencing factor on profitability of miners is the Bitcoin market price which will determine the profit margin for miners. However, Bitcoin's price development has been characterized by reoccurring price volatility. During a previous appreciation cycle in 2017 profitability margins temporarily increased by 2000%. Such distinctive dynamics of appreciations and depreciations of the Bitcoin price, naturally influence miners and their economic calculations (Kristoufek, 2020). Moreover, such order of magnitude increases in the Bitcoin price provide a monetary incentive for new miners to enter the mining market, especially if they compensate for less efficient hardware or more expensive electricity cost. However, due to the cut-throat

nature of competition in the Bitcoin mining market and despite reoccurring price surges during the past years, profit margins of mining operations globally nevertheless follow a downward trend and move towards the production costs (Kristoufek 2020).

Ultimately miners are assumed to be economically rational and only enter the market if the economic condition introduced above holds. During periods of price drawdowns, the margins between profit and production cost will be narrowed, however, this is dependent on a miner's individual constraints regarding ASIC selection employed and the respective price of electricity at a miner's location.

Depending on these factors different hardware models can withstand drawdowns in Bitcoin's price for varying lengths of time and still be profitable. For instance, the ASIC model *Antminer S19XP* at a price of ~0.05USD is currently estimated to be the most efficient model and able withstand drawdowns in Bitcoin's market price until a threshold of 7,925.84USD before reaching unprofitable territory (BTC.com, 2022).

### **3.5. Geographic location as an influencing factor**

Due to the competitive nature of the mining industry and the fact that mining software can be expedited globally, and Bitcoin mining is a global market, the location and global distribution of mining sites is somewhat obscure. What can be deduced from the economic constraints under which miners operate is that among important influencing factors of mining site selection will be the price of electricity miners are able to negotiate with energy plant operators, internet access as well as non-obstructive regulatory conditions.

Regardless, there exist distinct methodologies to get at least approximate values concerning the question of the geographical whereabouts of miners. One such approach has been developed by the Cambridge Center for Alternative Finance (CCAF) with the development of the so called "*Mining Map*" that utilizes IP addresses of mining pool operators to provide an indicator of the geographic distribution of hash rate (CCAF, 2022). According to their results, global hash rate distribution looks as follows. Firstly, ~38% of global hash rate of the Bitcoin network are estimated to originate from the United States. Secondly, the People's Republic of China (henceforth China) was found to contribute ~21%. This finding is somewhat paradoxical since China imposed an official ban on Bitcoin mining in May of 2021. The larger remaining contributions to the overall hash rate come from Kazakhstan (~13%), Canada (~6%) and the Russian Federation (~5%) (CCAF, 2022).

However, regarding localization methods it should be noted that there is large degree of uncertainty induced in such estimations and data in this regard should not be interpreted without caveat. The CCAF acknowledges that their estimations are based on mining pool IP address data that represents less than half of the total network hash rate. Additionally, some network participants disguise their location and anonymize their internet connection data by utilizing a TOR browser or a VPN that makes it increasingly harder to localize them (CCAF, 2022).

Stoll et al. (2019), also tried to estimate the global distribution of Bitcoin mining operations by tracking the IP addresses of mining hardware devices. According to their results, most miners were also estimated to be located in the United States, followed by Venezuela, Russia, and Ukraine (Stoll et al., 2019).

#### 4. The Bitcoin sustainability debate

The Bitcoin network has gained a considerable amount of attention in the public perception over the past few years, not least due to price appreciations of a total 17,260,63% since 2009 (CoinMarketCap, 2022).

As mentioned in the introduction, criticism has been voiced with increasing popularity and estimations about the network's energy requirements were no less spectacular than price appreciations, since the network was forecasted to be on the path towards consuming "(...) *all of the world's current energy production in order to support itself* (...)" until 2020 (Cuthbertson, 2017).

Academic studies that examined the potential impacts of Bitcoin mining and the emissions associated with it, concluded that the network alone could be responsible for bypassing the critical 2 degrees threshold of global warming implied in the Paris Agreement. Precisely, the authors estimated that this critical threshold would be reached by 2033 provided the Bitcoin network would evolve according to their projections (Mora et al., 2018).

In view of such claims, the network's application of the proof of work consensus mechanism and the resulting energy intensity of hash computation has been questioned increasingly, especially regarding its compatibility with public sustainability goals.

##### 4.1. Excursus: Sustainability

Despite its frequent occurrence, sustainability appears to be a somewhat vague, all-encompassing term that does not convey specific information about what is meant by it. The emergence of an increased focus on sustainability within a policy context can be attributed to the World Commission on Environment and Development (United Nations, 2022). The Commission, as a branch of the United Nations, in 1987 published the "*Report of the World Commission on Environment and Development: Our Common Future*", also referred to as "*Brundtland Report*", as an answer to the United Nations General Assembly's demand to postulate a paradigm shift with regards to human development (Brundtland Commission, 1987).

In their report the Commission addressed a wide range of developmental and environmental issues in the context of the occurrence of the greenhouse effect and its potential to increase global temperatures, which were estimated to have a severe negative impact on agriculture, crop yields, world hunger and poverty. Moreover, the report

addresses topics such as population growth, energy sources and their usage, globalization, and an interconnected international economy (Brundtland Commission, 1987).

With respect to sustainability, part three paragraph 27 discusses “Sustainable Development” and defines it as follows: “*Humanity has the ability to make development sustainable to ensure that it meets the needs of the present without compromising the ability of future generations to meet their own needs.*” (Brundtland Commission, 1987). When examined more thoroughly it becomes evident that the Commission’s definition of sustainable development encompasses multiple areas that are subject to this definition. For instance, the importance of conserving resources and treating nature with care is urged for. Elsewhere, it is emphasized that larger shares of the global population need to be integrated into the global economy. Precisely, developing countries ought to not only participate in it, but they should also benefit from economic growth (Brundtland Commission, 1987).

As a result, it can be deduced that sustainability has several pillars, upon which it is established. The United Nations (UN) have confirmed this notion and subsequently developed their approach towards sustainability within an international framework upon them. An examination of the UN resolution, adopted by the UN General Assembly during the 2005 World Summit provides information on how the UN defines sustainable development. Precisely, in the introductory section of the resolution in which “*Values and principles*” are explained in more detail, paragraph 10 provides three different dimensions to the term sustainable development. Strictly speaking, sustainable development is said to have an environmental dimension, an economic dimension, as well as a social dimension (United Nations General Assembly, 2005).

To determine the notion of objectives in the context of sustainability, the UN “*2030 Agenda for Sustainable Development*”, provides guidance and a point of reference with regards to the aims of sustainability. At the core of this framework are seventeen goals, the so-called “*Sustainable Development Goals*” (SDGs) formulated to provide a holistic and comprehensive approach to achieve predefined goals along the three sustainability dimensions. In the declaration to the framework, heads of states and policy makers commit themselves to humanitarian and developmental goals, which are to be achieved until the year 2030. SDG number 7 in this framework refers to energy sustainability specifically (United Nations, 2015).

Because the energy requirements of the Bitcoin network are at the center of the sustainability debate, but sustainability as such is not a quantifiable metric, applicable contents of SDG number 7 will be taken as a reference point in the final part of this work.

#### **4.2. Energy consumption and the bitcoin network: Existing literature**

Apart from Mora et al. (2018), the compatibility of the Bitcoin network with sustainability goals involving climate change mitigation, energy usage, mitigation of carbon dioxide emissions, etc., has been subject to further scrutiny within the academic realm.

O'Dwyer and Malone (2014) was one of the first analysis to investigate Bitcoin mining and its energy footprint. Dutch scholar de Vries has dedicated a large share of his research to the extrapolation of the network's resource insensitivity. Moreover, his research platform "*Digiconomist*" has conceptualized the so-called "*Bitcoin Energy Consumption Index*" (BECI), a metric that aims to trace the emissions output and electricity usage of the Bitcoin network (Digiconomist, 2022).

Other estimates were provided by Vranken (2017), Stoll et al. (2019) as well as the "*Cambridge Bitcoin Electricity Consumption Index*" by the CCAF (CCAF, 2022).

The following part will be dedicated to a review of the most cited literature around the relationship of the Bitcoin network with electricity consumption with the objective to get a credible estimate how much energy the Bitcoin network requires, and which methodologies estimates are generally based upon to derive conclusions.

##### **4.2.1. O'Dwyer and Malone (2014)**

As mentioned, a key component of the mining process is the total computational power applied to the network at a given point in time i.e., the total network hash rate at a certain difficulty level to find a correct nonce value. Total hash rate is a function of the individual performance of miners in terms of efficiency. According to the author's assumptions, the energy efficiency for mining devices at the time was within the range of 2 Mega hashes/Joule and 2000 Mega hashes/Joule, for the most competitive devices (ASIC miners were not yet widely available on the market at the time this analysis was conducted). It was assumed that the total number of mining devices applied to the network, has a combined average efficiency within this range. The mining technology selected included a basket of CPUs, GPUs, FPGAs and one ASIC and relied on manufacturer's specifications regarding power draw.

The authors then computed the overall network hash rate by multiplying the nonce value probability, according to the formula displayed above, with the difficulty and divided the result by the average block time of ten minutes i.e., 600 seconds.

The total hash rate was subsequently divided by an efficiency average of mining devices for total power consumption. As a result, it was estimated that the total usage of electrical power ranged from 0.1 gigawatts (GW) to 10GW. In a final estimate, the total electrical power demand of the network is assumed to be 3 GW, however, the authors do not provide additional information how this final estimate was derived (O'Dwyer and Malone, 2014).

#### **4.2.2. Vranken (2017)**

Considerate of the by then widely applied ASIC devices in Bitcoin mining, Vranken (2017) conducted a study aimed at estimating the power demand of the Bitcoin network per 01/01/2017. The analysis followed a similar approach that had been applied by O'Dwyer and Malone (2014), but with updated mining hardware data. Moreover, it was assumed that the maximum electrical power demand could be estimated by supposing that all mining revenue is spent on electricity cost. Ultimately it was estimated that the total electrical power demand might be around 100 MW (Vranken, 2017).

#### **4.2.3. Mora et al. (2018)**

For this approach, the year of 2017 also served at a reference point. Publicly available data of block difficulty from the website blocktrail.com was utilized. The number of average hashes per block was multiplied randomly by the efficiency rates of a preselected basket of hardware devices. During the course of research electricity consumption estimates for this particular study were only available in supplementary material of the paper which unfortunately was inaccessible. However, numbers were found in a paper from Masanet et al. (2019), who questioned the methodology applied by Mora et al. (2018) and performed a recalculation. Among other things, it was claimed that the ASIC basket would comprise mining devices that had no longer been profitable during the time. Moreover, the reevaluation of the analysis with an adjusted basket of mining devices yielded a total electricity consumption of 28 TWh hours in 2017 compared to the original approach at 114 TWh (Masanet et al., 2019).

This paper has gained a considerable amount of attention by infamously claiming that associated emissions of the Bitcoin network's electricity consumption “(...) *alone could push global warming above 2 °C.*” (Mora et al., 2018). With regards to the trajectory of electricity consumption, it was assumed that transactions on the Bitcoin network would be the main driver and scale similarly to exponential adoption rates of technologies such as credit cards or dishwashers. Lei et al. (2019) also criticized this approach for applying oversimplified assumptions regarding scaling trajectory.

#### **4.2.4. Stoll et al. (2019)**

Scholars Stoll et al. (2019) have attempted to derive an approximation value of the networks power demand. According to their methodology, a lower and an upper limit for the power demand were calculated. For the lower bound case, it was assumed that miners use only the most efficient ASICs available on the market. The respective efficiency rates were estimated according to market share of the largest ASIC manufacturers and their most efficient devices at the time. Subsequently, this number was then multiplied by the network's total hash rate, to establish a lower bound.

For the upper bound case it was assumed that miners behave in a manner that is economically rational and would continue mining as long as their mining revenues allowed them to cover electricity costs. Stoll et al. (2019) claimed that the lower bound case provided a more realistic scenario hence this approach is used to determine the overall power demand. Apart from hash rate and energy efficiency of best performing available hardware devices, an estimate for cooling requirements of hardware devices was included in their equation. Extrapolated to the year 2018, their results postulated a yearly electricity consumption of 45.8 TWh (Stoll et al., 2019).

#### **4.2.5. de Vries (2020)**

In a 2020 paper, an approach based on market dynamics meaning price movements of the market price of Bitcoin both to the downside as well as to the upside was proposed by de Vries. The study mentioned that price swings to the upside was likely introduce inefficiencies to the market as less efficient ASICs (in terms of J/GH) might be profitable again and thus reintroduced. Furthermore, miners might also be less inclined to capture electricity at the lowest possible price due to a higher Bitcoin spot price and thus were less concerned about their profitability margins. The methodology is centered around an

analysis of the Bitcoin market in 2019 during which it had experienced a significant price increase and thus an increase of the hash rate by 30 EH/s to a total of 92.5 EH/s by September 2019.

