



**HAL**  
open science

# **A comprehensive research framework for Bitcoin's energy use: Fundamentals, economic rationale, and a pinch of thermodynamics**

Horst Treiblmaier

## **► To cite this version:**

Horst Treiblmaier. A comprehensive research framework for Bitcoin's energy use: Fundamentals, economic rationale, and a pinch of thermodynamics. *Blockchain: Research and Applications*, 2023, 4 (3), pp.100149. <10.1016/j.bcr.2023.100149>. <hal-04403221>

**HAL Id: hal-04403221**

**<https://hal.science/hal-04403221v1>**

Submitted on 18 Jan 2024

**HAL** is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.



HAL Authorization

Contents lists available at [ScienceDirect](https://www.sciencedirect.com)

# Blockchain: Research and Applications

journal homepage: [www.journals.elsevier.com/blockchain-research-and-applications](http://www.journals.elsevier.com/blockchain-research-and-applications)

Research Article

## A comprehensive research framework for Bitcoin's energy use: Fundamentals, economic rationale, and a pinch of thermodynamics

Horst Treiblmaier

School of International Management, Modul University Vienna, 1190, Vienna, Austria

### ARTICLE INFO

#### Keywords:

Bitcoin  
Energy  
Energy use  
Energy consumption  
Proof of work  
Sustainability

### ABSTRACT

The energy use of Bitcoin is fiercely debated among academics, practitioners, and the general public. This debate is often biased and characterized by a lack of understanding. Therefore, I start this paper with a discussion of the fundamentals of Bitcoin, which includes the clarification of widely held misconceptions. Next, I illustrate how Bitcoin is related to energy and describe the underlying incentive mechanism. In the main body of the paper, I discuss various components of Bitcoin's energy use, including the amount, composition, and geographical distribution of the energy, as well as emerging positive and negative effects. These components are then combined into a comprehensive framework that provides a solid foundation for future academic research and presents practitioners with the big picture of how and why Bitcoin requires energy and whether this can be justified from an environmental point of view.

"... time is money"

(Benjamin Franklin)

"energy is money"

(author's educated guess about the original intention of Bitcoin)

### 1. Introduction

The amount of energy that is needed to create and maintain the Bitcoin blockchain has long captured the attention of academia and mainstream media. In particular, the latter gained public attention by using pointed headlines referring to the "voracious appetite" of Bitcoin or the "eye-watering amounts of power" needed to create the cryptocurrency [1]. Huang et al. [2] proclaimed that "the system wastes energy by design", and Jiang et al. [3] (p.1) even warned that "the growing energy consumption and associated carbon emission of Bitcoin mining could potentially undermine global sustainable efforts". Recently, Greenpeace launched an initiative titled "Change the Code - Not the Climate", pointing out that "switching to a low-energy protocol (i.e., Proof of Stake (PoS)) has proven effective and uses a fraction of the energy" [4]. At the

end of 2022, Bindseil and Schaff [5] from the European Central Bank announced "Bitcoin's last stand", writing that its recent volatility is "an artificially induced last gasp before the road to irrelevance".<sup>1</sup>

A more nuanced view comes from the United Nations [6], which contrasts statements referring to the Bitcoin network as a "pointless way of using energy" (citing WWW inventor Tim Berners-Lee) and blockchain's general potential to serve as "an important driver of sustainable development". Given its paramount importance, the topic has also drawn the attention of national decision-making bodies. In the U.S., for example, the Biden administration is searching for solutions to reduce the energy consumption of cryptocurrency mining [7]. Across the Atlantic, the European Parliament's Economic Affairs Committee decided on the Markets in Crypto Assets (MiCA) framework (i.e., the EU's legislation concerning digital assets) in March 2022, voting down a last-minute addition that strived to limit cryptocurrencies using Proof of Work (PoW) as a method to reach network consensus [8]. To date, the most restrictive measures have been taken by China, a former leader in cryptocurrency mining, and eight other countries that have banned cryptocurrencies outright [9], although not all of these decisions were solely based on the question of energy consumption.

Then, again, advocates of Bitcoin, or cryptocurrencies and distributed

E-mail address: [horst.treiblmaier@modul.ac.at](mailto:horst.treiblmaier@modul.ac.at).

<sup>1</sup> The webpage <https://99bitcoins.com/bitcoin-obituaries/> collects so-called Bitcoin obituaries that declare that Bitcoin is or will be worthless. Between 2010 and June 2023, 474 "official" obituaries have been collected, including this one.

<https://doi.org/10.1016/j.bcr.2023.100149>

Received 9 September 2022; Received in revised form 5 May 2023; Accepted 27 June 2023

2096-7209/© 2023 The Authors. Published by Elsevier B.V. on behalf of Zhejiang University Press. This is an open access article under the CC BY-NC-ND license (<http://creativecommons.org/licenses/by-nc-nd/4.0/>).

ledgers in general, have continually claimed that Bitcoin's energy use and its negative impacts are mostly exaggerated [10] or even that Bitcoin mining benefits the environment, for example, by accelerating the shift toward renewable resources [11]. In this regard, the Bitcoin Mining Council [12] stated that Bitcoin mining "uses an inconsequential amount of energy" and emphasized that "it is powered by a higher mix of sustainable energy than any major country or industry".

This ongoing debate juxtaposes positions on Bitcoin as either an environmental disaster or an environmental advantage, yet it is sometimes obfuscated by a lack of knowledge as well as inaccurate data. The environment-related interest generated by cryptocurrencies in general was illustrated by Wang et al. [13] index of cryptocurrency environmental attention (ICEA), which not only shows the growing interest in the subject matter but also reveals which major events are likely to attract public attention. Numerous mostly descriptive articles have been published on the subject matter, and the vast majority of them take one dedicated position, either for or against Bitcoin. The reported figures on energy use can regularly be traced back to a relatively small number of sources, and the same arguments are repeated over and over again. These arguments frequently diffuse unfiltered into more applied and management-oriented research, some of which is characterized by an insufficient understanding of the inner workings of Bitcoin. A recent and comprehensive assessment of the extant research on the energy and environmental footprint of cryptocurrencies (mostly Bitcoin and Ethereum prior to its switch to PoS) comes from Sai and Vranken [14], who scrutinized the methods and models applied to assess the energy use and the environmental footprint. Of the 244 articles they investigated, 34% (44) fail to include an explicit research design, 43% (53) do not share data, 67% (85) omit the source code, and 79% (101) fail to discuss the reliability of the external data they used. The authors concluded that there is a widespread lack of rigor in current research, which makes estimates and predictions questionable.

My motivation for writing this paper was to contrast existing arguments and data, irrespective of whether they originate from industry or academia, and to clarify popular misunderstandings with the goal of raising the ongoing discussions to a more productive and rigorous level. By summarizing the current state and creating a framework for future research based on a nomological network of Bitcoin's energy use that identifies its relevant components, I seek to develop an incremental research agenda in which implied causalities can be converted into hypotheses and tested in a rigorous manner. This will not only advance ongoing academic discussions but also inform the general public and support political decision-makers. Specifically, I propose the following research questions.

RQ1: Why does Bitcoin use energy?

RQ2: What are some common misconceptions surrounding Bitcoin's energy use?

RQ3: How is Bitcoin related to energy?

RQ4: What are the determinants of Bitcoin's energy use?

RQ5: How does Bitcoin's energy use positively affect the environment?

RQ6: How does Bitcoin's energy use negatively affect the environment?

RQ7: Which research questions can guide further rigorous investigations of Bitcoin's energy use?

To identify and cluster the relevant topics for this paper, I conducted a narrative literature review in academic databases, including EBSCOhost Business Source Premier, Google Scholar, ScienceDirect, and Web of Science. Additionally, I searched mainstream public media (including video sources) using the Google search engine and a snowballing approach that follows relevant references of the selected sources. The initial search terms were "Bitcoin", "cryptocurrency", "energy", "climate", and "sustainability". The identified sources were further scrutinized to eliminate articles that did not directly deal with the energy

use of Bitcoin but covered unrelated topics, such as the use of Bitcoin as a hedge against price movements of energy commodities or the analysis of the correlation between Bitcoins' price and energy markets. The remaining papers and media articles were then clustered according to the research questions presented above. Given that public media articles frequently rely on a single source of information, I did my best to identify the root source but also included "redundant" newspaper articles stemming from influential media outlets to illustrate the popularity of specific lines of argumentation. The overall approach in this paper is not to provide a quantitative assessment of the distribution of various opinions in the public media but, in a more qualitative manner, to use purposive sampling to highlight conflicting viewpoints, irrespective of their current popularity. This approach includes both mainstream and outsider opinions, which might be scrutinized as part of future research endeavors.

This paper is structured as follows: In Section 2, I answer RQ1 and RQ2 based on the workings of Bitcoin. This section is also meant to clarify misunderstandings by outlining what Bitcoin actually is and why it uses energy in the first place. Furthermore, I elaborate slightly on the goals of Bitcoin and how consensus in distributed ledgers can be reached in general as well as comment on widely held misconceptions and polemics that frequently complicate an open discourse. In Section 3, I discuss Bitcoin's relation to energy, answering RQ3. In Section 4, I discuss several determinants of Bitcoin's energy use (RQ4) and provide examples of how Bitcoin mining can exert positive (RQ5) and negative (RQ6) impacts on the environment. I finish this section with two frameworks that serve to structure and guide future research (RQ7). In Section 5, I highlight the most important findings from the viewpoints of academics and practitioners, notably policy makers. Section 6 wraps up my findings, lists several limitations, and paves the way for future research.

## 2. Exploring Bitcoin

At the core of the critical discussions surrounding Bitcoin lies energy. Energy is commonly defined as the ability to perform work and comes in several forms, such as electrical, motion, thermal, chemical, and nuclear energy. According to the first law of thermodynamics, the total amount of energy within an isolated system stays constant. This means that energy can be transformed between the different forms, but it can neither be created nor destroyed. The second law of thermodynamics poses that the amount of entropy—the energy that is unavailable for work—cannot decrease over time in an isolated system. Several decades ago, Georgescu-Roegen [15] noted that economic processes transform valuable (low entropy) resources into outputs of valueless (high entropy) waste and concluded that the real output of the economic process is the "mysterious immaterial flux of the enjoyment of life" (p. 353). While it is true that recycling, as envisioned by the circular economy [16], makes energy use and therefore economic activities more efficient, an influx of outside energy is always needed to sustain the economic process. Therefore, it is crucial that energy is used as efficiently as possible, not least since its creation regularly produces unwanted emissions. In summary, I would like to underline two important issues: First, every economic activity needs energy; second, in regard to electricity, it is not so much the use of energy but rather the detrimental side effects of its generation that determine its environmental impact and should be the center of attention.