For ASIC efficiency data, 2019 market sales of the newest devices sold by the three largest manufacturers according to market share were analyzed and then combined with the assumption that prior to the price appreciation, only the most efficient mining devices had constituted the dominant provider of hash rate. Subsequently, it was estimated that the average efficiency for mining devices applied to the network was at 0.0917 J/GH in 2019. From this assumption the total electricity consumption of the network is extrapolated to be at 85.8 TWh. After adjusting for parameters like delivery times of new mining hardware devices, this value is corrected upward to 87.1 TWh (De Vries, 2020).

#### **4.2.6. Digiconomist (2022)**

The methodology for Digiconomist's widely cited BECI is largely based on economic assumptions. Starting point for this approach is the total number of mining revenues as a function of Bitcoin rewarded per valid block including transaction fees, multiplied with the price of Bitcoin. Subsequently it is assumed that miners will approximately spend 60% of their total revenues on operational costs i.e., electricity costs. Subsequently, total electricity costs are then divided by 0.05USD per kWh, which is assumed to be the competitive electricity price. According to this methodology the Bitcoin network consumes approximately 127.15 TWh, which on a country level comparison is said to equal the electricity consumption of the UAE (Digiconomist, 2022).

#### **4.2.7. Cambridge Center for Alternative Finance (2022)**

A further assessment of the Bitcoin network's energy requirements is provided by the Cambridge Center for Alternative Finance and the widely cited Cambridge Bitcoin Electricity Consumption Index (CBECI) (CCAF, 2022).

Similarly, to Stoll et al. (2019) the CBECI model is constructed around a lower threshold and an upper threshold estimate. Moreover, a "*best-guess estimate*" is provided in this model. For both the lower threshold, the upper threshold, and the best-case scenario a snapshot for the real time electrical power demand is given as well as the extrapolation of the yearly electricity consumption in TWh based upon the electrical power demand in GW.

The model is subject to several assumptions. Firstly, it is presumed that miners behave economically rational and will continue mining as long as they can cover their variable cost. Congruent with other estimates, it is assumed that miners face a global constant average price of 0.05USD per kWh of electricity. Secondly, it is assumed that in case of unprofitability of all mining hardware devices on the market due to price drawdowns, the last available profitable equipment will be applied. Regarding the range of ASICs employed, only devices of manufacturers Bitmain, MicroBT and Canaan are considered in the estimation as they constitute the major share of the production market for ASICs. For a lifetime estimate, ASICs are assumed to be economically viable for a total of five years. Energy efficiency rates are estimated by assuming that all profitable ASIC models on the market are equally distributed to all market participants.

For the minimum consumption scenario, the following assumptions are made: Firstly, it is presumed that miners utilize the most efficient hardware available on the market and upgrade their existing hardware to more efficient devices if such were released. Secondly, “*Power usage effectiveness*” (PUE) is introduced as a metric for data centers to not only account for energy efficiency of mining hardware devices themselves, but more importantly for the energy efficiency of additional appliances at a mining facility like cooling devices, additional infrastructure, etc. The higher the PUE the less efficient a data center is run in terms of operational cost. For conventional data centers an average PUE of 1.8. is assumed, however, in the minimum consumption scenario a PUE of 1.01. is postulated for all mining facilities.

Considerate of these input data, an electrical power demand of 4.48 GW and a yearly electricity consumption of 39.24 TWh is estimated for the minimum threshold. On the other hand, for the maximum consumption scenario the following is presumed. Firstly, economically rationality is again presupposed, and miners are expected to utilize the least efficient but still profitable hardware available, solely based on their variable cost basis. Secondly, a PUE of 1.20. is postulated for all mining establishments. According to these upward adjusted input data, an electrical power demand of 21.03 GW hours and a yearly electricity consumption of 184.34 TWh are estimated (CCAF, 2022)

Given this comparatively broad range between both thresholds, it is acknowledged by the CCAF that neither the minimum, nor the maximum scenario provides a realistic estimate of the real conditions at present. As a result, an approximation is needed that is represented by the CCAF’s “*best-guess estimate*”. For this scenario the model assumes that miners will apply a mix of mining devices, that enables them to still cover their

variable cost for electricity. Furthermore, a PUE of 1.10 is estimated for all mining facilities. According to this approach an electrical power demand of 10.39 GW at present and a yearly electricity consumption of 91.10 TWh for the year of 2022 is estimated. Despite these estimates, it is acknowledged that the model is subject to limitations with regards to assumptions about the price of electricity, the mix of mining hardware employed, other cost factors, switching periods of hardware, etc. (CCAF, 2022).

### 4.3. Types of approaches

As can be seen, assessments of electricity consumption levels of the Bitcoin network are dependent on methodologies applied and certain assumptions regarding variables taken. As a general principle, methodologies can be grouped into the following approaches (Lei et al., 2021).

1) “*Top-down approach*” (Lei et al., 2021)

This approach has been utilized by O’Dwyer and Malone (2014) and Vranken (2017) for instance. It is computed by estimating an average efficiency out of a basket of mining hardware devices and multiplying it with the total network hash rate. According to the authors, it is believed that the top-down approach is viable for estimating a minimum energy consumption value (Lei et al., 2021).

2) “*Economic approach*” (Lei et al., 2021)

This approach is based upon the economic and profit conditions for Bitcoin mining. However, it is emphasized that this approach induces a great degree of uncertainty with regards to the validity of estimates, especially when it comes to three fundamental variables that this approach is based upon. Firstly, it is emphasized that the estimate is heavily dependent on a scholar’s assumption which share of total mining revenues will be spent on electricity. Secondly, it is argued that the volatility of the Bitcoin market price is extremely difficult to be accounted for reliably. Thirdly, it is stated that electricity prices vary across different locations, therefore general averages might be subject to error. The authors thus emphasize that results adherent to this approach might be subject to exaggerated results (Lei et al., 2021).

This notion is confirmed in another study, where it was stated that this approach must be presented within the context of larger economic developments at the time

of computation (Sedlmeir et al., 2020). Precisely, it is demonstrated that if miners had access to electricity prices that were half the price as the generally assumed 0.05USD per kWh (either through price drops or increased usage of cheaper renewable energy sources) and energy consumption would be estimated by dividing total electricity cost through price per kWh, energy consumption would instantly double according to model. Moreover, if the Bitcoin price would double together with a halving of electricity price, the total energy consumption would quadruple according to the model (Sedlmeir et al., 2020). As electricity production is subject to physical constraints, validity of such estimates is questionable. Moreover, from a purely basic economic reasoning, increased demand for electricity will have an increasing effect on respective prices, which, depending on the market price in a particular scenario, in the long term will make Bitcoin mining less attractive.

3) *“Hybrid top-down approach”* (Lei et al., 2021)

According to this approach it is presumed that ASICs are only applied in cases profitably at a certain Bitcoin market price. However, the exact distribution of ASICs in general cannot be determined with accuracy. Therefore, assumptions based on a certain ASIC distributions and thus overall electricity consumption extrapolations are subject to uncertainty.

4) *“Extrapolation based on direct measurement”* (Lei et al., 2021)

According to this approach the energy per computed hash and mining node in a known network can be utilized as a proxy for the larger network. However, it is acknowledged that the number of total nodes is obscure and PUE values cannot be determined according to this methodology.

To reduce the inaccuracy of the projections the following basic principles to be followed are proposed (Lei et al., 2021).

- Consideration of a design of a typical mining facility, which represents the mining process, including PUE values, in its entirety as realistically as possible.
- Usage of a bottom-up approach that considers energy consumption behavior over a certain period at a typical facility.

- Assessment of energy consumption data based on real life measurements instead of relying on manufacturer specifications.
- Consideration of rapid technological advancements in ASIC manufacturing and model application of ASICs only that are congruent with realistic application.
- Consideration of different power draws for different devices employed at a facility and their potential variations regarding usage depending on Bitcoin price dynamics.
- Consideration of geographical differences regarding electricity prices, cooling requirements and other cost.
- Application of a dynamic assessment approach that allows to account for a certain degree of unpredictability and therefore provide values in a certain range. Approaches that yield estimates within a certain range have also been advocated by Sedlmeir et al., (2020).
- Consideration of the pace of development to get an estimate of the order of magnitude of future energy consumption.
- Identification of realistic drivers of future electricity consumption and incorporation their respective development.
- Transparency and reproducibility of results.

(Lei et al., 2021)

According to the authors, the CBECI is said to currently incorporate most of these principles in its model (Lei et al., 2021).

#### **4.4. Energy consumption as a function of mining economics**

What can be deduced in view of overall electricity consumption is that the Bitcoin network's energy consumption is dependent on certain variables. Currently, assumptions of certain conditions prevail, and a definitive estimate is hard to compute due to potential differences regarding ASICs employed, electricity prices, PUEs, etc. What seems to hold true though is that overall energy consumption levels of the Bitcoin network are at least determined by a few key factors.

Firstly, the market price of Bitcoin is an important determinant with respect to the overall hash rate that will be applied to the of the network. As mentioned, the price of Bitcoin

together with the block reward will provide the monetary incentive for miners to engage in mining in the first place.

As a general principle what can be established is the following. If the market price of Bitcoin rises the overall hash rate will increase, thus electricity consumption will increase. In fact, the industrial character that the mining industry has evolved into is essentially due to strong appreciations of Bitcoin's market price.

Secondly, the price of electricity available to a miner will ultimately determine the efficiency rate of the hardware device that needs to be employed in order to mine Bitcoin at a profit. If miners have access to cheaper electricity compared to their competitors, their production cost will be lower, and they can employ less energy efficient ASIC models. This notion appears to be confirmed by the *Antminer S9* case mentioned above. However rather than seeing these three variables in an isolated way they appear to be intertwined and inherently determined by current market sentiment, geographic location, total network hash rate and individual factors like the cost structure of miners, the efficiency of their data centers, cooling requirements if applicable, and how efficiently they manage to operate their mining hardware. For instance, miners are employing hardware with different efficiency rates that will be switched on or off depending on price movements.

One could assume, like some estimations above, that the market price of Bitcoin is the ultimate key determinant when it comes to electricity consumption. In the long term this will likely be true, because ultimately miners will want to make a profit. However, if the current total hash rate is observed, this assumption appears to be incorrect. Despite a strong price drawdown by more than 50% since September 2021 (Blockchain.com), the overall network hash rate moved in a diametrically opposed direction and has been increasing. This implies that energy consumption has been increasing despite the Bitcoin price decreasing.

# Hash Rate

## 228.3 EH/s

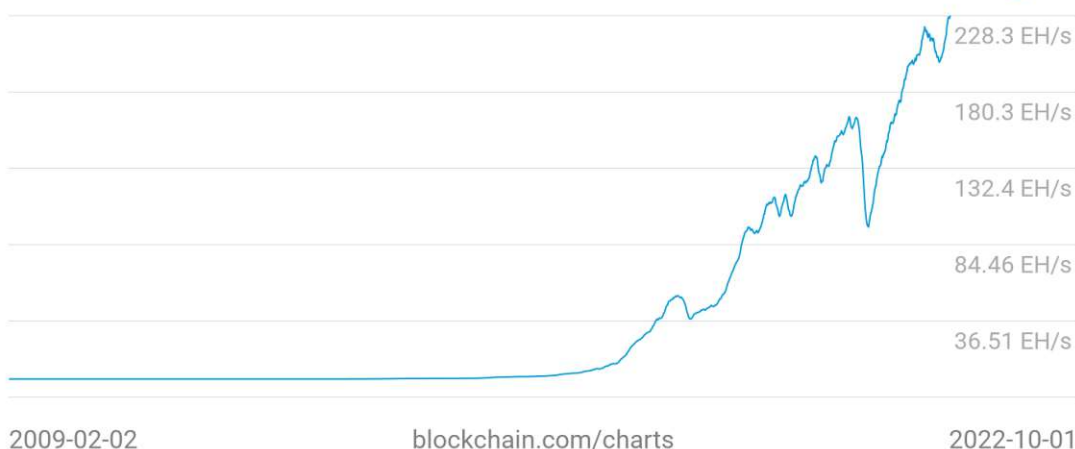


Figure 7. Bitcoin network hash rate (Blockchain.com).

As has been established, the market price of Bitcoin is not predictable. Furthermore, the structure of the fixed block reward and the difficulty adjustment pose a cap to miners' maximum revenue. However, total mining revenue from block rewards is decreasing, finite and subject to competition among miners in the market. It follows that the only mechanisms by which miners can increase their share of revenue compared to competitors in the market is by employing more efficient hardware than competitors and/or having access to cheaper electricity. This condition applies for every market scenario because miners must follow the rules determined by Nakamoto's Bitcoin protocol.

Market dynamics, however, do have an influence on miners which in turn does influence electricity consumption. Price increases will have a compensating effect for miners that employ less efficient equipment comparatively more expensive electricity and allows them to become profitable again.

Provided that price increases will lead to previously unprofitable miners to reenter the market, this implies greater hash rate and most importantly increases in the difficulty. In the long run this dynamic implies that most profits will still be captured by most energy efficient ASICs, miners with cheaper electricity, or both, due to more hashes per second computed at the same cost.

Conversely, price decreases will first force out miners that comparatively employ less energy efficient ASICs, have higher electricity cost than competitors, or both, because they are most vulnerable to diminishing profits. Moreover, if miners had not included

different price drawdown scenarios in their economic calculation they could be forced out of the market as well despite efficient hardware and low-cost electricity.

As discussed above, the issuance schedule of new units of Bitcoin has been predetermined and miners' rewards in terms of units of Bitcoin will be halved approximately every four years. The next halving is expected to take place in 2024, which means that units of bitcoin per block, by which miners calculate their revenues will decrease from 6.25 currently, to 3.125 by 2024. All else equal, for miners to sustain at least current profit levels, the price of Bitcoin would need to have doubled by 2024. In a scenario where miners' cost basis remains unchanged and the price of Bitcoin remains unchanged, halving events will imply that the electricity consumption of the Bitcoin network is going to decrease (Sedlmeir et al., 2020). This is due because under changed profit conditions some miners will have to leave the market because they cannot continue mining profitably. Subsequently the overall hash rate is going to decline, and electricity consumption is thus going to decrease. Furthermore, in the long-term miners are confronted with an economic environment where profit opportunities will decrease further. As previously mentioned, Bitcoins has a maximum supply of 21 million units that can be issued via the block reward. Whereas the issuance of the whole supply will have been completed by 2140, 19.174 million will have been mined by the end of 2022 (Ammous, 2018). On a percentage basis this means that mining with the objective to capture the block reward is already completed by 91,30%. To summarize, there is only a small share of mining revenue via the block reward that can ever be mined and miners that are less electricity efficient or face higher cost than competitors will be driven out of the market in the long run. Again, the only option for miners to continue or ever be profitable under uncertain market conditions, is via employing more energy efficient ASICs or cheaper electricity.

However, both these conditions are subject to constraints. ASICs cannot become more efficient. As discussed, efficiency rates are expected to increase less significantly in the future as they are strongly dependent on semiconductor innovation (BMC 2022; CoinShares Research 2022). Electricity costs on the other hand are a function of supply and demand. In that sense miners can effectively jeopardize their own business by bidding up electricity prices.

Because Bitcoin mining has evolved into an industry, it may help to apply a business perspective to the conditions miner's face. A mining business will strive to maximize profits; however, its only source of revenue is Bitcoin, the price of which is unpredictable.

As mentioned before ASICs constitute sunk costs for miners. Provided that miners are rational market actors, they will only buy an ASIC if they can at least cover their expenses. According to the CCAF (2022), new and more efficient ASICs are introduced to the market with latency and will likely not be equally distributed among all market participants (CCAF, 2022). Furthermore, under the premise that efficiency gains from new ASIC models will be less pronounced in the future and since electricity constitutes the only other cost miners will face, the only mechanism for miners to plan and hedge uncertain market conditions is to ensure access to optimize for the cheapest possible electricity source.

Considerate of the above figure, it appears that the Bitcoin price and the total network hash rate, i.e., electricity consumption, have been moving diametrically opposite to each. What can be deduced from this is that Bitcoin price and thus mining revenues may not provide an accurate indicator of overall electricity consumption. Primarily also because these metrics cannot be planned for in a miner's business plan.

Conversely, what the graph above does appear to indicate is that miners in fact have access to cheaper electricity, must have increased the energy efficiency of their operations or could be mining at temporary losses. However, at some point they would have to disconnect their ASICs from the network and the overall hash rate and thus electricity consumption would decrease.

In the long run, the price of Bitcoin will provide an indicator about the order of magnitude of electricity consumption, however, hash rate and difficulty will most likely be carefully considered in a miner's decision to enter the market or not because it will determine whether any profits can be made at all. In periods of price decreases miners could be assumed to first exploit options for more efficient hardware or cheaper electricity to increase. This would explain higher hash rate and higher electricity consumption. Ultimately, severity of price increases and decreases will ultimately result in recalibration of hash rate and difficult level, which will then determine overall electricity consumption. Future consumption will also be dependent on the evolution of transaction fees.

Under the assumption that Bitcoin price experiences a significant increase, the question remains how large future consumption can be and what the determining factors will be. Again, from a basic economics perspective at some point additional hash power applied to the market will most likely result in declining marginal productivity. Given that the mining market competes for a good that has a finite amount, the question is how this will affect the distribution of the hash rate since miners could refrain from employing ever

greater hash power to the market. If such a tipping point was reached, under consideration of the equilibrium function introduced above, this would imply that over time inefficient miners will be forced out of the market still and hash rate, thus electricity consumption would decline.

## 5. Energy sources employed

Apart from electricity consumption, a large part of the Bitcoin sustainability debate is about environmental implications and the alleged large carbon emissions of the Bitcoin network. The following part will be dedicated to the presumed energy mix of Bitcoin mining and the potential implications of the network's peculiarities for the development of renewable energy sources.

Estimations about the energy mix of Bitcoin mining is depended on the whereabouts of miners and their access to electricity. Like electricity consumption, the high degree of anonymity in the network makes this a difficult undertaking.

In their comprehensive report, Bendiksen and Gibbons (2019) estimated that mining energy mixes would be somewhat identical to the energy mix that supplied energy grids in a specific region where Bitcoin was mined. According to their estimates the major share of total hash rate in 2019 originated from China. In some regions like Sichuan, mining was estimated to be 90% powered by hydropower; whereas mining conducted in other Chinese provinces was estimated to be 44% powered by renewable energy sources. For the remaining share of global hash rate, a high degree of application of renewable energy sources was assumed except for countries like Iran, Kazakhstan, and Mongolia, where coal was believed to be used most frequently. For a global estimate it was believed that approximately 73% of the total hash rate was powered by renewable energy sources (Bendiksen and Gibbons, 2019).

Other estimations assumed a share of 60% to 70% percent of overall Bitcoin mining to be conducted in China (Schinckus, 2021). With regards to the respective energy sources that powered mining facilities in China, it was estimated that 58% of the overall originated from hydropower whereas 42% originate from coal (Stoll et al., 2019). For both cases it was found that a key reason for miners to migrate to China in the first place was that the Chinese government had heavily subsidized hydroelectric as well as coal power plants, which led to overproduction of electric power that was sold cheaply to miners (Blandin et al., 2020).

With regards to the carbon intensity, it was assumed that the Bitcoin network was responsible for carbon emissions of 22-22.9 MtCO<sub>2</sub>, which is estimated to be the same order of magnitude as the carbon emissions of Jordan (Stoll et al., 2019).

The 3<sup>rd</sup> Global Cryptoasset Benchmarking Study conducted in 2020, surveyed 75 mining companies and 30 individuals to gain more insight regarding the energy mix employed in the mining process for all proof of work based blockchains. It was estimated that 39% of the total global hash rate of proof of work blockchains was provided by renewable energy sources and 76% of all miners employed renewable energy sources in their energy mix. With regards to energy sources hydropower, coal, and natural gas were found to be the most widely utilized sources (Blandin et al., 2020).

However, as mentioned previously the mining market experienced quite substantial changes as China imposed an official ban on Bitcoin mining which resulted in miners transitioning to other countries. According to a commentary by De Vries et al. (2022) it was estimated that shortly after the mining ban in China, renewable energy sources temporarily constituted only a quarter of the total energy mix as miners had primarily migrated to Kazakhstan where coal was a dominant energy source. Furthermore, it was argued that power demand for Bitcoin mining generally would elevate the baseload demand on the energy grid, therefore decommissioned coal plants could potentially be reactivated to provide additional sources of electrical energy (De Vries et al., 2022).

According to Digiconomist (2022), it is estimated that the current carbon intensity, based on the assumed energy mix of the network, is in the same order of magnitude to the nation of Oman at 78.35 MtCO<sub>2</sub> (Digiconomist, 2022). Other studies also confirmed an intermittent increase of carbon intensity of the network after the mining ban in China, but a slight downward trend in carbon intensity from the ban until December of 2021. Overall, it was estimated that global Bitcoin mining energy mix by December of 2021 was constituted of coal (35%), gas (24%), hydropower (21%), nuclear power (11%), wind power (4%), a mixture of oil, solar power, geothermal power (5%) and others respectively. In total it was assumed that the network was responsible for 39 Mt of CO<sub>2</sub> emissions, constituting 0.08% of carbon emissions on a global scale (CoinShares Research, 2022).

Since the United States currently is assumed to host the largest share of hash rate from a country perspective, the Bitcoin mining landscape has been evolving there. In this regard the so-called Bitcoin Mining Council (BMC), an association of 45 mining companies that are estimated to constitute 50.5% of the global hash rate, provided data from miners on

the council and an extrapolation of global estimates. According to their Global Bitcoin Mining Data Review on the Bitcoin mining market for the second quarter of 2022, it was assumed that 59.5% of the total energy mix stemmed from “*sustainable energy sources*”. Miners on the council were estimated to employ an energy mix that was 66.8% supplied by sustainable energy sources. According to the BMC’s definition, sustainable energy sources in this context comprise hydroelectric power, wind power, solar power, nuclear power, and geothermal power. With regards to carbon emissions on a global scale, it is estimated that the Bitcoin network is responsible for 0.086% MtCO<sub>2</sub> (BMC, 2022).

## 6. Bitcoin mining relationship with renewable energy sources

Renewable energy sources like wind, solar and hydropower play a crucial role in the transition away from fossil fuels and CO<sub>2</sub> emissions into the atmosphere, thus limiting climate change (Dincer, 2000). Since the Bitcoin network has been criticized in the past of using vast amounts of energy and contributing to CO<sub>2</sub> emissions, claims have also been made in recent years that the network would dispose of unique properties, which made it an ideal customer for renewable energy producers. For instance, some reports argued that miners behaved like “*(...) a global electricity buyer of last resort and therefore tends to cluster around comparatively under-utilised renewables infrastructure.*” (Bendiksen and Gibbons, 2019). Therefore, it was postulated that Bitcoin miners could be a catalyst for making renewable energy plants economically viable in areas where they have not been viable before due to their high degree of global mobility and the fact that they are not as location bound as other industries (Bendiksen and Gibbons, 2019).

In 2020, a researcher from the Frankfurt School of Finance & Management, published an informal article that was underpinned by a similar argument. Namely that renewable energy sources like wind and solar power had lower marginal cost for energy producers thus Bitcoin miners would prefer them regardless, compared to more expensive energy sources like coal (Sandner, 2020).

For a cost comparison it is reckoned that fossil fuel powered energy plants produce electrical energy at 0.03EUR - 0.05EUR per kWh, whereas hydroelectric plants and windfarms are assumed to produce electrical energy at 0.02EUR - 0.04EUR per kWh. This is because renewable energy plants do not require the same degree of maintenance

and expensive equipment. More important, the energy source itself does not have to be bought and burnt like coal or gas to generate electricity but is rather sourced directly. Additionally, it is claimed that renewable energy providers are faced with a key constraint, that is overproduction of renewable energy because of inflexible production and a frequent disequilibrium with demand periods. As a result, loads often cannot be sold as energy grids are constrained regarding their maximum capacity. Subsequently, it is argued that energy producers could sell cheap energy that could not be utilized otherwise to Bitcoin miners as cheaper electricity implies a competitive advantage for them (Sandner, 2020).

While these arguments seem conclusive, no evidence or real-world application of this theory is provided. However, three recent studies by Bastian-Pinto et al. (2021) Fridgen et al. (2021) and Niaz et al. (2022) could provide more insight into the network's relationship with renewable energy sources and confirm this notion.

### **6.1. Economic improvement of renewable energy production via Bitcoin mining?**

Renewable energy sources, especially wind power and solar power face a key constraint as production periods are cyclical and weather depended, thus difficult to predict. Energy demand and energy availability do not match throughout, therefore investments into development of renewable sources bear a large risk for capital providers and investors.

In Brazil, for instance, a country where renewable energy production is already higher than the OECD average by a factor of 3.5, these conditions pose a risk for the development of further develop renewable energy production capacity. To mitigate this risk and encourage investments, price volatility of already constructed windmills needs to be subsidized by governments. However, interventions by regulators and uncertainty cause significant delays to developments, thus posing a threat to energy security. A study investigating the economics of Brazilian windfarms postulated that simultaneous investments in ASICs to mine Bitcoin could help risk mitigation, improve profitability, and moreover help to increase further development of renewable energy sources (Bastian-Pinto et al., 2021).