### 2.1. Nature of Bitcoin

To be able to critically assess statements such as "Bitcoin consumes energy" and to establish a reasonable basis for the following discussions, it is indispensable to first define and understand Bitcoin: a step that is regularly skipped in both public and academic discussions. More often than not, Bitcoin is implicitly equated with the cryptocurrency of the same name. However, this is an oversimplification that complicates all further communication. According to Bendiksen [17], Bitcoin is a set of

rules that runs on (and creates) a decentralized network.<sup>2</sup> Together, the set of rules (i.e., the protocol) and the Bitcoin network (i.e., nodes that run a specific Bitcoin software) yield a decentralized currency system that simultaneously constitutes its internal unit of account (i.e., the coin). The cryptocurrency Bitcoin is the respective unit of account that the network operates on or, in other words, the asset that is created. This asset has been defined as “a decentralized digital currency that you can buy, sell, and exchange directly, without an intermediary like a bank” [18].

As opposed to multipurpose blockchains (e.g., Ethereum), Bitcoin was presumably designed with only one apparent use case, namely, the immutable transfer of cryptocurrency from one entity to another (i.e., payment/settlement) without having to rely on an intermediary. The current widespread use as a store of value emerged since Bitcoin quickly gained in popularity and its value (regularly expressed in terms of its exchange rate with fiat money) soared, which induced speculators to buy and hoard (“hodl”) it in the hope of selling it later at a profit. Recently, Bitcoin ordinals emerged that allow data to be attached to an individual satoshi (the smallest denomination of Bitcoin) to create digital artifacts that resemble Non-Fungible Tokens (NFTs). Nonetheless, the underlying Bitcoin protocol and its respective implementations are inextricably linked to its main application, namely, the transfer of value. Even though there are other cryptocurrencies (and, of course, non-blockchain-based applications) that fulfill the same purpose, Bitcoin possesses various characteristics (e.g., capped supply, secure network, and first-mover advantage) that make it unique. In the remainder of this paper, I therefore do not explicitly differentiate between the protocol, its implementation, and its applications, other than using lowercase “bitcoin” to refer to the cryptocurrency and uppercase “Bitcoin” to refer to the protocol or the network. Table 1 provides several definitions to overcome the Babylonian confusion surrounding Bitcoin terminology. It also includes the Bitcoin blockchain as the shared ledger in which all transactions are recorded and the understanding of Bitcoin as an implementation/software and an application.

## 2.2. Goal of Bitcoin

To put the energy use of Bitcoin into perspective, it is crucial to first elaborate on its current and potential future use cases. This step is indispensable since an objective assessment of the costs and negative externalities of any technology only makes sense if the resulting (or envisioned) benefits as well as the positive side effects are also considered. Satoshi Nakamoto [19], who created Bitcoin, titled his original paper “Bitcoin: A Peer-to-Peer Electronic Cash System”, referencing previous seminal works including Wei Dai’s B-money and Adam Back’s Hashcash. Judging it only by the title, Bitcoin was intended to enable online payments, which requires solving the issue of double spending to prevent actors from making exact copies of a digital good. However, the message left by Satoshi Nakamoto in the genesis block hints at a somewhat more ambitious goal: “The Times 03/Jan/2009 Chancellor on brink of second bailout for banks”. In line with this statement, Bitcoin has accumulated a strong followership over the years that emphasizes its potential to replace existing fiat money systems with a currency (money?) that has a predictable supply and cannot be deliberately inflated. Numerous benefits of such a system have been identified over the years, ranging from financial inclusion and the abolishment of inflation to restricting the ability of governments to finance war by printing fiat money [20].

A realistic assessment of Bitcoin at the time of finalizing this paper (June 2023) makes it clear that these ambitious goals have not yet been

<sup>2</sup> While the network governance and the consensus mechanism of Bitcoin are decentralized, several other features are not. For example, the mining process is currently controlled by a handful of powerful mining pools and the wealth distribution (i.e., bitcoin ownership) is highly concentrated.

**Table 1**  
Bitcoin terminology.

Term	Meaning	Definition
bitcoin	cryptocurrency	The cryptocurrency bitcoin is a digital currency that only exists online, is not backed by any asset, can be transferred in a decentralized manner, and uses cryptography to authorize and secure transactions.
Bitcoin	protocol	The basic set of rules that establish the structure and functioning of Bitcoin is outlined in Nakamoto’s white paper [19].
Bitcoin	implementation/ software	A program that follows the Bitcoin protocol rules and runs a Bitcoin node that is able to interact with the Bitcoin network (e.g., Bitcoin Core).
Bitcoin	application (general)	The generic intended use of bitcoin (e.g., payment, investment and potentially also speculation).
Bitcoin	application (specific)	Software that uses the cryptocurrency bitcoin to implement a specific use case (e.g., payments, remittances).
Bitcoin Bitcoin	network blockchain	A network of nodes that run the Bitcoin software. A shared ledger that comprises transaction records.

achieved and that bitcoin’s current usage does not accomplish three core functions of money: acting as a medium of exchange, a unit of account, and a method of deferred payment (which is debatable in the case of Bitcoin anyway). On a global scale, bitcoin is mainly used as a store of value (the fourth monetary function) and in many cases for purely speculative purposes. Just two countries thus far (i.e., El Salvador and the Central African Republic) adopted Bitcoin as a legal tender, presumably to escape the hegemony of the U.S. dollar and the Central African franc, respectively. In 2023, the Central African Republic repealed the legislation that gave bitcoin the status of legal tender.

Clarifying one’s underlying standpoint is therefore an important prerequisite for any open discussion and is needed to put things into perspective. Feign [21], for example, emphasized that Bitcoin uses less than half of the energy of the banking system and listed the huge amount of infrastructure (i.e., physical branches, ATMs, data centers, secure transport vehicles, and card machines) on which the latter depends. Such a direct comparison of absolute energy values would require that Bitcoin offers the same services as the existing banking system, which is clearly not the case in 2023. Then, again, it is also important to point out that the potential of Bitcoin might not yet be fully realized, as it only gained public attention in the middle of the 2010s, whereas the dominant monetary system has evolved over millennia and is regularly backed by national authorities. Furthermore, Bitcoin’s current status has been accomplished in spite of strong headwinds generated by powerful incumbents who benefit from the existing system, including commercial and investment banks (quite a few of whom have ceded to public demand to include cryptocurrencies in their offerings over the years), central banks, and governments. As such, any kind of comprehensive assessment also needs to take into account potential future developments of Bitcoin, whether it is beneficial or detrimental [22].

Therefore, what exactly is the potential of Bitcoin? Is it a decentralized, peer-to-peer, democratizing monetary revolution that has the potential to replace the existing financial system and eliminate wars? Or is it rather an out-of-control game for crypto nerds and greedy investors that threatens to destabilize existing monetary systems? In 2023, individual answers to this question heavily depend on one’s understanding of Bitcoin as well as one’s underlying political viewpoints and level of personal involvement. Since the weak point of Bitcoin is its energy use, which is a prerequisite for the creation of new bitcoins, its opponents mostly attack the public media from this perspective. To fully understand Bitcoin’s energy use, it is crucial to first discuss how peer-to-peer networks can reach consensus.

### 2.3. Consensus in distributed networks

Reaching consensus is an important component in enabling the effective functioning of a distributed network. Participants in such a network need to organize themselves without any particular hierarchical structure and follow principles that allow them to agree on the state of a shared ledger. This agreement can be achieved by using so-called consensus mechanisms, of which numerous variants exist. The more open the network is, the more complicated it becomes to reach consensus. Other differentiating factors also exist. For example, in regard to finality—the state in which a transaction can no longer be altered or reversed—consensus mechanisms can either be immediate or probabilistic. Consensus mechanisms with immediate finality (e.g., Practical Byzantine Fault Tolerance) exhibit increasing communication complexity as the number of nodes increases. Bitcoin, as an open network with a potentially unlimited number of participants, therefore relaxes consistency assumptions and offers probabilistic finality. This means that the likelihood that a transaction will stay in the ledger increases over time [23]. Properties such as this need to be considered when discussing potential changes to Bitcoin.

It is a commonly held belief that Bitcoin uses a PoW consensus. More precisely, it uses the so-called Nakamoto consensus that includes PoW to reduce Sybil attacks, which refers to nodes in a peer-to-peer network faking identities to gain disproportionate influence. Other important parts of the Nakamoto consensus are public key cryptography and elliptic-curve cryptography to enable authentication and data integrity as well as a block-selection rule (“longest-chain-wins”) to solve disputes in case different versions of the chain emerge. The Nakamoto consensus is a solution to the Byzantine Generals Problem of whether (and how) it is possible to reach agreement in a network of distributed nodes that operate on a peer-to-peer basis [24].

Apart from PoW, there exist numerous alternatives to reach consensus in blockchains, including Proof of Authority (PoA; based on reputation), Proof of Elapsed Time (waiting time is randomly generated), Proof of Burn (destruction of virtual currency tokens), Proof of Useful Work (solving real-world problems), or Proof of Capacity/Space (based on allocation of memory), among numerous other suggestions. Distributed ledgers that do not exhibit a chain-like structure, such as Directed Acyclic Graphs (DAGs), use completely different procedures. For example, Tangle in IOTA requires each user who wants to conduct a transaction to verify two other transactions [25]. The most prominent contender to PoW in public and permissionless environments—where everyone is allowed to read, write, and validate transactions—is currently PoS. Rather than using computational power to solve a mathematical problem as is done in PoW, it requires network participants to lock tokens to be able to validate transactions and reap the rewards. Delegated Proof of Stake (DPoS) constitutes a more plutocratic system in which network users elect delegates who can then validate transactions and blocks. Obviously, these concepts change the entry hurdles for potential validators.

Consensus mechanisms can be changed, as evidenced by the transition from PoW to PoS in the popular blockchain Ethereum. This transition, called “The Merge” since the original execution layer was joined with the PoS consensus layer, occurred in September 2022 and, according to the Crypto Carbon Ratings Institute [26], reduced its energy consumption by 99.988% and the carbon footprint by 99.992%. This number seems to be conclusive proof for some that a transition of Bitcoin to PoS (which is doable in theory) would be the appropriate means to “improve” the protocol and to avoid public criticism [27]. The devil is in the details, however, since such a transition would fundamentally alter (some would even say “violate”) some of Bitcoin’s underlying principles. PoW and PoS look quite similar in regard to their underlying goal, which is reaching consensus in a network of computers that do not trust each other. However, the differences in the way this is done and the governance implications are substantial. In this regard, Lowery [28] formulated a framework called “Power Projection Theory” and argued that

Bitcoin (and other PoW technologies) secures important information by imposing severe physical costs on potential attackers. In contrast, PoS resembles abstract power hierarchies in real life (e.g., ranks based on inheritance or job title) that do not use energy and therefore are prone to attacks, exploitation and corruption.

Furthermore, not all PoS systems are created equally, and there are significant differences between the respective implementations. Those PoS mechanisms that can function in permissionless environments also have a larger energy footprint than permissioned distributed ledgers with a small number of validators and high throughput [29]. A detailed comparison between PoW and PoS is beyond the scope of this paper, but it can be said that neither offers a universal solution for all current issues and, in general, PoW is better in ensuring security and decentralization, while PoS provides better scalability [30]. Similarly, the International Telecommunication Union (ITU) [31] highlights the inverse relationship between trust and energy demand. If trust decreases, more energy is needed and vice versa. In this regard, PoA has the least energy demand, PoW the most and PoS lies between the two. For the sake of completeness, it must be mentioned that the use of PoW has also been suggested in permissioned blockchains. This allows final users to evaluate the costs for changing confirmed transactions but also needs to solve the problem that mining rewards are not expected in a permissioned context [32].

### 2.4. Mining Bitcoin

Applying the Nakamoto consensus and using PoW is the one activity that uses almost all of the energy needed for the operation of Bitcoin. According to Urquhart & Lucey [33] (p. 37), “adding transactions to a digital ledger, such as the blockchain [...] demands verifications by algorithms. All those calculations consume energy”. Actually, the huge amount of energy is consumed neither by the verification nor by the addition of transactions to the ledger, but rather by the search for a suitable nonce (number only used once) that determines which miner is granted the right to produce a new block. In contrast, the validation process, which keeps the peer-to-peer network running, consumes only limited resources and can easily be performed by a Bitcoin core client running in the background of a regular desktop computer [34].

To better understand the purpose of PoW, it helps to go back in time and explore its origins. The concept was originally introduced in 1992 to combat junk mail by requiring e-mail senders to compute a moderately hard function to gain access to a resource [35]. While this does not seriously affect ordinary e-mail users, it inhibits spammers who seek to transfer large amounts of unsolicited e-mails. Based on PoW, Adam Back created Hashcash to prevent Denial-of-Service attacks, which are executed by overwhelming a machine with requests [36]. Conceptually similar ideas can be found in completely distinct areas, such as the Tobin tax, which was suggested to be levied on spot currency transactions to prevent short-term currency speculation [37].

In Bitcoin, the so-called mining process refers to the bundling and verification of new transactions and putting them on the Bitcoin blockchain. To avoid confusion on the network, only the miner that has found the correct nonce is allowed to add a new block and receives a certain amount of newly minted bitcoin (and some transaction fees) in return. This reward started out as 50 bitcoin in 2009 and is halved every four years (i.e., 210,000 blocks). The last halving occurred in May 2020, and the reward for adding a block stands at 6.25 bitcoin in 2023. Bitcoin mining was originally performed using standard central processing units (CPUs), but increasing interest over the years has spurred competition. Over time, CPUs were replaced by graphics processing units (GPUs), followed by field programmable gate arrays (FPGAs), and, finally, by application-specific integrated circuits (ASICs) whose sole purpose is Bitcoin mining [38].

The decision regarding which miner is allowed to add a block depends on who is first able to find the aforementioned nonce that creates a hash value (i.e., a checksum) for a block of transactions that fulfills a specific criterion. This process can only be performed by calculating the

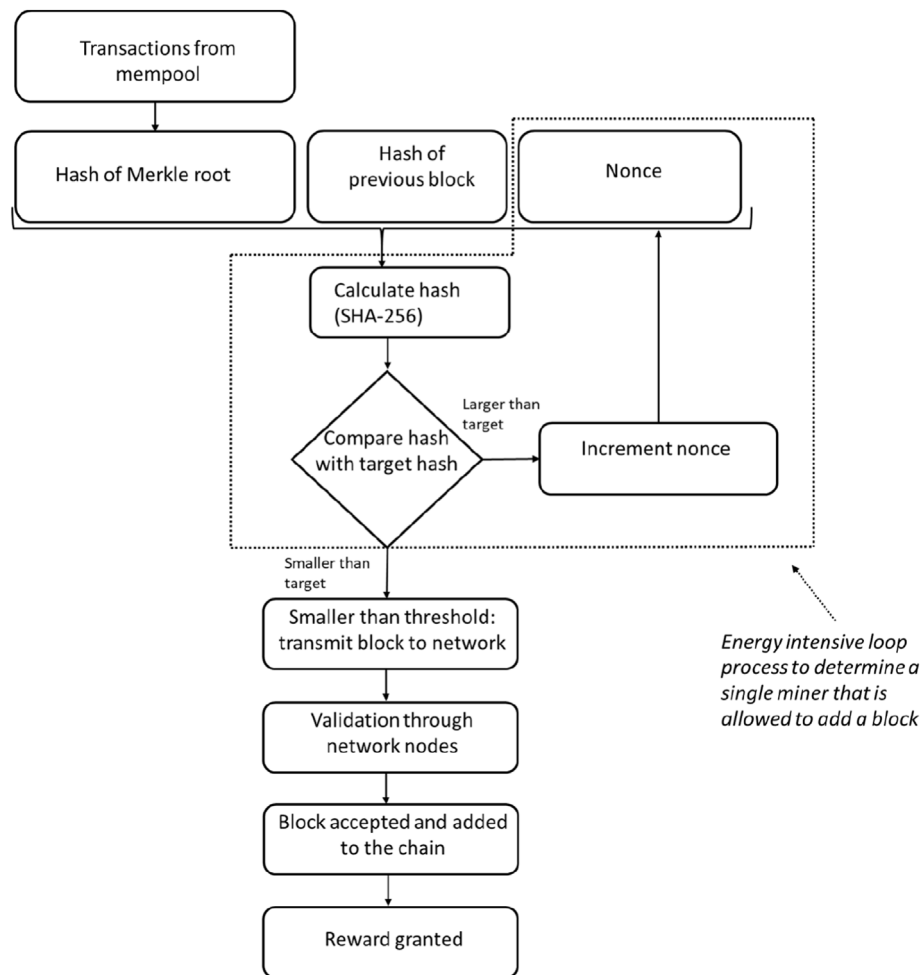


Fig. 1. Overview of the Bitcoin mining process.

hash algorithm numerous times via brute force and it ensures that a new block is created approximately every 10 min. If competition increases, the target hash becomes more difficult to undercut, but importantly, this process can also be reversed if competition decreases. This so-called difficulty level adjusts every 2016 blocks, which is roughly every 14 days. Fig. 1 provides a (simplified) summary of this procedure and illustrates that it is neither the collection and bundling of transactions from the mempool (a database of unconfirmed transactions), nor their initial validation, nor their transmission to the Bitcoin network that causes the huge energy demand, but rather the repetition of the hashing procedure time and again to find a suitable nonce and determine a single miner that is allowed to add a new block.

In summary, miners need to invest computing power to find the correct hash value. Since this process has become increasingly competitive with the rise of bitcoin's value in fiat currency terms, they need to invest a significant amount of computing power, which is why this process is also called PoW. To set things straight, it is neither the number of transactions to be validated, nor the current size of the bitcoin network, nor the amount of remaining bitcoin, but rather the competition between the miners that determines the computing effort that is needed to create a new Bitcoin block and reap the rewards. The level of competition between miners, in turn, is determined by the current and future gains they expect from their activities. In other words, it is the miners who consume energy via their equipment and not Bitcoin (the protocol) or the full nodes that validate transactions and blocks. The miners participate to make personal gains, but in so doing, they make the network viable and secure. Bitcoin started with hardly any energy usage, and apart from some improvements over the years, such as Segregated Witness (SegWit),

which allowed more transactions to be stored in a block, it has produced exactly the same output in the past<sup>3</sup> as it does today. The difference over time is not in the activities of validating transactions, bundling them into a block, and submitting them to the network per se but rather in the security of the network since potential attacks have become prohibitively expensive. In other words, it would have been relatively easy for an evil-minded attacker to hamper the network by double spending or blocking other users' transactions in the early days of Bitcoin. In 2021, the hardware costs to launch such an attack on Bitcoin for 1 h were estimated to be 5.5 billion USD. A more realistic attack would be to use a synthetic hashrate (i.e., a hashrate sold on exchanges or via cloud mining contracts) by taking over three to five mining pools and using them to rewrite history (i.e., reorg attack) and mine empty blocks [39].

## 2.5. Common misconceptions

The debate surrounding Bitcoin and its energy use is frequently complicated by several deep-rooted misunderstandings that mostly pertain to the functioning of blockchain and why Bitcoin needs energy in the first place (as described above). Although the Bitcoin whitepaper was published in 2008 and the protocol has been implemented since 2009, numerous myths or false assumptions continue to linger in the public media and academic publications. Prior to clarifying Bitcoin's relation to energy, I would therefore like to discuss some of the most common

<sup>3</sup> In case we measure output as the number of confirmed transactions it was from the time on when there were enough transactions to fill a block.

misconceptions in the naive hope that they will no longer bias ongoing discussions.