Precisely, a 2- year and a 4-year accompanying investment in a Bitcoin mining facility decreased the probability of a negative net present value by 14 and 23 percentage points for the project respectively. According to the authors the possibility of Bitcoin miners being applied as a hedge against electricity price risk has the potential to accelerate the development of not only windfarms, but also other intermittent energy power plants as

supply could be sold to miners instead in periods when it was not demanded by the market (Bastian-Pinto et al., 2021).

A similar approach was utilized in a study that examined the economic viability of an integration of a Bitcoin mining facility into a windfarm energy plant in Germany. According to the authors, under certain assumptions regarding difficulty and Bitcoin price, it was found that an integration of a Bitcoin mining facility into a wind energy plant did improve the net present value of the plant by 32% compared to an investment in just the windfarm (Fridgen et al., 2021).

Furthermore, it is argued that such an implementation could also contribute to a higher share of renewable energy in Bitcoin mining since 73% of the electricity used for mining in the integrated model originated from renewable sources. Moreover, plant operating times were estimated to have improve by more than a factor of 2, compared to a setup without integrated mining. Lastly, was reckoned that an integrated approach may contribute positively to stability of the grid as generated electricity could be sold to integrated miners during times when there was sufficient supply available on the market (Fridgen et al., 2021).

A third, recently conducted study examined the application of Bitcoin mining at renewable energy plants to mitigate energy curtailments at the example of Texas and California in the United States. Both locations are reported to have increased rates of

energy overproduction that needs to be curtailed in times when there is a lack of demand or a lack of storage solutions whose installment involves additional cost (Niaz et al., 2022).

Given the numbers of curtailed electricity from wind and solar production, the model designed by Niaz et al. (2022) investigated, form the viewpoint of a system operator and an investor, at the example of the situation around curtailed wind and solar energy in Texas, whether Bitcoin mining could be applied so it would allow to maximize electricity that could not have been sold otherwise. Under certain assumptions regarding mining difficulty, hardware life expectancy, potential penalty costs for curtailed energy as well as implemented security measures to hedge against unpredictable price fluctuations, it was argued that ASICs could be implemented as a tool to reduce curtailment and earn additional profits. Precisely, under a cost minimization scenario it was concluded that

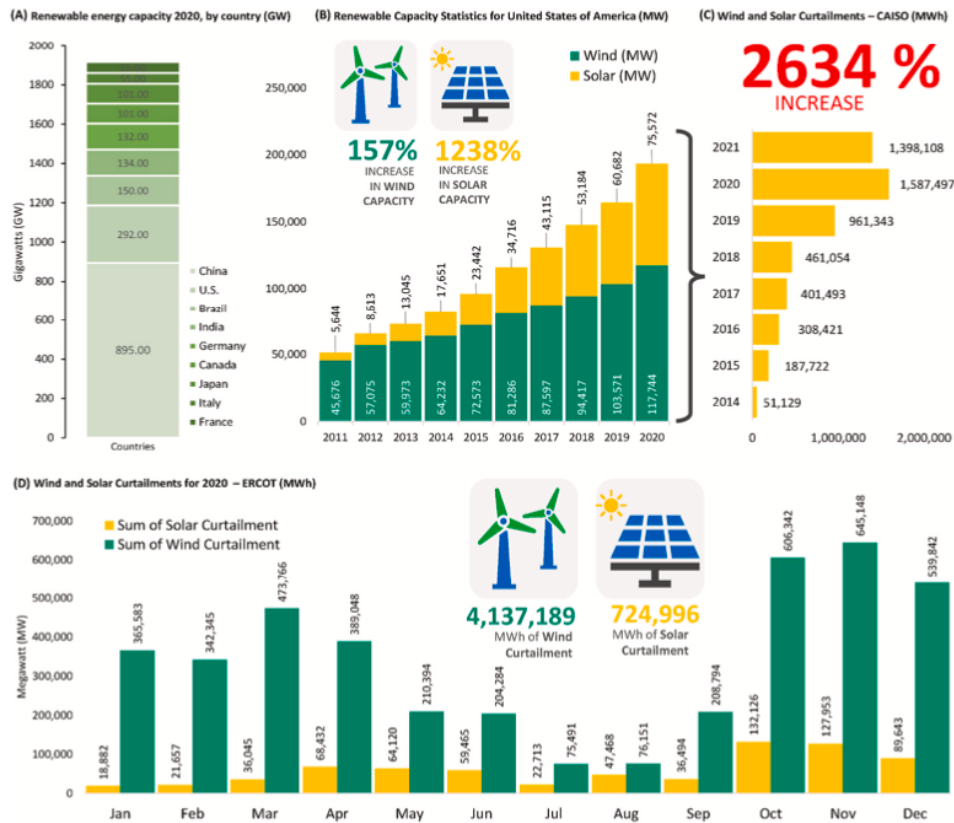


Figure 8. Renewable energy capacity and curtailment rates (Niaz et al., 2022).

93% of electricity oversupply could be used at additional profits of 239 million USD. Under a profit maximization scenario, 69.8% of electricity oversupply could be sold to Bitcoin miners at additional profits of 605 million USD. Moreover, the authors argued that their model could be applied in tandem with energy storage media to expand Bitcoin mining to other renewable energy facilities as a medium to maximize otherwise unutilized oversupplies (Niaz et al., 2022).

## 7. Potential usage of wasted byproducts

Apart from renewable energy sources, there exist implications to also utilize otherwise wasted natural gas for the purpose of Bitcoin mining (Vazquez and Crumbley, 2022).

Generally, the flaring of natural gas occurs at oil drilling facilities, where gas as a byproduct of oil drillings cannot be used or recovered otherwise and therefore must be burnt. Remoteness of drilling areas pose obstacle to selling gas on the market, because

often additional costly expenses in pipeline infrastructure would be required and make an investment not worthwhile (Snytnikov and Potemkin, 2022).

In 2018 145 billion cubic meters of petroleum gas as a byproduct of oil drillings was flared globally, with Russia, the United States, Iran, Algeria and Iraq among the major players. Apart from economic losses due to the gas not being sold, there is also an environmental cost associated with such practices as flared gas was estimated to be responsible for 350Mt of CO<sub>2</sub> and other greenhouse gas emissions into the atmosphere. (Nezhadfar and Khalili-Garkani, 2020; Snytnikov and Potemkin, 2022).

While the installment of turbines for purposes of electric power production with extracted gas have already been deemed a viable practice to gain additional revenue and mitigate emissions, the electricity generated can often not be sold due to remoteness and hence lack of local markets. According to a study on the situation in Russia it was estimated that the amount of petroleum gas extracted during oil drillings, could generate approximately 67 TWh of electricity per annum. To mitigate the environmental impact of gas flaring and generate additional income, Bitcoin mining and cryptocurrency mining in general was proposed as a method to implement a “*gas on-site monetization*” on the premises of remote oil drilling facilities (Snytnikov and Potemkin, 2022).

According to the authors’ estimations it is assumed that the break-even point between additional investments for mining hardware devices could be under twelve months, depended on overall market conditions and the price of the underlying cryptocurrency that is mined. Additionally, their model proposes a circular approach as it is argued that the heat emitted from ASICs could be utilized to supply on site greenhouse farms, which are to be used as additional CO<sub>2</sub> capture (Snytnikov and Potemkin, 2022). With regards to the latter, the authors unfortunately do not specify to what degree greenhouse gas emission could be mitigated by this approach.

According to a similar study conducted on the conditions in the United States, it was estimated that the overall potential of CO<sub>2</sub> emission mitigation by utilizing gas to generate electricity for cryptocurrency mining purposes instead of flaring it is at 63% compared to current levels (Vazquez and Crumbley, 2022).

Furthermore, other greenhouse gas emissions like methane or nitrogen oxides could also potentially be diminished by 98% and 89% respectively (Phan, 2022; Crusoeenergy, 2022). To incentivize the usage of “*stranded natural gas*”, states like North Dakota and Wyoming already provide incentives via tax credits to drilling companies that adopt such approaches to mitigate flaring (Vazquez and Crumbley, 2022). Currently it is estimated

that flared gas approximately 2.4% of the total Bitcoin mining energy mix in 2021 (CoinShares Report, 2022).

With regards to greenhouse gas emission mitigation, new industry branches incorporating Bitcoin mining appear to be developing. For instance, a company from California claims to be able to reduce methane emissions from municipal landfills by a substantial margin via the installment of micro turbines to convert emissions into electricity. This electricity will subsequently be utilized to power ASICs for the purposes of mining Bitcoin on site to provide an additional revenue stream for landfill owners (Vespeneenergy, 2022).

However, this industry seems to be in its infancy and claims need to be taken with caution. Precise data is needed to determine the total addressable market and whether this is a viable approach for greenhouse gas emission mitigation.

Regardless of these implications, the different nature of the gas deposits in different locations add some complexity to this method that must be considered. While it has been acknowledged that electricity generation with otherwise flared gas can be a viable approach both environmentally and economically, it has also been emphasized that such an approach is heavily depended on the machinery employed for electricity generation and the nature of the gas deposit in question (Nezhadfar and Khalili-Garkani, 2020).

Precisely, the chemical composition and flow rate of natural gas available at a particular drilling site will determine the type of turbine required for electricity conversion and the type of additives that may need to be added to the gas. Ultimately, the composition of gas will determine the economic viability and thus influence amortization periods. Regarding environmental concerns, it is mentioned that conversion to electricity instead of flaring does indeed have a mitigating effect on greenhouse gas emission, however, specific life cycle assessments at sites in question would be necessary to be able to quantitatively determine an exact emission reduction capacity for applied cases (Nezhadfar and Khalili-Garkani, 2020).

## **8. Implications for increasingly renewable infused energy grids**

Regardless of the implications of Bitcoin mining for renewable energy generation, there remain potential hazards for energy grids and energy producers, as Bitcoin miners increase base load demand and potentially overexerting the energy grid to the point where fossil fuels need to be utilized (de Vries, 2022).

A recent 2022 report, compiled by the international corporate consulting company Roland Berger, investigated the relationship between Bitcoin miners and the energy grid. According to Vaughan et al. (2022) the installment of miner capacity on energy generation facilities can provide an entity for baseload balancing of the electricity grid, especially in climate areas where there are large seasonal discrepancies of baseload demand. Precisely, it was reckoned that the installment of ASICs can help to increase the use of power generators during colder seasons when certain power drawing entities, for instance air conditions, are omitted. Such a practice could also be applied in a more distributed grid where ASICs could be installed strategically to compensate for low demand time frames throughout the day when less energy might be demanded from the grid, but electricity feed-in happened regardless. The authors also indicated that miners could function as “*demand response*” entities, which are needed when grid management needs to curtail excessive demand to keep the electricity grid stable (Vaughan et al., 2022).

A potential best practice case for Bitcoin miners performing demand response is provided by the operation of Bitcoin miners within the energy grid ERCOT in Texas in the United States. During a July 2022 heatwave in Texas, miners were asked to decrease power draw, thereby making a load of 1,000 MW available to other grid participants to be able to deal with peak demand (Pan, 2022). Such a practice is enabled because ASICs constitute a “*Controllable Load Resource*”, meaning that their power draw can be decreased or increased in incremental steps. This is due to the interruptibility of mining operations since hashes are computed independently from each other (Mellerud and Helseth, 2022). Because of that miners differ from other grid participants in the sense that they can disconnect ASICs from the grid, essentially interrupting their production, but face less opportunity cost in doing so compared to other production industries or public facilities.

## **9. Bitcoin energy consumption viewed in perspective**

What can be seen from several estimations discussed above is that the underlying determinant in a quest to assess the electrical energy consumption of the bitcoin network is the methodology applied in a particular study. As discussed, important input factors like efficiency rates of miners or electricity prices may be based on simplified assumptions due to a lack of information and data difficult to obtain. Moreover, absolute numbers of the Bitcoin network’s assumed electricity consumption do not convey

instructive information, however, they seem to dominate in analysis where the network's electricity consumption is mostly compared to electricity consumption of nation states. The question arises whether such comparisons are expedient as the Bitcoin network is of course not a nation.

On a comparative basis purely based on electrical energy usage it is estimated that the Bitcoin network's share of electricity consumption globally is 0.42%, based on the CBECI's "*best guess*" estimate (CCAF, 2022).

According to the 2022 Coin Shares report, that estimated the energy consumption of the Bitcoin network to be in the same order of magnitude at 89 TWh annually, the Bitcoin network was responsible for 0.05% of global electricity consumption (162,194 TWh) (CoinShares Research, 2022).

From an industry perspective, the energy consumption of the bitcoin network under the "*best guess estimate*" (94 TWh) was also compared to other energy-intensive large-scale industries on a global scale: Chemicals (1349 TWh), Iron and Steel (1233 TWh), Data Networks (250 TWh), Data Centers (200 TWh) (CCAF, 2022).

### **9.1. Differentiation according to service**

One comparison that is encountered in the literature quite frequently, is the comparison of transactions on the Bitcoin network with transactions via the VISA payment network and the comparatively lower electricity consumption per transaction (Schinckus, 2021; Digiconomist, 2022).

Precisely, under the assumption that the total consumption of the Bitcoin network is 140.47 TWh (at the time this study was conducted), it is reckoned that a single transaction via the Bitcoin network would consume 1518.41 kWh, which is estimated to supply an average American household for almost two months with electricity (Digiconomist, 2022). However, electricity consumption is primarily a function of mining with the aim to add a new block to the blockchain. This electricity is consumed because of mining and not because of the number of transactions contained in a block and theoretically is independent of the number of transactions in a block (CCAF, 2022).

Moreover, provided that second layer protocol applications on top of the Bitcoin blockchain like the Lightning Network prove themselves to be viable, this will also imply that transaction volume can scale independent of and without additional energy consumption (Antonopoulos et al., 2021).

Apart from these implications the type of transaction on the Bitcoin network is also not comparable to a payment network like VISA. As can be read in the first part of Nakamoto's whitepaper, one of the main objectives the network aims to achieve is: "(...) *to make non-reversible payments for non-reversible services.*" (Nakamoto, 2008).

As mentioned elsewhere, in Bitcoin network transactions are processed directly and irreversibly settled on the blockchain every ten minutes on average. Conversely, as payment networks like VISA do allow for reversibility of transactions both systems do not offer the same type of transactions (VISA, 2019).

From a purely transactional viewpoint, final settlement transaction properties are comparable to real-time gross settlement systems (RTGS) employed by central banks to settle transactions globally. For instance, Fedwire Funds Service and CHIPS in the United States, or TARGET 2 in the European Union (Ante and Fiedler, 2021).

RTGSs provide the mechanism for central banks, financial and credit institutions to settle transactions in a final manner on an international and to provide liquidity channels for central bank loans (Allsopp et al., 2009). According to a World Bank report there are 98 different RTGSs in place, with some nations sharing the same infrastructure (Allsopp et al., 2009). From a structural perspective, RTGS like the Fedwire Funds Service host several domestic institutions such as commercial banks, thrift institutions, credit unions and foreign bank branches to finally settle transactions on one layer (Badev et al., 2021). From a structural perspective RTGSs are pyramid shaped with a central bank on top and financial intermediaries below. At the bottom, commercial banks provide access to the overarching RTGS for companies and individual customers. (Badev et al., 2021).

## **9.2. Differentiation according to security model**

Despite the similarities in the nature of the transactions, there are significant differences between the properties of a RTGS and the Bitcoin network from a network perspective which raises the question whether a focus on electricity consumption should be a sustainability determining metric in the Bitcoin network at all.

### ***Entry barriers and operation***

RTGS do not exist in an isolated manner, meaning they are subject to governance, typically by a central bank. This has profound implications with regards to accessibility. Financial institutions that wish to utilize a country specific RTGS must comply or fulfil the criteria stipulated by a central bank (The Federal Reserve, 2014). This implies that

access to a RTGS could be denied or that such a system could potentially be leveraged against other institutions by deliberately prohibiting them from access to an RTGS (Allsopp et al., 2009).

With respect to the implementation of cross border payments between nations, different time zones of country specific RTGSs pose an obstacle to interoperability and can result in significant delays (Bindseil and Pantelopoulos, 2022). Compliance and usage criteria also trickle down to the lowest layer of the RTGSs, since individuals who want to open a bank account must comply with banks' criteria in order to be granted access to their services that finally settle via superordinate systems.

Conversely, the Bitcoin network operates in a permissionless and decentralized manner. This implies there is no authority that can deny accesses. On the contrary, users themselves can perform network maintenance via engaging in the mining mechanism or operate nodes to validate network transactions. Provided that such services are used legitimately, the magnitude of the possibility for individuals who do not comply with formal criteria of established institutions, to now have an opportunity to engage in commerce or exchange value via the Bitcoin network internationally, could be transformational.

### ***Asset type settled***

RTGSs settle payments in different fiat currencies of both the payer and the payee (Bindseil and Pantelopoulos, 2022). For instance, CHIPS and the Fedwire Funds Service settle transactions in USD, whereas on TARGET2 transactions are settled in EUR. Fiat currencies in general are emitted and managed by central banks and are subject to monetary policy which is dependent on different mandates and macroeconomic developments.

The legal status of the native asset of the Bitcoin network *Bitcoin*, has been subject to debate for some time. According to the BIS, IMF, and various central banks Bitcoin does not possess the characteristics of a currency due to energy intensity, decentralized nature, and lack of guarantee of the asset by any central authority (Truby, 2018).

In more recent papers Bitcoin is classified as an "*independent third asset*", i.e., it is a uniform standard for both the payer and the payee regardless of their geographic whereabouts (Bindseil and Pantelopoulos, 2022).

### ***Security/Integrity model***

For a RTGS to be secure and viable there needs to be governance provided by a legal framework and compliance standards. For a legal framework to be sustainable, laws need to be enforceable to provide trust, reliance and refrain against abuse or illicit activities. For digital transactions cybercrime poses another attack vector against which protective measures must be built. To retain security standards an increasing number of security measures needed to be implemented in RTGSs in recent years (Bindseil and Pantelopoulos, 2022). In the Bitcoin network on the other hand, security is provided by the interplay of the principle of emerging consensus, the proof of work mechanism and the various checks nodes perform on transactions and blocks that have been described elsewhere.

Security levels of both systems can best be viewed from a ledger perspective. For a RTGS there exists only one ledger because there is only a single entity i.e., a central bank, that is responsible for its maintenance and is also entrusted with security measures. Conversely, the Bitcoin network lacks such a single authority. Despite the network being accessible, trust is not awarded to a single node from the start. To demonstrate trustworthiness and be allowed to implement changes on the blockchain, proof of work needs to be demonstrated. Like a RTGS there also needs to be one single valid ledger, because if there were multiple ledgers, transactions would not be possible. The overall lifetime of such a network would probably be relatively short as no one would trust it to safely transact with each other. To ensure continued security the proof of work needs to be done continuously for every block that is added.

Since security requirements of an underlying blockchain determine the type of consensus mechanism implemented thus energy consumption (Sedlmeir et al., 2020), it can be reasoned that the Bitcoin network optimizes for security.

### ***Confidence model***

As has been established, RTGS do not exist in an isolated manner, users need to meet the compliance criteria of the RTGS operator, and they are reliant on different currencies to be traded. However, the latter are not of equal importance and status, especially on a global scale. Precisely, a global reserve currency that is uniformly accepted around the world is endowed with greater confidence than other currencies.

Since the post WWII era this role has been assumed by the United States and the United States Dollar. There are multifold reasons why the USD is established as a trusted

currency. Contractual obligations to trade the globe's most crucial resource, crude oil, in USD, the existence of well-developed financial infrastructure and capital markets in the United States are two such reasons (Costigan et al., 2017).

To retain confidence and the stance of currency hegemony, which is associated with enormous privileges, the simultaneous existence of military hegemony seems hardly coincidental. Given these circumstances, they might reduce neutrality, even in superordinate systems as nations which issue currencies of global reserve status will have no aspirations to voluntarily relinquish this status.

A clue that a cross-border payment environment might not be founded on the principle of egalitarianism, can be demonstrated by means of the SWIFT, an international messaging tool that plays a fundamental role in communications between nations to ensure security of transactions. Despite SWIFT being an independent Belgian entity with corporate structure, it became subject to political pressure by the US administration to leverage monetary sanctions against the Iranian government in 2018 (Nabilou, 2020).

This is not to say that such actions are justified or unjustified, but simply to demonstrate that different systems can be pressured in different ways. The point is of course not that the Bitcoin network is comparable to the USD, but that both confidence models are fundamentally different both in their underlying structure and the ability to leverage it. Whereas confidence in comparable payment networks is reliant on institutions, intangible social norms and, dependent on the global relevance of the currency, even a military complex. The Bitcoin network's trust and confidence model on the other hand, is reliant on miners willing to expand energy out of their own incentives but can provide confidence neutrally and globally in a uniform manner precisely because it is not a nation.

The following figure illustrates the difficulty of energy/carbon intensity-driven comparisons of the Bitcoin network with institutions providing comparable services.

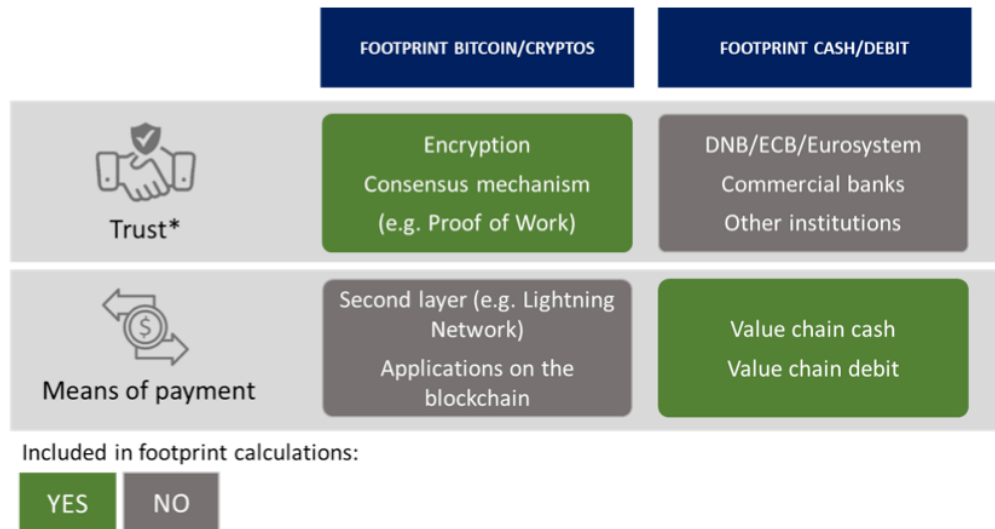


Figure 9. Transparency disequilibrium of energy/carbon footprint (Trespalacios and Dijk, 2021).

What can be deduced from this is that existing payment networks require superordinate institutions, which gain confidence from social and political norms that are hard to quantify and different in nature. Conversely, the Bitcoin network is governed by a set of algorithmic rules that enable security by requiring energy expense. Since this governing model is transparent it allows for a quantitatively evaluation of its security and trust model. If Nakamoto's whitepaper is examined, the obvious intention behind these rules is to provide trust, but not in a centralized way (Nakamoto, 2008).

As a result, the question is whether a comparison based on energy consumption is meaningful at all because both systems are fundamentally different in terms of basic concepts. Therefore, for means of comparative analysis a focus solely on energy consumption, while at the same time not incorporating the underlying drivers for that energy demand appears to be misplaced. A mere comparison, without contextualizing the parameters for which the Bitcoin network and its consensus rules try to optimize and incorporating them in a comparison, does not allow any conclusions to be drawn at all as to whether its energy consumption is too high, too low, or irrelevant altogether. Within the context of Nakamoto's consensus rules the requirements of energy expenditure can be perceived as a proxy for security, because they maximize the opportunity cost for mining nodes should they try to launch an attack on the system in a malicious manner as they are also required to expand a physical resource before an attack can be launched (Sedlmeir et al., 2020). Conversely, the opportunity costs for attacks on institutionally

backed networks will be of legal nature or, dependent on the currency status, may even be of warlike nature in an international context. However, they are hardly quantifiable.

### 9.3. Debate around proof of work and market signals

A large part of the debate around the energy consumption of the Bitcoin network is driven by forecasts about ever greater electricity consumption and environmentally damaging emissions from the network's electricity usage. A remedy that is proposed frequently is the claim that the network needed to change its consensus mechanism as the proof of work consensus mechanism is deemed to be inefficient and wasteful (Truby, 2018; Roeck and Drennen, 2022). One proposition has been the change of the network's proof of work consensus mechanism to the so-called proof of stake mechanism which is assumed to be less energy intensive (Truby 2018; Schinckus 2021; de Vries 2022).

However, it remains questionable whether a change to another consensus mechanism could be feasible for the Bitcoin network without jeopardizing its central value proposition. As shown above, the proof of work mechanism does fulfill certain key functions in the Bitcoin network. To change the network's consensus mechanism would require a "*Bitcoin Improvement Proposal*" (BIP). Alterations of the protocol, however, require coordination and agreement of all network participants, which are known for a large degree of reluctance towards substantial protocol changes (Antonopoulos, 2018). Apart from that, diversions from the proof of work consensus mechanisms are in fact possible. If a certain number of miners and nodes agree upon a fundamental change, a so-called "*Hard Fork*" can be implemented, meaning a split of the blockchain into two chains, which then operate simultaneously under different consensus mechanisms (Antonopoulos, 2018).