### 2.5.1. Bitcoin is blockchain

Bitcoin was the first working online solution to solve the problem of double spending on digital goods. It did not come out of the blue, but rather through the clever combination of a multitude of preexisting underlying technologies. Interestingly, prior to its invention, there were many who thought that transferring value online in a peer-to-peer manner via an artificially created asset was impossible—both from an economic and a technical perspective. In regard to the former, the regression theorem from Ludwig von Mises states that the value of money stems from its value as a commodity [40], which does not seem to be the case for Bitcoin, although differing opinions exist (e.g., Ref. [41]). From a technical perspective, Narayanan and Clark [42] provided a chronology of key ideas found in Bitcoin starting in the 1980s that includes linked timestamping, verifiable logs, digital cash, PoW, Byzantine fault tolerance, public keys as identities, and smart contracts. This component-based structure is a key feature of blockchain technology, which, depending on the respective manifestation of the components, yields the desired properties of distributed ledgers. These are flexibility, opaqueness, performance, policy, practicality, and security [43]. Importantly, many of these properties exhibit trade-offs such that no “perfect” solution exists or is ever likely to exist. How exactly these properties are achieved depends on the underlying protocol: the rules that determine how the blockchain network functions. These rules control the governing and validation of transactions, the interaction of the nodes, and, occasionally, the application programming interface (API) [44].

Over the years, numerous variations of the underlying components have emerged, leading to a plethora of distributed ledgers, some of which do not even exhibit a chain-like structure (e.g., DAGs). In this respect, Bitcoin is just one of many possible combinations of technical features that is technically feasible, and its energy-consuming consensus procedure is its own feature but not necessarily one of other blockchain applications. In contrast, there are numerous so-called green blockchain-based applications that benefit the environment and are not controversial [45]. In this context, it is noteworthy that many purists do not consider blockchain applications that are private and permissionless to be “real” blockchains, but this debate is beyond the scope of this paper.

### 2.5.2. The Bitcoin protocol is immutable

The immutability of data stored on blockchain is occasionally confused with the immutability of the underlying protocol or, more precisely and in the case of Bitcoin, the rules implemented in its source code, which was first deployed on January 3, 2009. As of June 2023, Bitcoin Core, the most popular bitcoin client, and its reference implementation runs on version 25.0. In previous years, numerous formal Bitcoin Improvement Proposals (BIPs) have been made to undertake upgrades such as bug fixes, efficiency improvements, and the addition of new features [46]. Many of those BIPs were implemented by Bitcoin Core [47]. It is therefore possible for developers to introduce changes to Bitcoin, but these changes cannot be forced upon the users of the software [48]. In this context, it is also important to mention that this flexibility safeguards Bitcoin from future improvements in quantum computing, which threatens the security of existing asymmetric cryptography [49] and especially those Bitcoin addresses whose public keys have not been hashed. The effect of quantum computers on Bitcoin mining is predicted to be substantial, and researchers expect that existing mining procedures will become obsolete and that a new hashing function will need to be employed, probably resulting in a Bitcoin hard fork [50].

To give just one example that demonstrates that the implementation of Bitcoin is not immutable: On March 11, 2013, versions 0.7 and 0.8 of the Bitcoin software diverged from each other and caused an unintended fork, which is a splitting of the chain. The critical situation was resolved

within a couple of hours and, interestingly, showed the “effectiveness of a strong central leadership” exerted by core developers [51]. This incident not only illustrates that the Bitcoin software can be updated but also that it is not perfectly decentralized and rather pursues the goal of decentralization maximalism (i.e., “as decentralized as possible”). Therefore, it is theoretically feasible to change Bitcoin’s current PoW procedure; practically, however, this is unlikely to happen since it would fundamentally alter the way in which consensus is reached. This would not only change the core properties of Bitcoin but also contradict the interests of existing Bitcoin miners, most of whom have already invested substantial amounts of money in their equipment and mining activities. The most likely result of introducing an alternative way to reach consensus in Bitcoin (e.g., by PoS) would be a so-called hard fork in which a new strand of blockchain comes into existence in addition to the existing chain. Such hard forks of Bitcoin have actually happened in the past (e.g., Bitcoin Classic in 2016, Bitcoin Cash and Bitcoin Gold in 2017), and in all of these cases, the majority of the users followed the traditional implementation. This situation is also present in Ethereum, whose switch to PoS was not followed by Ethereum Classic, a previous hard fork committed to retaining PoW.

### 2.5.3. PoW is an essential component of all cryptocurrencies

Not surprisingly, Bitcoin’s energy debate has huge spillover effects on other blockchains and cryptocurrencies through a halo effect, which might be welcomed by those who oppose the technology in general. The simplification that all blockchains or cryptocurrencies are more or less alike pertains not only to their environmental impact but also to other features such as their level of pseudonymity/anonymity. Statements that connect cryptocurrencies with money laundering or drug payments make catchy headlines but conceal the important differences between the respective currencies. Given the focus of this paper on energy use, it is noteworthy that cryptocurrencies exist that have already implemented PoS (e.g., Ethereum (ETH), Cosmos (ATOM), Cardano (ADA), Polkadot (DOT), Solana (SOL), VeChain (VET), and Tezos (XTZ) [52]) and that all of the others that use PoW need considerably less energy than Bitcoin. This is due to their lower popularity in comparison to Bitcoin or the use of variants such as ASIC-resistant mining in which highly specialized hardware cannot be used to gain a competitive advantage (e.g., Monero (XMR), Ravencoin (RVN), and Vertcoin (VTC)) [53]. Again, these differences bear substantial implications that mainly pertain to the security of the network, and therefore, a comparison based solely on the use of energy use without taking into account the overall network security and additional features (e.g., transaction finality) does not make much sense.

Another interesting question in this context is whether anything other than the PoW mechanism would have sufficed to launch Bitcoin. The answer is most likely “no” since this mechanism was able to bootstrap Bitcoin from scratch and overcome the aforementioned regression theorem, which states that the value of money originates from its previous non-monetary use. As can be inspected by anyone in a publicly available Bitcoin explorer, the first bitcoin transaction between peers occurred in block 170 on January 12, 2009, when Satoshi Nakamoto transferred 10 bitcoins to Hal Finney. Prior to that, it was most likely Satoshi alone who collected all the rewards (called coinbase) for creating new blocks. This specific transaction in block 170 most likely served as a demonstration and did not include a value exchange. Presumably, the first true value exchange happened on May 22, 2010, when Bitcoin developer Laszlo Hanyecz paid 10,000 bitcoins for two pizzas (block 57,043). In summary, PoW might have been the only way to start a project such as Bitcoin that originated from the ideas of one person or team and was able to scale to a global network using the same protocol. Bitcoin was highly vulnerable to potential attacks in the early days, and the fact that these did not transpire was most likely due to a lack of incentives and awareness. Everyone was free to join this project, and Satoshi presumably even refrained from mining new blocks in the first minutes of each block interval to give others a chance to succeed in block creation [54]. In summary, while

PoW is not an essential component of cryptocurrencies, it was most likely the only option to launch an open public project that functions independently of the number of participants.

#### 2.5.4. Huge energy consumption is a feature of blockchain/Bitcoin

As can be deduced from the previous sections in which I outlined that Bitcoin is not synonymous with blockchain and that PoW is not an essential component of cryptocurrencies (or blockchain in general), the substantial amount of energy that is currently used by the Bitcoin network to generate new blocks is not a feature of blockchain. Strictly speaking, it is not even a necessary feature of Bitcoin but rather one that has emerged as a side effect of its increasing popularity. The amount of energy that goes into Bitcoin is mainly determined by (1) bitcoin's valuation (usually in terms of its exchange rate with fiat currencies) and (2) the reward that is given for Bitcoin mining. In this regard, the Bitcoin Mining Council [55], a voluntary and open forum for Bitcoin miners, notes that Bitcoin mining will become "dramatically more energy efficient in the next eight years" due to a sixfold improvement in mining efficiency and the quartering of Bitcoin mining rewards through two periodic halvings. The latter is a highly important factor that will certainly reduce the amount of investment directed toward Bitcoin mining. However, it is also important to simultaneously consider the valuation of bitcoin in fiat money; the effect of a mining reward reduction would be nullified if Bitcoin's value goes up by four times in the same time period. Of course, this effect also works in the opposite direction, such that a decrease in Bitcoin's exchange rate will further reduce the incentive for miners to pay for energy.

However, I am skeptical about the first argument made by the Bitcoin Mining Council, namely, that Bitcoin will become more energy efficient by improving mining efficiency. Under the assumption that everyone has exactly the same access to state-of-the-art mining equipment, whether they are honest Bitcoin miners or potential adversaries, it is not the efficiency of the technology that determines Bitcoin's price. Instead, it is the cost of energy in fiat currency terms that determines the competition, and any improvement in mining efficiency just raises the bar (i.e., the hashrate) for all. In this respect, the hardware is just the medium that transforms energy into hashrate and, ultimately, security. This is evidenced by the evolution of mining equipment over the years. As outlined above, Bitcoin mining started with CPUs, followed by GPUs, FPGAs, and, finally, ASICs. Through these changes, Bitcoin mining has already become 100 billion times faster (i.e., efficient) over the years [56]. Did the aggregate energy consumption drop because of this? The answer is a resounding "no" due to the arguments outlined above. Other factors that also need to be taken into account include the lack of alternative uses for current mining equipment, since Bitcoin ASIC mining hardware cannot be applied for any other purposes, as well as miners' beliefs in the future development of Bitcoin's valuation, which might incentivize them to tolerate short-term losses. In addition, an increase in the efficiency of newer mining equipment will make older machinery unprofitable, thus increasing the total amount of e-waste.

In summary, the currently huge energy use is by no means intrinsic to Bitcoin, and it is not dependent on the number of users or transactions being processed. Instead, the amount of energy that is used and paid for to compete in the race for new Bitcoin blocks reflects the willingness of miners to pay for specialized hardware and energy. It is therefore not the tasks of validating and bundling transactions, which have stayed more or less the same from the very beginning of Bitcoin with only minor changes in the protocol, that necessitate the energy. Bitcoin's energy use was negligible in the beginning since there were low levels of competition between the few miners who sought to receive the newly minted bitcoin. Competition is now high because its exchange rate with fiat currencies has soared over the years, which has induced many additional miners to participate in the race to create new blocks and invest in sophisticated equipment.