Ethereum the second largest cryptocurrency, according to market capitalization, is estimated to switch from the proof of work consensus to the proof of stake consensus (Sedlmeir et al., 2020). The viability of such a change could provide valuable insights and reveal potential tradeoffs to determine the future trajectory for major cryptocurrencies and potential synergies.

While an analysis of the proof of stake consensus mechanism is beyond the scope of this work, from examining the corresponding whitepaper it appears that the Ethereum network aims to innovate in a different area than the Bitcoin network (Buterin, 2014). This underscores the need to incorporate the fundamental value proposition of different solutions into comparisons to determine if comparisons are meaningful. As a result, for

comparative purposes to compare both consensus mechanisms purely based on energy consumption does not allow for any conclusion to be drawn and does not go far enough without a thorough investigation of the underlying problem a particular blockchain solution aims to solve. Rather a comparative standard based on energy consumption can only be conclusive if energy reductions can be made without jeopardizing or impairing the trust and security model of the underlying blockchain. As a result, different consensus mechanisms appear to be implemented in alignment with the area of application of different blockchains and do not represent perfect substitutes.

Furthermore, market signals appear to indicate an interest for the Bitcoin network globally which ought to be considered. According to a recent report on cryptocurrency demand compiled by the Bank of International Settlements, Bitcoin is said to dominate search engine queries for cryptocurrencies across different continents (BIS, 2022). Current market capitalization metrics also list Bitcoin as the largest cryptocurrency at ~38% percent overall market share (Coingecko.com, 2022).

## **10. Inferences and discussion**

What can be deduced from investigating different approaches around electricity consumption is that results are determined by methodologies applied. Methodologies currently suffer from assumptions and imprecise data regarding crucial inputs, for instance competitive electricity prices and different efficiency rates of ASICs employed. Subsequently this induces a large degree of uncertainty and impreciseness into estimations. Moreover, such approaches cannot incorporate individual differences across different mining and thus need to generalize assumptions. Increased research is needed to gain more knowledge and insights into procedures at mining facilities directly, ASICs employed, efficiency of operations, energy utilized and respective prices.

With regards to the energy mix of Bitcoin mining, this will be dependent on the energy mix of a given region that miners will locate at. As a result, the degree to which the network utilizes renewable energy and thus becomes increasingly environmentally sustainable, will be determined by the share of renewable energy in the overall mix.

As has been discussed extensively, the key reason for miners locating at a particular place will be the price at which electricity can be obtained. From a cost perspective, solar power and wind power have experienced significant decreases over the past decade due to expansion of capacity and technological advancements, reducing costs below cost levels

for fossil fuels or at least similar ranges (IRENA, 2021). This implies that the overall share of renewable energy in the total energy mix is most likely going to increase as grids will become more renewably driven. However, as has been discussed, renewable energy production currently still suffers from a few inefficiencies regarding supply-demand disequilibria, which result in delays and reluctance in new investments. New capacity development is also still reliant on public fund subsidies (Bastian-Pinto et al, 2021; Fridgen et al., 2021).

Although there is not sufficiently available data yet, the studies discussed above provide valuable points of reference to apply Bitcoin mining strategically to both improve the unit economics of renewable energy producers, reduce risk, and utilize renewable energy oversupply, which is expected to increase with increasing renewable energy capacity development (Bastian Pinto et al., 2021; Fridgen et al., 2021; Niaz et al., 2022). In this regard some scholars even view Bitcoin mining application as a potential catalyst for increased renewable energy capacity development (Bastian-Pinto et al., 2020).

This could not only help to reduce the carbon intensity of the energy mix employed for Bitcoin mining, but for other industries as well. If oversupply is met with additional demand by miners, prices could also dampen electricity prices for the rest of grid participants. Whether such an application is viable needs to be determined on a case-by-case basis as different facilities may have different characteristics. Moreover, potential risks need to be evaluated carefully, especially because the Bitcoin market price plays an important role as well as efficiency factors on site, mining hardware selection available, etc.

With regards to the usage of gas as an unprofitable byproduct of oil drillings and methane from landfills, increased research efforts are needed to fully determine the true potential of such applications. Methane usage by the Bitcoin mining industry currently is in an early developmental stage and there exists no credible data available yet on the total addressable market, the true emission reduction potential, or potential adverse effects. Mining with flared gas is also dependent upon various factors as discussed above. Regardless of these implications, the incentive structure to earn additional revenue with previously wasted byproducts could lead to increased interest in Bitcoin mining for energy producers as a method to reduce and even monetize previous inefficiencies. As it appears, Bitcoin mining has a potential to monetize energy directly on a global scale without the need for much additional infrastructure apart from the installation of mining

hardware and turbines. Additional areas of application for such a technology might not have been fully discovered yet.

With regards to existing literature, the need for increased research in the context of energy and environmental concerns of the Bitcoin network was also underscored by the existence of diametrically opposed statements. Whereas some scholars argue that the bitcoin network's electricity consumption "*threatens*" the earth, others claim that there is no evidence for such implications. Moreover, energy consumption appears to automatically be equated to high carbon intensity and negative environmental implications (Truby 2018; Sedlmeir et al., 2020).

However, the evolution of the Bitcoin network's energy consumption in the long term is dependent on multiple uncertain factors. For instance, how much electricity will be sold to the network and where potential synergies can improve energy markets. Furthermore, with efficiency gains of ASIC devices slowing, profit opportunities for miners will also decrease. This effect will be exacerbated by halving events, the finite Bitcoin supply and the evolution of transaction fees as a substitute for miner income.

Conclusively, future energy consumption will be a function of developments of the Bitcoin network and its adoption over time. Paradoxically, increasing prices thus increasing hash rate thus increasing energy consumption will at some point imply increased adoption levels. If wider adoption levels are the case at some point, it remains questionable whether electricity consumption remains such a controversial topic.

## 11. Policy Implications

With regards to policy approaches, the negative reputation of the Bitcoin network might pose a hindering factor to the imposition of effective policy. Some scholars have advocated regulation for energy intensive blockchains (Truby, 2018).

However, whether regulation based on energy consumption will be an effective approach is questionable since electricity is bought by miners and not taken forcefully. The main objective should of course be to adopt measures that further mitigate the carbon footprint caused by the network's computation activities. Such policies would also fit in the broader context of adhering to the objectives established in the Paris Agreement. However, policy makers are constrained by the following factors regarding regulation of the Bitcoin network.

### 1) *Lack of precise data*

Despite the above-mentioned estimations are available, methodologies of electricity consumption indexes have been criticized of being flawed and largely based on assumptions. (Truby 2018; Lei at al., 2021; BMC 2022). Since miners are globally distributed and protect their anonymity, estimates are still subject to a large degree of uncertainty regarding both devices applied, the energy mix employed and the price of electricity at mining sites. Moreover, energy mixes differ across different countries. In some jurisdictions like Iceland mining is highly driven by renewable energies, whereas in others like Kazakhstan gas or coal still constitute the major input factor (Bendiksen and Gibbons, 2019; CoinShares Research 2022).

This highlights the importance of adaptive and local policy measures.

### 2) *Peculiarities of the mining industry*

Despite the network constituting comparatively minuscule shares of carbon emissions, a ban of the industry, access to the network in a particular jurisdiction or excessive taxation resulting in a quasi-indirect ban, might seem to be a straightforward measure if policy makers were concerned about the network's environmental impacts.

However, different policy makers and jurisdictions do not perceive the Bitcoin network and the mining industry all in the same manner. On the contrary, some

jurisdictions welcome the network and the mining industry (Alvarez et al., 2022). Subsequently, political cooperation on a global level to implement a direct ban of the mining industry or an indirect ban by means of excessive taxation seems unrealistic. The global accessibility of the network, comparatively low entry barriers of the mining market introduce a policy arbitrage opportunity. As miners are globally mobile and primarily driven by price signals of cheap electricity, they will relocate their operations to a jurisdiction that might not be hostile towards them, as was observable after the mining ban in China.

Bans could hypothetically be implemented after mining operations have been established for some period of time, however, electricity grids where miners were already integrated well will likely not have an incentive to lose a buyer that can improve their profitability.

### 3) *Opportunity cost*

With regards to excessive taxation, it has been acknowledged that such policies might negatively impact the greater blockchain industry in a certain jurisdiction. Since the industry is comparatively young, innovation is ongoing, and the full potential of applicability is not yet evident in all areas of application. This could negatively impact economic growth and most likely have a stifling effect on innovation and competitiveness of comparatively unfriendlier jurisdictions (Truby, 2018).

There is opportunity cost associated with such policies as the Bitcoin network already incorporates a larger industry and already has ties with the energy industry in some jurisdictions. Apart from that, mining hardware manufacturers, software developers, companies implementing blockchain applications and talent could transition to jurisdictions that provide more favorable treatment, thus also arbitrage hostile policy.

As a result, policy makers need to be aware of potential market signals they might send by imposing regulation. If comparatively new industry sectors are heavily taxed or banned in a particular jurisdiction, this will likely negatively impact capital allocation and financial flows to this jurisdiction. Moreover, as governments seek to maximize tax revenue, some of this will be foregone if the industry is forced to move away and develops in other jurisdictions.

#### 4) *Rebound effects*

Opportunity costs do not merely have to be incurred economically, but also environmentally. As de Vries et al. (2022) have assumed, the share of renewable energy sources in the bitcoin network's overall energy mix has decreased after the mining industry was officially banned from China. Hence from an environmental perspective policy makers ought to consider such potential adverse effects. As some public Bitcoin mining companies are already committed to an environmentally sustainable approach via renewable energy usage, policy makers need to be aware of already existing synergies between mining companies, energy providers and grid operators and consider potential opportunity cost of terminating such relationships (Hut 8 Mining, 2022, Iris Energy 2022, Bitfarms, 2022).

#### 5) *Market dynamics*

As has been discussed above, the electricity consumption of the network is not only hard to estimate, but also not predictable in the long term and inherently depended on market dynamics, which can change rapidly and are not forecastable. Policy makers need to be aware of distinct market dynamics and network peculiarities, especially regarding the impact of block reward bisections and its impact on energy consumption due to changed profit opportunities for miners.

To summarize, policy makers are faced with some peculiarities when it comes to regulation of the mining industry and the Bitcoin network. A ban of Bitcoin mining is conceivable; however, such a ban can likely only be implemented locally and will merely shift mining operations to a more favorable jurisdiction. Since 21% of the global hash rate are estimated to originate from China still, this casts doubt on effectiveness of bans overall (CCAF, 2022). On the other hand, the peculiarities of the industry could provide policy makers with the opportunity to direct miners with targeted incentives to where integration can be most beneficial in terms of renewable capacity development. However, an integrative strategy might primarily be pursued to nations adhering to the principles of liberal democracy and free market economics.

Such an approach can be implemented congruently with the Paris Agreement, precisely with the "*principle of common but differentiated responsibilities*", stipulated in Art. 2(2)

that will consider a country-specific energy mix and requires countries to take approaches according to their own unique capabilities (Paris Agreement, 2015).

### **11.1. Approaches for integrating the mining industry in an environmentally sustainable manner**

#### *Increased research*

Firstly, policy makers need to foster and encourage new research on the topic. Currently, the literature available on the topic is a mixture of scarce academic literature that is both peer reviewed and non-peer reviewed. Reports and papers by industry affiliated companies are also available, but ought to be read with caution as results might suffer from underlying conflicted interests. Moreover, there needs to be clarity that different blockchain solutions optimize for different parameters, hence provide different fields of applications and are not merely substitutable.

Secondly, policies generally ought to foster increased efficiency and decarbonization of electricity usage from an environmental point of view (Belke et al., 2011). As has been discussed above, the competitive economic dynamics of the mining process have been incentivizing an ongoing automatic shift towards more efficient mining hardware as better efficiency optimized hash power and this profitability. Decarbonization of the Bitcoin network will be the best starting point for policy makers.

However, this will be a function of efforts to decarbonize electricity production, which is the cause of carbon emissions (Roeck and Drennen, 2022).

#### *Interdisciplinary discourse and identification of best potential fields of application*

Policy makers need to be aware of the Bitcoin mining industry and understand its dynamics and potential regarding renewable energy development and emission mitigation.

Climate scientists, mining companies, grid operators and energy producers therefore ought to be involved in a dialogue to determine on a case-by-case basis where a potential implementation of mining can positively foster new investments in renewable capacity developments. Such an approach has the potential to be effective because it can align the incentives of all parties involved. As renewable

energy producers could reduce oversupplies and improve profitability of their investments, this could ease pressure on the need to publicly subsidize expansion of renewable energy sources.

According to the United Nations Sustainable Development Goals Report 2022, on SDG 7 a slowdown of investments made in renewable energy expansion, particularly in developing countries, has been recognizable since 2019. Moreover, the report posits: “*Effective climate action will require strengthening policy support in all sectors and implementing effective tools to further mobilize private capital, particularly for developing countries.*” (United Nations, 2022).