Other factors (e.g., Bitcoin's use as a store of value or medium of exchange) might also play an important role in the years to come, but, by

and large, the marginal costs to mint new bitcoin (and reap transaction rewards) will correspond to the marginal costs of hardware and energy that are needed to do so. In a fully efficient and flexible market (i.e., one without significant sunk costs for mining equipment), the product of "block reward" and "bitcoin price" equals the product of "hashrate" and "cost per hash". In other words, the hashrate is positively correlated with the reward times bitcoin's exchange rate and negatively correlated with the costs of hashing. Miners that operate inefficiently due to outdated equipment or above-average operational costs are forced out of business (Wingen, 2018). To provide just one example, according to Brown [57], the Antminer S9 needs 98 W/Th (Watts per Terahash) as opposed to the newer model Antminer S19j, which needs 34.44 W/Th. Importantly, energy costs to mine a single bitcoin can also differ substantially between countries (e.g., due to subsidies or varying energy sources), ranging from 1394 USD in Kuwait to 246,531 USD in Venezuela according to NeoMam Studios [58].

#### 2.5.5. Bitcoin's energy consumption will grow forever

In 2017, the World Economic Forum published a story using the catchy headline "In 2020 Bitcoin will consume more power than the world does today" [59]. This prediction was obviously generated by extrapolating an exponential growth pattern over a prolonged period of time, which is rarely a good idea, and has been debunked by the mere passage of time. Indeed, this predicted scenario should always have been considered unrealistic since most energy-consuming applications are more valued by society than Bitcoin and the simple principles of supply and demand would not allow for such an allocation of scarce resources. In a frequently cited study from Nature Climate Change, Mora et al. [60] warned that "Bitcoin emissions alone could push global warming above 2 °C" (p. 931) and projected the trend of Bitcoin usage adoption to "a global total of ~314.2 billion cashless transactions" per year (p. 933). This prediction ignores the fact that the number of transactions that can actually be carried out on Bitcoin's layer 1 (i.e., the base level of its blockchain architecture) is limited. According to Statista [61], Bitcoin's daily transactions between January 2017 and April 2021 hovered between 150,000 and slightly less than 400,000. Consistently reaching the higher daily value would only amount to an annual maximum of 146 million transactions. To compensate, layer 2 solutions/sidechains (e.g., Lightning, Liquid) and other solutions (SegWit) have been implemented to increase the "economic density of Bitcoin transactions" [62], which means that more economic value can be secured by each energy unit. The key point is that these solutions do not need much additional energy. The approach from Mora et al. was also criticized by Masanet et al. [63], who pointed out other serious flaws in the design and execution of the study, including the mixing of block difficulty and number of transactions as emission drivers, improbable departures from historical trends, the application of outdated data for mining rig efficiencies, the forward projection of 2017 per-transaction energy use and CO<sub>2</sub> emission values, and errors in analyzing adoption rates. On the other side of the debate, Sedlmeir et al. [64] went so far as to postulate that [PoW blockchains in general] "do not pose a large threat to the climate, mainly because the energy consumption of PoW blockchains does not increase substantially when they process more transactions" (p. 606). However, this line of argumentation does not take into account of other factors that might drive the energy use of PoW and fails to acknowledge that the current impact of Bitcoin's energy use is already substantial.

It is indeed true that Bitcoin's energy use has grown steadily and substantially over the years, as triggered by the expected monetary gains. As far as miners' incentives are concerned, Urquhart and Lucey [33] emphasized that "the reward diminishes in value but is still high: it started out at 50 bitcoins and halves every 210,000 blocks (roughly every 4 years), reaching 6.25 bitcoins for each block created in 2022" (p. 38). While this is technically correct, it is not the reward in bitcoin that ultimately matters but the gains as expressed in fiat currency, as I discussed previously. In this regard, much confusion can be avoided by clarifying the question of whether bitcoin is inflationary. Most bitcoins have

already been mined, but their supply still grows at a predictable and declining rate. Since inflation is defined by the purchasing power of money and not purely by the increase in monetary supply, for most of its existence bitcoin has been deflationary since its exchange rate to fiat currency appreciated. In summary, any calculation of inflation is only straightforward if the currency in question is simultaneously the unit of account. Otherwise, as is the case with bitcoin, two factors come into play, namely, the increase in money supply and the exchange rate to the existing unit of account. Bitcoin's loss in purchasing power in recent years has forced several miners to sell their bitcoin or even file for bankruptcy [65].

Munro [66] labeled Bitcoin as an “unstoppable energy locust” and argues that there is not much that can be done against it. He concluded that if miners “fall behind, that income drops off and it will very quickly become impossible to catch up again”. Furthermore, he argued that if miners turn off their machines when prices drop, the difficulty will go down, and the network will become increasingly profitable for other competitors. While this makes intuitive sense, it also means that the sum total of miners' energy costs will never exceed the expected gains. This is a strong claim that warrants an investigation of the causal relationship between bitcoin price and its mining activities. According to Sandner et al. [11], this is a reciprocal relation with a strong short-term impact of bitcoin prices on mining activities and a weak long-term effect of mining on the bitcoin price. The latter effect is determined by the stock-to-flow model that postulates that the price of bitcoin is based on the relation between its circulating supply and the amount of newly minted coins. Investigating the same topic from a different angle, Schinckus et al. [67] postulated a positive impact of trading volume on energy consumption. Presumably, the increase in trading goes along with a higher appraisal, which in turn increases miners' incentives to participate. Gonzalez-Barahona [68] summarized that Bitcoin's energy consumption depends on minting, transaction fees, exchange rates, energy prices, and amortization costs. As I have already outlined above, the mining rewards in Bitcoin are the only predictable factor in this equation due to the planned and periodic halving of the block rewards, which decreases miners' incentives to further invest. All other factors will remain volatile and depend on Bitcoin's use and valuation.

The elaborations above are mainly based on theoretical reasoning. Empirical data are also available that illustrate that the actual hashrate can have strong fluctuations. According to Glassnode [69], the hashrate (as a proxy for energy use) dropped from 162 Eh/s (exa hashes per second) in May 2021 to 100 Eh/s in July 2021. This sharp drop was caused by the ban of crypto mining in China and went hand in hand with a decline in difficulty (i.e., how hard it is to mine a block) [70]. Following this event, there has been a steady increase up to 219 Eh/s in May 2022, which was likely caused by mining equipment being shipped to the U.S. at substantial costs [71] as well as the reemergence of Bitcoin mining in China through miners essentially ignoring or circumventing the ban [72]. It is important to mention that this ban was welcomed by some parts of the crypto community since such measures have the potential to foster decentralization (e.g., by reducing the power of centralized exchanges) [73]. At the end of 2022, the collapse of the FTX exchange caused numerous miners to default on their loans, and many of them had to send the machines, which served as collateral, back to the lenders [74]. This caused a drop in the hashrate from approximately 270 Eh/s to approximately 240 Eh/s and a decline in bitcoin's price [75].

## 2.6. Discourse and polemics

The heated debates surrounding Bitcoin come as no surprise since it is a technology—or rather a bundle of technical components—that touches upon the core interests of powerful economic and political entities, including players in the financial sector as well as state authorities. These interests are frequently reflected in the language that is used in the public discourse. For example, Huang et al. [2], who referred to Bitcoin's electricity *use* in the title of their New York Times article, concluded:

“This is how Bitcoin mining turns electricity into security. It's also why the system *wastes* [emphasis added] energy by design”. The underlying rationale behind the frequently used term “waste” is that there is ultimately only one miner that finds the correct nonce and succeeds in attaching a block to the existing chain. The authors considered the rest of the mining energy to be wasted, but, again, this argumentation overlooks the fact that it is the sum total of the used energy that allows everyone to participate in the network while simultaneously protecting it from malicious attacks. Similarly, it is also interesting to note that the phrase “Bitcoin's dirty secret” [76] is still circulating even after several years of intensive media coverage [77].

According to Wolff-Mann [78], several winners of the Nobel Memorial Prize in economic sciences did not see any promising use cases for Bitcoin, and he headlined his story in a way that indicates that Bitcoin is “only good for drug dealers”. In response, Bitcoin proponents might present a 1984 quote from the late Friedrich Hayek, a winner of the Nobel Memorial Prize himself and defender of classical liberalism: “I don't believe we shall ever have a good money again before we take the thing out of the hands of government, [...] we can't take them violently out of the hands of government, all we can do is by some sly roundabout way introduce something that they can't stop” [79]. In fact, Bitcoin has numerous actual and envisioned use cases, including financial inclusion and hedging against inflation [20]. In regard to criminal activities, recent data from Chainalysis' Crypto Crime report [80] illustrate that the growth of legitimate cryptocurrency usage far outpaces the growth of criminal activities. The company also uses case studies such as the 2021 Colonial ransomware attack to illustrate how stolen funds were tracked and seized by the FBI. However, the report also notes “that Bitcoin-based laundering could become increasingly attractive to traditional criminals” (p. 21). Of special concern is the applicability of Bitcoin in ransomware, which is a criminal scheme that would be unthinkable in fiat money. It is noteworthy, however, that other cryptocurrencies might be better suited for this task, given Bitcoin's pseudonymity, immutability, and traceability [81]. In this regard, Cong et al. [82] wrote that while the techniques of ransomware groups have become more aggressive over time, blockchain transparency and digital footprints enable digital forensics that help to track, monitor, and shut down cybercriminals.

De Vries et al. [83] warned that “Bitcoin might enable tax evasion” (p. 788). From an academic perspective, Bitcoin is a so-called INUS condition: an insufficient but necessary part of an unnecessary but sufficient condition [84]. In less convoluted language, this means that Bitcoin can indeed be part of new schemes of tax evasion (i.e., a “facilitator”). Consequently, the public media warns of cryptocurrencies such as bitcoin posing “a significant risk of tax evasion” [85]. Simultaneously, other media stress that “there is no technological barrier to complying with tax laws” [86] and that numerous more or less sophisticated tax evasion strategies have existed since long before Bitcoin and will presumably continue to do so. Those who benefit most from tax evasion, particularly powerful multinational companies and wealthy individuals, have always found opportunities to do so by legal means without having to rely on cryptocurrencies [87]. In addition, the use of an immutable and traceable data structure in combination with pseudonymous identities (Bitcoin is not anonymous since the address of every transaction is recorded) might therefore not be the most ingenious way to conduct illegal transactions. In this vein, Sabu [88] argued that the Internal Revenue Service (IRS) is increasingly capable of policing transactions on Bitcoin, which renders it “unusually regulable for tax purposes” (p. 181). In summary, technology in general is capable of simultaneously facilitating tax evasion and its detection, and it is currently unclear which trend will dominate [89].

A strong indicator that the ongoing discussion is also (partly) politically motivated is the relative neglect by the public media to cover other sources of energy consumption and CO<sub>2</sub> emissions to the same extent as Bitcoin, such as energy that is indeed *wasted* [sic!] by the stand-by mode of electronic appliances (2% of total electricity consumption and 1% of CO<sub>2</sub> emissions [90]), air conditioning (which amounts to 10% of global electricity consumption according to the International Energy Agency

[91]), the military (according to the environmental news site The Ecologist, the U.S. military is a bigger polluter than as many as 140 countries, respectively [92]), the use of private jets (e.g., an average CO<sub>2</sub> intensity of 1300 g/pax.km (transport of one passenger over 1 km) in private aircraft as opposed to 128 g/pax.km in commercial planes [93]), food waste (170 million tons (Mt) of CO<sub>2</sub> equivalent greenhouse gas emissions in the U.S. alone) [94], the U.S. movie industry (15 Mt of CO<sub>2</sub> per year back in the early 2000s [95]), and many others that readers might identify for themselves. Big cars, expensive yachts, or private jets are still largely presented by the media as desirable status symbols and accepted as such in the public perception, rather than as a waste of energy. According to Hao [96], even deep learning models have a substantial carbon footprint. She claims that the emissions arising from the training of a single artificial intelligence (AI) model match those of five cars over their lifetimes.

Finally, it is only fair to mention that many defenders of Bitcoin also have a vested interest in using fancy labels for Bitcoin due to their personal investments or business models. To give just one example, bitcoin has also been designated a “climate savior” [97], a role that it is clearly not playing at the moment (i.e., June 2023). Additionally, many of Bitcoin’s most spectacular use cases are in a very early stage, and the network itself is fairly concentrated in both its distribution of wealth and mining power [98].

### 3. Bitcoin and its relation to energy

As described in the previous sections, electrical energy is needed to create new blocks in the Bitcoin blockchain, which forms the basis for the popular yet misleading statement that bitcoin consumes energy. The first law of thermodynamics reveals that energy cannot be *consumed*, instead it is converted into heat, and in the physical world this process is performed by the mining equipment rather than Bitcoin (the protocol and the network) [99]. While this might sound like nitpicking to some, this differentiation is important, since the created thermal energy might be put to good use in the best-case scenario or might require additional energy to cool the mining equipment in the worst case. Consequently, it would be advisable to replace “Bitcoin consumes energy” with “Bitcoin uses electrical energy”. Electricity is gained by converting primary sources of energy (e.g., coal, natural gas, nuclear, and renewables) into electrical power, and importantly, not all of these sources are created equal. For the functioning of Bitcoin, it does not matter how the electricity is gained, yet this makes all the difference to its environmental impact. To be precise, it is not the amount of energy used by Bitcoin that is of primary concern. Instead, it is mostly the amount of CO<sub>2</sub> that results from the production of this energy. Given the differences in emission intensities between the sources, energy production cannot be said to be equivalent to carbon emissions [100]. Pehl et al. [101] created a climate protection scenario for 2050 and projected life-cycle emissions from fossil fuel carbon capture and sequestration plants of 78–110g CO<sub>2</sub>eq (carbon dioxide equivalent) kWh<sup>-1</sup>. In comparison, nuclear, wind, and solar power have 3.5–12g CO<sub>2</sub>eq kWh<sup>-1</sup>, and the life-cycle emissions from hydropower and bioenergy equal approximately 100g CO<sub>2</sub>eq kWh<sup>-1</sup> but are hard to predict. Potential alternative uses of this energy also need to be considered, as do the various environmental impacts stemming from the production of Bitcoin-specific hardware (i.e., ASICs), which cannot be used for any other purpose.

The complex relation between Bitcoin and its underlying energy can also be expressed as the proposition that Bitcoin’s intrinsic value stems from the substantial amount of energy and capital investment that is needed for its creation [102]. As Sztorc [103] pointed out, “Satoshi’s design insight was to channel that inevitable work into a cumulative process, to optimally stabilize a peer-to-peer clock in a cartel-resistant way”. In this regard, Bitcoin bears a striking resemblance to the ideas of Vaclav Smil [104], who saw energy as the only universal currency, and Henry Ford, who championed the creation of an “energy currency” as the basis for a new monetary system about 100 years ago. While this did not

happen in Ford’s time, the likelihood that Bitcoin will establish itself as such a currency increases with the amount of time it is around (“Lindy effect”) [105]. In this view, Bitcoin links energy, money, and the economy. Bitcoin is basically information, which is gained by reducing entropy. This bears a striking resemblance to the philosophical conception of money as information in the “Information Theory of Money” [106]. This entails that energy needs to be used to reduce entropy and to create information, which makes Bitcoin store energy. Hatzis [107] argued that Bitcoin is a battery that can store money—a metaphor that is criticized by Luther [108], who pointed out that this might induce people to believe that energy can actually be stored in Bitcoin such that it creates value. Finally, Alizart [109] combined all concepts: “Cryptocurrencies enable the optimal adjustment of the relationship between money and activity by serving as a converter between information and energy” (p. 110).

Another complex topic is the actual amount of energy that goes into Bitcoin and miners’ motivations to invest in it. As outlined above, this amount is not determined by the network but follows from the design of the PoW mechanism that adapts its difficulty to the prevailing level of competition. Edwards [110] empirically confirmed a close relationship between Bitcoin’s price and its energy value and concludes that “increased energy input increases the fair value of Bitcoin (and vice versa for decreases)”. This justifies the approximation of Bitcoin’s intrinsic value as the sum total of all energy invested [102]. Based on the rationale outlined in the previous sections, therefore, I suggest a description of how the Bitcoin incentive system works to reach consensus within the network and how it determines the amount of electricity used:

*Bitcoin (the protocol) provides a game-theoretic incentive that is paid out via Bitcoin (the network) in bitcoin (the cryptocurrency), which induces miners to perform algorithmic calculations that turn electricity into heat. The primary motivation for the vast majority of the miners lies in making personal gains in the form of rewards for block creation and transaction fees as well as future price increases in the bitcoin they hold. These game-theoretic incentives are intended to promote computational work to secure the network. Miners’ motivation to invest money (mainly to pay for hardware and electricity) is therefore positively correlated with their current and future evaluation of the cryptocurrency bitcoin in fiat money terms.*

What follows from this description is that neither Bitcoin (the protocol, the software, the network, and the blockchain) nor bitcoin (the cryptocurrency) are ultimately responsible for the amount of energy usage, which is regularly implied in the statement “Bitcoin uses/wastes/consumes energy”. This is an anthropomorphic misconception that attributes human intentions, behaviors, and, consequently, responsibilities to non-human entities. It is a bit like saying that my car (yacht? or private aircraft?) uses fuel, but I do not. Any means of transport has at least an engine that converts gasoline or electric energy into torque (i.e., mechanical work). Other than Bitcoin mining, which is done for monetary purposes (securing the network is only a side effect), cars, yachts, and aircraft fulfill transportation needs. In contrast, Bitcoin/bitcoin neither has an engine that depends on energy, nor does it make decisions. This anthropomorphism, rather conveniently for some, shifts the responsibility from those who purposefully decide to participate in the network primarily for monetary reasons to an abstract entity. In the case of Bitcoin, this is nothing more than a nine-page paper that inspired the creation of a network of computers exchanging information or a cryptocurrency that exists in digital records of unspent transaction outputs (UTXOs) on several thousand distributed computers. This nuanced view makes a huge difference for all further considerations since there are many ways in which energy for Bitcoin mining can be generated.

### 4. Modeling Bitcoin’s energy use

In this section, I present the main factors in the Bitcoin energy discussion. Initially, I elaborate on the amount, composition, and geographical distribution of the energy used for Bitcoin mining, all three of which are frequently discussed in the literature. In contrast, the actual amount of energy needed to secure the network is basically ignored. The

following lists of positive and negative effects illustrate the complexity of this topic. I end this section with several proposed solutions, all of which warrant further investigation, and a framework for the assessment of Bitcoin mining that suggests the integration of economic, technical, and legal/regulatory viewpoints. Finally, I present a network of interdependencies that is intended to objectivize or at least enlighten the discussion surrounding Bitcoin’s energy usage.

4.1. Amount, composition, and geographical distribution of energy consumption

The public discourse mostly revolves around the amount of energy or, more specifically, the amount of CO<sub>2</sub> resulting from the electricity that Bitcoin uses. To obtain the full picture, it is crucial to also consider the composition of the energy, the geographical location where it is produced, and its possible alternative uses (see Fig. 2). I round off this section with a couple of popular Bitcoin comparisons.