Within the efforts to decarbonize the electricity sector, Bitcoin mining ought to be considered as a potentially “*effective tool*” to foster expansion of renewable energy. Naturally, there will not be a “one-size fits all” approach, but policy makers ought to detect potential application areas. Contractual obligations between miners and grid providers, for instance at the example of Texas, can serve as a best practice example how miners can be incorporated into the grid responsibly as a demand response entity that provides flexibility during high demand periods. Moreover, welcoming the mining industry with more favorable policy could provide more accurate data about industry metrics.

Lastly, the utilization of uneconomic byproducts of oil drillings and landfill gases provide concepts to be further investigated. On a global scale it is assumed that 688 TWh of flared gas could be recovered for electricity consumption. At current levels, this amount of electrical energy could supply the Bitcoin network 7.4 times (CCAF, 2022).

For purposes of identifying mitigation potential of such applications, Art. 9 (2) (c) of the United Nations Framework Convention on Climate Change (UNFCCC), whose principles are incorporated into the Paris Agreement, also provides adequate guidance how new technologies shall be identified and implemented in an environmentally sustainable manner. (UNFCCC, 1992).

#### *Mitigate risks and adverse effects*

Potential negative externalities need to be considered as well, as the introduction of Bitcoin mining was also found to improve the economics of fossil fuel driven energy plants (Roeck and Drennen, 2022).

However, like other industries miners must of course comply, with the specified environmental regulations in a particular jurisdiction, if applicable However, as facilities and applications will differ, location-specific life cycle assessments can provide an apt tool to tailor mining capacities to a certain facility with minimal environmental impact.

On the other hand, the price of Bitcoin has historically been subject to volatility. Therefore, if mining is being integrated as a supplement to energy plants, potential price evolvment scenarios need to be modeled to hedge against price declines.

## 12. Conclusion

In conclusion, what can be stated is that electricity consumption levels of Bitcoin mining do not provide an insightful metric for policy decision if viewed in an isolated manner. As has been discussed, comparisons of the network with other networks that provide similar services are also not well suited to classify the energy consumption by order of magnitude due to its decentralized security and confidence concept.

Regarding comparative analysis, whether energy consumption provides an apt metric for blockchain technology in general is questionable since centralized IT solutions are probably less energy intensive regardless of the consensus mechanism applied. The fundamental promise of this industry sector seems to decentralize centralized trust and security models to mitigate human error and make applications more robust. Energy consumption as a metric appears to have been transferred into the field of blockchain technology to determine which solution might be more environmentally sustainable than others. However, it seems to be generally assumed that all solutions aim for the same objective and will optimize for the same metric. Moreover, it appears to be assumed that electricity consumption automatically implies environmental damage. The latter being rather a function of electricity production. Evidently such assumptions are oversimplistic, lack context and assume that tradeoffs are nonexistent. Moreover, the central problem with the argument that the electricity usage of the network is wasteful, is that such claims are not falsifiable. This is of course dependent on an individual's perception and valuation of the services the network offers.

On a global scale the electricity consumption of the Bitcoin network at current levels is comparatively miniscule. Future consumption is constrained by the network's architecture and physical conditions and will be dependent on future adoption. The perception of this consumption as being problematic will likely be a function of the latter.

## References

- Allsopp P., Summers B., and Veale J., 2009. The Evolution of Real-Time Gross Settlement: Access, Liquidity and Credit, and Pricing. *The World Bank Financial Infrastructure Series: Payment Systems Policy and Research*. Retrieved from: <https://documents1.worldbank.org/curated/en/736521468331852042/pdf/490020WP0THeEv10Box338937B01PUBLIC1.pdf>
- Alqassem I., and Svetinovic D., 2014. Towards Reference Architecture for Cryptocurrencies: Bitcoin Architectural Analysis. *2014 IEEE International Conference on Internet of Things (iThings), and IEEE Green Computing and Communications (GreenCom) and IEEE Cyber, Physical and Social Computing (CPSCom)*, 436-443. Retrieved from: <https://doi.org/10.1109/iThings.2014.78>
- Alvarez F. E., Argente D., Van Patten., 2022. Are cryptocurrencies currencies? Bitcoin as legal tender in El Salvador. National Bureau of Economic Research: Working Paper 29968. Retrieved from: <https://doi.org/10.3386/w29968>
- Ammous S., 2018. Can cryptocurrencies fulfil the functions of money? *The Quarterly Review of Economics and Finance*, 70, 38-51. Retrieved from: <https://doi.org/10.1016/j.qref.2018.05.010>
- Ammous S., 2019. Blockchain Technology: What is it good for? *Banking & Finance Law Review*, 34 (2), 239-251. Retrieved from: <https://www.proquest.com/scholarly-journals/blockchain-technology-what-is-good/docview/2207838734/se-2?accountid=39579>
- Ante L. and Fiedler I., 2021. Bitcoin's Energy Consumption and Social Costs in Relation to its Capacity as a Settlement Layer. *BRL Working Paper Series No.23*. Retrieved from: <https://dx.doi.org/10.2139/ssrn.3910778>
- Antonopoulos A., 2018. *Bitcoin & Blockchain: Grundlagen und Programmierung: die Blockchain verstehen, Anwendungen entwickeln*. 2nd ed. Heidelberg, dpunkt.verlag GmbH
- Antonopoulos A. M., Osuntokun O., and Pickhardt R., 2021. Mastering the Lightning Network: A Second Layer Blockchain Protocol for Instant Bitcoin Payments. Sebastopol, California: O'Reilly Media Inc.
- Badev A., Clark L., Ebanks D., Marquardt J., and Mills D., 2021. Fedwire Funds Service: Payments, Balances, and Available Liquidity. Finance and Economics Discussion Series 2021-070. Washington: Board of Governors of the Federal Reserve System. Retrieved from: <https://doi.org/10.17016/FEDS.2021.070>
- Bank of International Settlements., 2022. Banking in the shadow of Bitcoin? The institutional adoption of cryptocurrencies. *BIS Working Papers No 1013*. Monetary and Economic Department. Retrieved from: <https://www.bis.org/publ/work1013.pdf>

Bastian-Pinto C. L., V. de S. Araujo F., Brandao L. E., Gomes L. L., 2021. Hedging renewable energy investments with Bitcoin mining. *Renewable and Sustainable Energy Reviews*, 138. Retrieved from: <https://doi.org/10.1016/j.rser.2020.110520>

Belke A., Dobnik F., and Dreger C., 2011. Energy consumption and economic growth: New insights into the cointegration relationship. *Energy Economics*, 33 (5), 782-789. Retrieved from: <https://doi.org/10.1016/j.eneco.2011.02.005>

Bendiksen C. and Gibbons S., 2019. The Bitcoin Mining Network: Trends, Average Creation Costs, Electricity Consumption & Sources. *CoinShares Research, December 2019 Update*. Available from: <https://coinshares.com/assets/resources/Research/bitcoin-mining-network-december-2019.pdf>

Bindseil U., and Pantelopoulos G., 2022. Towards the holy grail of cross-border payments. *European Central Bank Working Paper Series*, No 2693, August 2022. Retrieved from: <https://www.ecb.europa.eu/pub/pdf/scpwps/ecb.wp2693~8d4e580438.en.pdf>

Bitcoin Mining Council., 2022. Global Bitcoin Mining Data Review Q2 2022. [Accessed 22 August]. Available from: <https://bitcoinminingcouncil.com/wp-content/uploads/2022/07/2022.07.19-BMC-Presentation-Q2-22-Presentation.pdf>

Bitfarms., 2022. Environmental, Social and Governance. [Accessed 19 September 2022]. Available from: <https://bitfarms.com/investors/esg>

Blandin A., Pieters G., Wu Y., Eisermann T., Dek A., Taylor S., and Njoki D., 2020. 2020 CCAF 3<sup>rd</sup> Global Cryptoasset Benchmarking Study. *SSRN Electronic Journal*. Retrieved from: <https://dx.doi.org/10.2139/ssrn.3700822>

Blockchain.com., 2022. Bitcoin Total Hash Rate. [Accessed 12 August 2022]. Available from: <https://www.blockchain.com/charts/hash-rate>

Blockchain.com., 2022. Bitcoin Total Hash Rate. [Accessed 3 October 2022]. Available from: <https://www.blockchain.com/charts/hash-rate>

BTC.com., 2022. Mining Profit Estimate. [Accessed 3 August 2022]. Available from: <https://pool.btc.com>

Böhme R., Christin N., Edelman B., Moore T., 2015. Bitcoin: Economics, Technology and Governance. *Journal of Economic Perspectives*, 29 (2), 213-238. Retrieved from: <http://dx.doi.org/10.1257/jep.29.2.213>

Brühl V., 2017. Bitcoins, Blockchain Und Distributed Ledgers. *Wirtschaftsdienst*, 97 (2), Springer. Retrieved from: <https://doi.org/10.1007/s10273-017-2096-3>.

Buterin V., 2014. Ethereum: A Next-Generation Smart Contract and Decentralized Application Platform. [Accessed 10 September 2022]. Available from: [https://ethereum.org/669c9e2e2027310b6b3cdce6e1c52962/Ethereum\\_Whitepaper\\_-\\_Buterin\\_2014.pdf](https://ethereum.org/669c9e2e2027310b6b3cdce6e1c52962/Ethereum_Whitepaper_-_Buterin_2014.pdf)

Cambridge Center for Alternative Finance: Cambridge Bitcoin Electricity Consumption Index., 2022. [Accessed 10 August 2022]. Available from: <https://ccaf.io/cbeci/index>

Cambridge Center for Alternative Finance: Cambridge Bitcoin Electricity Consumption Index: Comparisons, 2022. [Accessed 24 August 2022]. Available from: <https://ccaf.io/cbeci/index/comparisons>

Cambridge Center for Alternative Finance: Cambridge Bitcoin Electricity Consumption Index: Methodology, 2022. [Accessed 20 July 2022]. Available from: <https://ccaf.io/cbeci/index/methodology>

Cambridge Center for Alternative Finance: Cambridge Bitcoin Electricity Consumption Index: Mining Map, 2022. [Accessed 20 July 2022]. Available from: [https://ccaf.io/cbeci/mining\\_map](https://ccaf.io/cbeci/mining_map)

Carter N., and Stevens R., 2021. NYDIG: Bitcoin Net Zero. [Accessed 11 September 2022]. Available from: [https://assets.website-files.com/614e11526f6630959fc98679/616df63a27a7ec339f5e6a80\\_NYDIG-BitcoinNetZero\\_SML.pdf](https://assets.website-files.com/614e11526f6630959fc98679/616df63a27a7ec339f5e6a80_NYDIG-BitcoinNetZero_SML.pdf)

Coingecko.com., 2022. Global Cryptocurrency Market Cap Charts [Accessed 3 October 2022]. Available from: <https://www.coingecko.com/en/global-charts>

CoinMarketCap.com., 2022. Bitcoin Halving Countdown. [Accessed 30 June 2022]. Available from: <https://coinmarketcap.com/halving/bitcoin/>

CoinMarketCap.com., 2022. Bitcoin to USD chart. [Accessed 30 June 2022]. Available from: <https://coinmarketcap.com/currencies/bitcoin/>

Coinshares.com., 2022. The Bitcoin Mining Network: Energy and Carbon Impact. [Accessed 12 September 2022]. Available from: <https://coinshares.com/research/bitcoin-mining-network-2022>

Costigan T., Cottle D., and Keys A., 2017. The US Dollar as the Global Reserve Currency: Implications for US Hegemony. *World Review of Political Economy*, 8 (1), 104-122. Retrieved from: <https://doi.org/10.13169/worlrevipoliecon.8.1.0104>

Crusoeenergy., 2022. Digital Flare Mitigation®. [Accessed 27 August 2022]. Available from: <https://www.crusoeenergy.com/digital-flare-mitigation#progress-graph>

Cuthbertson A., 2017. Bitcoin mining on Track to Consume All of the World's Energy by 2020. *Newsweek*, 12/11/17. Available from: <https://www.newsweek.com/bitcoin-mining-track-consume-worlds-energy-2020-744036>

Delgado-Mohatar O., Felis-Rota M., Fernández-Herraiz C., 2019. The Bitcoin mining breakdown: Is mining still profitable? *Economic Letters*, 184, Retrieved from: <https://doi.org/10.1016/j.econlet.2019.05.044>

De Vries A., 2020. Bitcoin's energy consumption is underestimated: A market dynamics approach. *Energy Research & Social Science*, 70. Retrieved from: <https://doi.org/10.1016/j.erss.2020.101721>

De Vries A., Gellersdörfer U., Klaaßen L., and Stoll C., 2022. Revisiting Bitcoin's carbon footprint. *Joule*, 6, 495-502. Retrieved from: <https://doi.org/10.1016/j.joule.2022.02.005>