4.1.1. Amount

Bitcoin’s energy use has generated a lot of media coverage, and over the years, numerous approaches have been used to estimate Bitcoin’s demand. I briefly discuss some of the more recent sources here and provide a summary in Table 2. Using a feed-forward neural network, Calvo-Pardo et al. [111] estimated the carbon footprint of Bitcoin mining to be 2.77, 16.08, and 14.99 Mt (megaton) CO<sub>2</sub>eq for 2017, 2018, and 2019, respectively. Küfeoğlu and Özkuran [112] considered the performance of 269 different hardware models (CPUs, GPUs, FPGAs, and ASICs) and concluded that peak Bitcoin mining power use occurred during the two-week period commencing on 18 December 2017, with a demand of between 1.3 and 14.8 GW (gigawatt), whereby the maximum

demand figure is comparable to the demand of Finland or Denmark. Based on data from June 2018, they estimate the energy use of Bitcoin to be between 15.47 and 50.24 TWh (terawatt hours/year). Köhler and Pizzol [113] applied a life cycle assessment in an in-depth analysis of the past and future environmental impacts of Bitcoin. They estimated 31.29 TWh and a carbon footprint of 17.29 Mt of CO<sub>2</sub>eq for 2018, which, as the authors pointed out, is lower than the numbers in most related studies. On September 30, 2019, de Vries [114] applied a market dynamics approach and concluded that the Bitcoin network used 87.1 TWh of electrical energy. Kononova and Dek [115] developed a method to estimate Bitcoin mining’s carbon footprint based on miners’ geographical locations and, on September 2019, estimated a yearly use of 78.93 TWh and a range from 44.12 to 80.43 million tons of carbon emissions. Using a vector autoregression (VAR) framework, Fahmy [116] calculated approximately 43 Mt of CO<sub>2</sub>eq for 2020. For 2021, Rybarczyk et al. [117] estimated the electricity use of the Bitcoin network to be approximately 113.89 TWh and contrast this number with the global annual energy supply (~166,071 TWh), the global annual electricity generation (~26,730 TWh) and the amount of electricity lost annually in transmission and distribution (~2205 TWh).

Chereshnia [118] estimated that 2.98 Mt of CO<sub>2</sub> equivalent are emitted by Russian Bitcoin production and that the total emissions from cryptocurrency mining in Russia amount to 4.47 Mt of CO<sub>2</sub> equivalent. Based on data from the Cambridge Bitcoin Electricity Consumption Index (CBECI), McCook [119] quantified Bitcoin’s CO<sub>2</sub> output at 61.2 Mt of CO<sub>2</sub>. Sandner et al. [120] analyzed the period from September 2020 to August 2021 and wrote that an average Bitcoin transaction on the blockchain has a size of 670 bytes, estimating its carbon footprint to be 369.49 kgCO<sub>2</sub>eq. Their estimated electricity use was 90.86 TWh and 37.97 Mt of CO<sub>2</sub>eq (cf. also the estimate of the Bitcoin Mining Council).

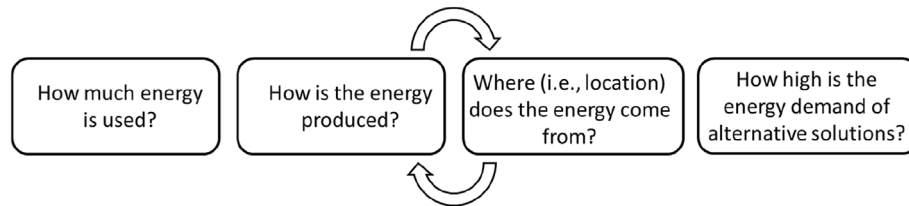


Fig. 2. Core questions pertaining to Bitcoin’s energy consumption.

Table 2  
Estimates of Bitcoin’s electrical energy and CO<sub>2</sub> footprints.

Estimate period	Energy use (TWh/year globally, unless stated)	Carbon emissions (Mt of CO <sub>2</sub> eq/year globally, unless stated)	Source
2017		2.77	Calvo-Pardo et al. [111]
2018		16.08	
2019		14.99	
Year to June 2018	15.47–50.24		Küfeoğlu & Özkuran [112]
2018	31.29	17.29	
Year to September 2019	87.1		Köhler and Pizzol [113]
Year to September 2019	78.93		de Vries [114]
2020		44.12–80.43	Kononova and Dek [115]
2021		43	Fahmy [116]
2021	113.89		Rybarczyk et al. [117]
Year to May 2021		2.98 (Mt: Russia)	Chereshnia [118]
September 2020–August 2021	90.86	61.2	McCook [119]
2021		37.97	Sandner et al. [120]
2022		369.49 (kg for a single transaction)	
2022	220	37.97	Bitcoin Mining Council [12]
2022	123.75	831 (kg for a single transaction)	MoneySuperMarket [121]
2022	1173 (kWh: single transaction)		
2022		88.44 (tons for one power plant)	Roeck and Drennen [122]
2022		68	Tandy [123]
2022		78 (Bitcoin and Ethereum)	Knutson [124]
July 2022	83.87		Cambridge Centre for Alternative Finance [125]
2022	7.26 (TWh/month)		
2022	107.65		Cambridge Centre for Alternative Finance [126]
February 2023	83.76	46.72	Digiconomist [127]

Interestingly, the Bitcoin Mining Council, a forum of Bitcoin miners that is naturally a strong proponent of Bitcoin, produced the highest estimate of 220 TWh for 2021 [12]. In regard to a single Bitcoin transaction, MoneySuperMarket [121] reported 831 kg of CO<sub>2</sub> output. Roeck and Drennen [122] presented a life cycle assessment of a natural gas power plant that mines Bitcoin behind-the-meter and estimated that it produces 88.44 tons of CO<sub>2</sub>eq per year and that this number would increase to 656.98 tons if the plant exclusively focused on Bitcoin mining. Tandy estimated the annual footprint for all cryptocurrencies to be 68 million tonnes of CO<sub>2</sub> [123]. An estimate published in *Forbes Magazine* quantified the combined output of Ethereum and Bitcoin mining as more than 78 Mt of CO<sub>2</sub>, equaling the tailpipe emissions of 15.5 million cars [124].

Interestingly, the data of most of the published articles can be traced back to a relatively small number of sources, most notably the “Bitcoin Energy Consumption Index” and the “CBECI”. The former is an estimate from the Cambridge Centre for Alternative Finance, which calculates annualized 2022 consumption of 83.87 TWh [125] (estimate: July 2022) and 107.65 TWh [126] (estimate: February 2023), respectively. The CBECI is maintained by the platform Digiconomist, which was founded in 2014 by Alex de Vries with the goal of “exposing the unintended consequences of digital trends”. According to this index, Bitcoin’s electricity use in July 2022 would be 7.26 TWh, 31.96% lower than the estimate of 10.67 TWh for May 2022, which illustrates that Bitcoin’s energy use can drop significantly over the course of just two months. Furthermore, the measurements in TWh yield the first noticeable energy use in May 2011 (i.e., 0.01 TWh), illustrating that Bitcoin’s energy use prior to that was not visible on a TWh scale. As of February 3, 2023, the Digiconomist lists the electrical energy need of bitcoin as 83.76 TWh per year and the corresponding carbon footprint as 46.72 Mt of CO<sub>2</sub> [127].

Another popular indicator for Bitcoin’s size is the network hashrate, which not only reflects the amount of energy but also takes into account the efficiency of the mining hardware. Increasingly, sophisticated hardware in combination with more spending on energy motivated by a higher bitcoin evaluation has led to soaring hashrates. The current measurement unit is EH/s (exahashes per second) with one EH/s equaling one quintillion (i.e., 10<sup>18</sup>) hashes per second. According to the Cambridge Centre for Alternative Finance [128], the global hashrate in January 2022 surpassed 175 EH/s. Newer estimated for August 2022 exceeded 200 EH/s [129]. Taking into account the future rewards per block and assumed price levels, Rhodes et al. [130] created different scenarios for Bitcoin and forecasted a possible global hashrate (Ex/s) for 2030 of 2000 Ex/s (assumed price: 150,000 USD/BTC).

#### 4.1.2. Composition

A substantial part of the energy discussion surrounding Bitcoin ignores the fact that not all energy is created equal. Specifically, electricity is a secondary energy source that is produced by converting primary sources (i.e., coal, nuclear energy, natural gas, solar energy, and wind energy) into electrical power. Electricity then serves as an energy carrier that can be converted into mechanical energy or heat. Importantly, electricity itself is neither renewable nor non-renewable, as this distinction pertains only to primary energy sources [131]. When the Bitcoin mining discussion is framed in an environmental context, as it usually is, it is not the amount of energy that matters most but rather the amount of CO<sub>2</sub> that results from its production, as well as other negative effects, such as the problematic disposal of radioactive waste in case nuclear energy is the primary source. As Carter [100] noted, energy use is not equivalent to carbon emissions, but it is rather the energy mix that determines Bitcoin’s environmental impact. For example, Köhler & Pizzol [113] investigated the environmental drivers of Bitcoin mining in their life cycle assessment study and concluded that “the influence of changes in electricity mix on the environmental impact is substantial” (p. 13602). It is therefore the carbon intensity of electricity—the number of grams of CO<sub>2</sub> that it takes to create one KW/h (kilowatt hour) of electricity—that matters, which heavily depends on how the electricity is generated. A recent CoinShares report compares the carbon intensity of

numerous countries, ranging from Kazakhstan (787 g/kWh), Azerbaijan (638 g/kWh), the United States (447 g/kWh), and China (318 g/kWh) to countries such as Norway (7 g/kWh) and Iceland (0 g/kWh), where hydropower is abundant [132].

In the 3rd Global Cryptoasset Benchmarking Study from 2020, which was published by the Cambridge Centre for Alternative Finance, the authors pointed out that “the topic [i.e., the environmental impact of PoW mining] is typically misrepresented in most sources and on both sides of the debate” [133] (p. 26). Based on survey data collected from 280 entities in 59 countries between March and May 2020, they found that 76% of the hashers (i.e., miners producing hashrates) use renewable energies as part of their energy mix and that the share of renewables in the total energy consumption amounts to 39%. The most commonly used power sources (by the number of hashers, who can use more than one source) are hydroelectric (62%), coal (38%), natural gas (36%), wind (15%), solar (15%), nuclear (12%), and geothermal (8%). Coinbase [134] noted that in May 2021 (i.e., prior to the Chinese government’s crackdown on mining), half of global mining was done in Sichuan, China, where abundant hydroelectric power led to 95% of mining being done with renewable sources. They also stated that 75% of miners worldwide use a mix that includes renewable energy. Based on CBECI data from January 2022, Neumueller [135] estimated that fossil fuels account for almost two-thirds (62.4%) of Bitcoin’s total electricity mix and only 37.6% stems from sustainable energy sources (renewables: 26.3%; nuclear: 11.3%).