De Vries A., and Stoll C., 2021. Bitcoin's growing e-waste problem. *Resources, Conservation and Recycling*, 175. Retrieved from: <https://doi.org/10.1016/j.resconrec.2021.105901>

Digiconomist., 2022. Bitcoin Energy Consumption Index. [Accessed 4 August 2022]. Available from: <https://digiconomist.net/bitcoin-energy-consumption>

Dincer I., 2000. Renewable energy and sustainable development: a crucial review. *Renewable and Sustainable Energy Reviews*, 4 (2), 157-175. Retrieved from: [https://doi.org/10.1016/S1364-0321\(99\)00011-8](https://doi.org/10.1016/S1364-0321(99)00011-8)

Fridgen G., Körner M-F., Walters S., and Weibelzahl M., 2021. Not All Doom and Gloom: How Energy-Intensive and Temporally Flexible Data Center Applications May Actually Promote Renewable Energy Sources. *Business & Information Systems Engineering*, 63, 243-256. Retrieved from: <https://doi.org/10.1007/s12599-021-00686-z>

Hut 8 Mining., 2022. Thinking bigger: 2021 Environmental, Social & Governance Report. [Accessed 19 September 2022]. Available from: [https://hut8mining.com/wp-content/uploads/2022/05/HUT-8\\_2021-ESG-Report\\_5-10-2022.pdf](https://hut8mining.com/wp-content/uploads/2022/05/HUT-8_2021-ESG-Report_5-10-2022.pdf)

International Renewable Energy Agency (IRENA)., 2021. Renewable Power Generation Costs in 2021. [Accessed 12 September 2022] Available from: [https://irena.org/-/media/Files/IRENA/Agency/Publication/2022/Jul/IRENA\\_Renewable\\_Power\\_Generation\\_Costs\\_2021.pdf](https://irena.org/-/media/Files/IRENA/Agency/Publication/2022/Jul/IRENA_Renewable_Power_Generation_Costs_2021.pdf)

Iris Energy., 2022. ESG. [Accessed 19 September]. Available from: <https://irisenergy.co/esg/>

Kavanagh R., Hash rate: A measure of the computing power on a cryptocurrency network that is a key security indicator. 2022. [Accessed 4 July 2022]. Available from: <https://www.businessinsider.com/personal-finance/hash-rate>

Kristoufek L., 2020. Bitcoin and its mining on the equilibrium path. *Energy Economics*, 85. Retrieved from: <https://doi.org/10.1016/j.eneco.2019.104588>

Kroll J. A., Davey I. C., Felten E. W., 2013. The Economics of Bitcoin Mining or Bitcoin in the Presence of Adversaries. *The Twelfth Workshop on the Economics of Information Security (WEIS 2013)*. Washington, DC, June 11-12, 2013. Available from: <https://asset-pdf.scinapse.io/prod/2188530018/2188530018.pdf>

Küfeoğlu S., and Özkuran M., 2019. Bitcoin mining: A global review of energy and power demand. *Energy Research & Social Science*, 58, 1-12. Retrieved from: <https://doi.org/10.1016/j.erss.2019.101273>

Lei N., Masanet E.Y., and Koomey J., 2021. Best practices for analyzing the direct energy use of blockchain technology systems: Review and policy recommendations. *Energy Policy*, 156. Retrieved from: <https://doi.org/10.1016/j.enpol.2021.112422>

Masanet E., Shehabi A., Lei N., Vranken H., Koomey J., and Malmudin J., 2019. Implausible projections overestimate near-term Bitcoin CO<sub>2</sub> emissions. *Nature Climate Change*, 9, 653-654. Retrieved from: <https://doi.org/10.1038/s41558-019-0535-4>

Meiklejohn S., Pomarole M., Jordan G., Levchenko K., McCoy D., Voelker G. M., & Savage, S. 2013. A fistful of bitcoins: characterizing payments among men with no names. In Proceedings of the 2013 conference on Internet measurement conference (pp. 127-140). Retrieved from: <http://dx.doi.org/10.1145/2504730.250474>

Mellerud J., and Helseth A., 2022. How Bitcoin Mining can transform the Energy Industry. *Arcane Research, September 2022*. [Accessed 22 September 2022]. Available from: <https://arcane.no/research/how-bitcoin-mining-can-transform-the-energy-industry-summary>

Mora C., Rollins R.L., Taladay K., Kantar M. B., Chok M. K., Shimada M., and Franklin E.C., 2018. Bitcoin emissions alone could push global warming above 2°C. *Nature Climate Change*, 8, 931-933. Retrieved from: <https://doi.org/10.1038/s41558-018-0321-8>.

Nabilou H., 2020. Bitcoin Governance as a Decentralized Financial Market Infrastructure. Retrieved from: <https://dx.doi.org/10.2139/ssrn.3555042>

Nakamoto S., 2008. Bitcoin: A Peer-to-Peer Electronic Cash System. Available from: <https://bitcoin.org/bitcoin.pdf>

Nezhadfar M., and Khalili-Garakani A., 2020. Power generation as useful option for flare gas recovery: Enviro-economic evaluation of different scenarios. *Energy*, 204. Retrieved from: <https://doi.org/10.1016/j.energy.2020.117940>

Niaz H., Liu J. J., and Fengqi Y., 2022. Can Texas mitigate wind and solar curtailments by leveraging bitcoin mining? *Journal of Cleaner Production*, 364. Retrieved from: <https://doi.org/10.1016/j.jclepro.2022.132700>

O'Dwyer K. J., and Malone D., 2014. Bitcoin Mining and its Energy Footprint. *ISSC 2014/CICT 2014*. Retrieved from: <https://mural.maynoothuniversity.ie/6009/1/DM-Bitcoin.pdf>

Pan D., 2022. Bitcoin Miners Shut as Texas Power Grid Nears Brink. [Accessed 24 August]. Available from: <https://www.bloomberg.com/news/articles/2022-07-11/bitcoin-miners-shut-off-rigs-as-texas-power-grid-nears-brink>

Paris Agreement., 2015. [Accessed 21 June 2022]. Retrieved from: [https://unfccc.int/sites/default/files/english\\_paris\\_agreement.pdf](https://unfccc.int/sites/default/files/english_paris_agreement.pdf)

Phan T., 2022. Methane Is a Big Climate Problem That Bitcoin Can Help Solve. [Accessed 27 August 2022]. Available from: [https://www.washingtonpost.com/business/energy/methane-is-a-big-climate-problem-that-bitcoin-can-help-solve/2022/05/03/bf9eaf48-cae1-11ec-b7ee-74f09d827ca6\\_story.html](https://www.washingtonpost.com/business/energy/methane-is-a-big-climate-problem-that-bitcoin-can-help-solve/2022/05/03/bf9eaf48-cae1-11ec-b7ee-74f09d827ca6_story.html)

Roeck M., and Drennen T., 2022. Life cycle assessment of behind-the-meter Bitcoin mining at US power plant. *The International Journal of Life Cycle Assessment*, 27, 355-365. Retrieved from: <https://doi.org/10.1007/s11367-022-02025-0>

Rybarczyk R., Armstrong D., and Fabiano A., 2021. On Bitcoin's Energy Consumption: A Quantitative Approach to a Subjective Question. *Galaxy Digital*, May 2021. Available form: <https://docsend.com/view/adwmdeeyfvqwecj2>

Sandner P., 2020. The Green Bitcoin Theory: How are Bitcoin Electricity Consumption and Green Energy Related? [Accessed 23 August]. Available from: <https://philippsandner.medium.com/the-green-bitcoin-theory-how-are-bitcoin-electricity-consumption-and-green-energy-related-b541b23424ab>

Schinckus C., 2021. Proof-of-work based blockchain technology and Anthropocene: An undermined situation? *Renewable and Sustainable Energy Reviews*, 152. Retrieved from: <https://doi.org/10.1016/j.rser.2021.111682>

Sedlmeir J., Buhl H. U., Fridgen G., and Robert Keller., 2020. Ein Blick auf aktuelle Entwicklungen bei Blockchains und deren Auswirkungen auf den Energieverbrauch. *Informatik Spektrum*, 43, 391-404. Retrieved from: <https://doi.org/10.1007/s00287-020-01321-z>

Sedlmeir J., Buhl H. U., Fridgen G., and Keller R., 2020. The Energy Consumption of Blockchain Technology: Beyond Myth. *Business & Information Systems Engineering*, 62, 599-608. Retrieved from: <https://doi.org/10.1007/s12599-020-00656-x>

Snytnikov P., and Potemkin D., 2022. Flare gas monetization and greener hydrogen production via combination with cryptocurrency mining and carbon dioxide capture. *iScience*, 25 (2). Retrieved from: <https://doi.org/10.1016/j.isci.2022.103769>

Sowell T., 2015. *Basic Economics: A Common Sense Guide to the Economy*. Fifth Edition, New York, New York: Basic Books, a member of the Perseus Books Group.

Steinmetz F., Lennart A., and Fiedler I., 2020. *Blockchain and the digital economy: The socio-economic impact of blockchain technology*. Newcastle upon Tyne: Agenda Publishing Limited.

Stoll C., Klaaßen L., Gallersdörfer U., 2019. The Carbon Footprint of Bitcoin. *Joule*, 3 (7), 1647-1661. Retrieved from: <https://doi.org/10.1016/j.joule.2019.05.012>

Szmigielski A., 2016. *Bitcoin Essentials: Gain insights into Bitcoin, a cryptocurrency and a powerful technology, to optimize your Bitcoin mining techniques*. 1<sup>st</sup> ed. Birmingham, UK: Packt Publishing Ltd.

The Federal Reserve., 2014. The Fedwire® Funds Service: Assessment of Compliance with the Core Principles for Systematically Important Payment Systems. [Accessed 27 September 2022] Retrieved from:  
[https://www.federalreserve.gov/paymentsystems/files/fedfunds\\_coreprinciples.pdf](https://www.federalreserve.gov/paymentsystems/files/fedfunds_coreprinciples.pdf)

The World Commission on Environment and Development, 1987. Report of the World Commission on Environment and Development: Our Common Future. Retrieved from:  
<http://www.un-documents.net/our-common-future.pdf>

Truby J., 2018. Decarbonizing Bitcoin: Law and policy choices for reducing the energy consumption of Blockchain technologies and digital currencies. *Energy Research & Social Science*, 44, 399-410. Retrieved from: <https://doi.org/10.1016/j.erss.2018.06.009>

Trespalacios J.P. and Dijk J., 2021. The carbon footprint of bitcoin. Retrieved from:  
<https://www.dnb.nl/media/1ftd2xjl/the-carbon-footprint-of-bitcoin.pdf>

United Nations Framework Convention on Climate Change., 1992. New York 9 May 1992. [Accessed 27 September 2022]. Retrieved from:  
<https://unfccc.int/resource/docs/convkp/conveng.pdf>

United Nations., 2022. The Sustainable Development Goals Report 2022. [Accessed 18 September 2022]. Available from: <https://unstats.un.org/sdgs/report/2022/The-Sustainable-Development-Goals-Report-2022.pdf>

United Nations., 2015. Transforming Our World: The 2030 Agenda For Sustainable development. *A/Res/70/1*. Retrieved from:  
<https://sdgs.un.org/sites/default/files/publications/21252030%20Agenda%20for%20Sustainable%20Development%20web.pdf>

Vaughan C., Samaties P., Kemp B. and Sanaulla F., 2022. Implications of the crypto economy for the electric system. [Accessed 23 August]. Available from:  
<https://www.rolandberger.com/en/Insights/Publications/How-crypto-mining-will-transform-the-energy-industry.html>

Vazquez J., and Crumbley D. J., 2022. Flared Gas Can Reduce Some Risks in Crypto Mining as Well as Oil and Gas Operations. *Risks*, 10 (6), 127. Retrieved from:  
<https://doi.org/10.3390/risks10060127>

Vespeneenergy., 2022. Fueling the transition to a renewable energy future. [Accessed 28 August 2022]. Available from: <https://vespene.energy>

VISA., 2019. Authorization Reversals: The importance of providing the correct information. [Accessed 26 August]. Available from:  
<https://usa.visa.com/dam/VCOM/download/merchants/authorization-reversals.pdf>

Vranken H., 2017. Sustainability of bitcoin and blockchains. *Current Opinion in Environmental Sustainability*, 28, 1-9. Retrieved from:  
<https://doi.org/10.1016/j.cosust.2017.04.011>

Zheng Z., Xie S., Dai H., Chen X., and Wang H., 2017. An Overview of Blockchain Technology: Architecture, Consensus, and Future Trends. *2017 IEEE International Congress on Big Data (BigData Congress), 2017*, pp. 557-564. Retrieved from:  
<https://doi.org/10.1109/BigDataCongress.2017.85>

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