De Vries et al. [136] presented estimations for Bitcoin’s electricity mix that show a strong decline in the use of renewables between 2020 (41.6%) and August 2021 (25.1%) and attributed this to the crackdown on mining in China. In this context, it also needs to be considered that the impacts of average and marginal emissions differ. Renewables and nuclear plants are regularly dispatched first to meet electrical loads, and more flexible resources (i.e., coal and natural gas) are dispatched to follow load fluctuations. An increasing demand from crypto-asset mining would therefore lead to the increased use of these more polluting energy sources, thus widening the gap between average emissions and marginal emissions [137]. This is disputed by Bitcoin proponents who proclaimed that Bitcoin could become the “first monetary system to hit net zero emissions by 2024” [138]. The logic is that by using renewables and factoring in carbon-negative mining (e.g., the use of previously vented sources of methane emissions), 72.7% of all Bitcoin mining is predicted to be zero-emission in March 2023, and full net zero-emission can be achieved by December 2024 [139]. Similarly, Carter and Stevens [140] calculated several future price scenarios for Bitcoin. In their base case (assuming that bitcoin reaches 60,000 USD by 2030), they expect electricity use and emissions to peak in 2024 (120 TWh, 47 Mt) and then to decline rapidly. They predict that by 2028, emissions will be below a net-zero pathway leading to a full reduction of carbon emissions in 2050. In a high price scenario (bitcoin at 490,000 USD by 2030), electricity use will peak in 2027 and fall thereafter. In this case, carbon emissions are predicted to be 22 Mt in 2040.

Conversely, the Bitcoin Mining Council estimated that 57.7% of the Bitcoin electricity mix stemmed from sustainable resources in Q3 2021 [141], which is substantially higher than the aforementioned estimates. Despite the variation in estimates and allowing for potential biases in the survey-based data sets, the numbers still indicate that the proportion of renewable energy used in Bitcoin mining is substantially higher than that in the U.S. grid [100]. Another suggestion to reduce energy use comes from Geels [142], who suggested applying phase change materials (i.e., materials that absorb and release thermal energy in the process of changing phase) to help mining farms reduce the energy requirements of their climate control systems.

#### 4.1.3. Geographical distribution

Bitcoin mining is popular around the globe, which is an important factor to consider in the assessment of its aggregate environmental impact since the composition of energy mixes varies strongly by region. Sun et al.

[143] reported that mining activities have been detected at more than 6000 geographical locations in regions across 139 countries. Importantly, the Cambridge Centre for Alternative Finance makes it clear that their data generation procedures hinge on three main assumptions: namely, that (a) the IP addresses of mining facility operators accurately indicate hashrate location, (b) the data provided by the participating mining pools represent Bitcoin's total geographic hashrate distribution, and (c) the available samples of regional data represent the total hashrate distribution within a given country. Under these assumptions, the United States held 71% of the Bitcoin network hashrate in January 2022, while mainland China and Kazakhstan held 21.11% and 13.22%, respectively [128]. Before the crackdown, mining in China primarily took place in four provinces, namely, Xinjiang and Inner Mongolia, where many coal plants are located, as well as Sichuan and Yunnan, where hydropower is prevalent [144].

Náñez Alonso et al. [145] used the Environmental Performance Index (EPI) as a starting point to create a list of 144 countries organized according to the sustainability of their cryptocurrency mining. They consider factors such as the energy mix, energy price, temperature, human capital, legal constraints, and R&D&I (Research, Development, and Innovation). Denmark and Germany lead the ranking of the most sustainable countries to perform cryptocurrency mining, and, in total, eight of the top ten most sustainable countries are located in Europe. The lowest-ranking countries are Venezuela, Libya, Suriname, and Bolivia. According to this ranking, the United States and China, the dominant cryptocurrency mining countries, are in the 25th and 40th positions, respectively. According to Sigalos [146], it was the expulsion of Chinese miners in 2021 that led to a drop in the overall hashrate and allowed the U.S. to become the major mining hotspot.

#### 4.1.4. Comparisons

To put things into perspective, the energy use of the Bitcoin network is regularly compared to global energy consumption (~170,000 TWh per year), global electricity consumption (~25,000 TWh), other cryptocurrencies, and alternative energy use cases. The Cambridge Centre for Alternative Finance makes it clear on its website that “there is nothing quite like Bitcoin that can be readily used for an apples-to-apples comparison” [126]. Comparisons of Bitcoin with other payment systems rarely take into account assessment criteria such as transaction finality and security [147], which is similar to comparing apples and oranges.

Bitcoin advocates frequently point out that cryptocurrency may use quite some energy in absolute terms but that this is still only a minor fraction of worldwide energy usage. In this regard, Alden [148] assumed a worldwide energy use of over 170,000 TWh per year to estimate the percentage attributable to Bitcoin at 0.1%. The Bitcoin Mining Council [12] stated that Bitcoin needs 0.14% of the world's total energy use; Carter [100] estimated 0.55%. If one takes the highest estimate from Table 2 (220 TWh from the Bitcoin Mining Council) and compares it to worldwide electricity consumption (24,877 TWh according to Enerdata [149]), this would produce an upper limit of 0.88% of the world's electricity usage. The Bitcoin Mining Council compares this number to the consumption of residential buildings (26,481 TWh), road vehicles (15,424 TWh), or non-residential buildings (9630 TWh). Or, to provide less vital examples, gold mining (571 TWh), computer games (214 TWh), and holiday lights (201 TWh). In terms of emissions, Sandner et al. [120] estimated a total Bitcoin footprint of 0.08% of worldwide CO<sub>2</sub>eq.

Comparing cryptocurrencies with metals, Krause and Tolaymat [150] wrote that “mining Bitcoin, Ethereum, Litecoin and Monero consumed an average of 17, 7, 7 and 14 MJ (Megajoule) to generate one US\$, respectively. Comparatively, conventional mining of aluminum, copper, gold, platinum and rare earth oxides consumed 122, 4, 5, 7 and 9 MJ to generate one US\$, respectively”. Elmandjra [151] claimed that, on a global scale, Bitcoin is more efficient than traditional banking and gold mining and estimates that Bitcoin emits 61 Mt of CO<sub>2</sub> as opposed to gold mining (144 Mt) and traditional banking (1368 Mt). Another popular comparison is between different consensus mechanisms. For example, Platt et al. [29] wrote that Bitcoin's energy use is at least three orders of

magnitude higher than that of the most demanding PoS systems. This number is confirmed by Gallersdörfer et al. [152], who assessed six PoS networks and found a range of electricity use from 70 MWh (megawatt hour) (Polkadot) to 1967 MWh (Solana), all of which are considerably lower than Bitcoin.

Finally, a highly popular comparison is that between Bitcoin and Visa or SWIFT (Society for Worldwide Interbank Financial Telecommunication). According to de Best [153], a single Bitcoin transaction uses 2189 kWh, while 100,000 Visa transactions need 149 kWh, which would make Visa 1,469,128 times more energy efficient than Bitcoin. Urquhart and Lucey [33] wrote that SWIFT “process[es] payments in seconds and handle[s] quadrillions of dollars per year” (p. 38), and Kohli et al. [154] compared the carbon footprint per transaction between Visa (0.00045 kg CO<sub>2</sub>) and Bitcoin (844.13 kg CO<sub>2</sub>). However, these comparisons regularly ignore the fact that SWIFT is a messaging network and VisaNet is a global network that processes payments, while Bitcoin is a settlement network. This means that in the latter case, the recipients can be confident that an inbound transaction cannot be reversed [147]. According to LeClair and Rule [155], Bitcoin is the world's most efficient value settlement network. Most importantly, comparisons such as these are based on current (estimated) values and therefore do not consider the possibility that layer 2 solutions might process the majority of future transactions off-chain, which would have a substantial impact on Bitcoin's “CO<sub>2</sub> per transaction” metric.

Of course, these comparisons work equally well in the other direction, and Bitcoin proponents regularly refer to the costs of gold mining, banking, or even the entire financial system. For example, McCook [119] noted that Bitcoin emits 61.2 Mt of CO<sub>2</sub>, gold mining emits 144 Mt of CO<sub>2</sub>, and the finance and insurance sector emits 1368 Mt of CO<sub>2</sub>. While gold acts as a store of value (including jewelry, which is by far its outstanding use case [156]) and might be an appropriate counterpart, Bitcoin is clearly not able to match the sum total of services provided by the global financial sector as of 2023.

#### 4.2. Energy needed for network security

The overarching question that dominates the public discourse and academic publications alike is “How much energy does Bitcoin use?” Almost completely neglected, however, is the related question of “How much energy does Bitcoin need?” or, more specifically, “What would be the minimum amount of energy needed to enable Bitcoin to function as a means of payment and store of value?” For example, CoinCarbonCap [157] compared numerous cryptocurrencies and ranked them according to their energy efficiency by including metrics such as transactions per MWh and CO<sub>2</sub> output per transaction. Bitcoin comes in last in this list, which is topped by Bitcoin SV and Bitcoin Cash. What is missing in the ranking, however, is the consideration of the level of network security generated for the price paid. This can be expressed in terms of the amount of energy it would take to compromise the network, for example, by performing a 51% attack, which would allow the attacker to reverse transactions and rewrite a part of the blockchain. This metric is important since the evaluation of a cryptocurrency correlates with its attractiveness to potential attackers, and more popular cryptocurrencies might provide greater incentives for attacks.

As outlined above, the amount of energy *used* is driven by monetary incentives and is under close scrutiny. Meanwhile, the amount of energy *needed* to keep the network alive and secure is more or less ignored. This amount depends on numerous factors, including the incentives for attacks (e.g., monetary gains, prestige, and destruction/discreditation of a competing system) and the effort that would be needed to launch an attack. Nevertheless, it might be worth considering, especially in case measures to curb Bitcoin mining (e.g., by taxation or regulation) are taken in the future. Such measures would not impact the way the network works or how many transactions can be processed but would affect its level of security, which is simultaneously the security of the stored transactions. The core issue is that the amount of energy invested is not

determined by the amount that is needed to secure the network (as would be done in conventional security systems) but rather by the monetary incentives that are generated by the chance to earn newly minted bitcoin and some transaction fees. This clever game-theoretic mechanism operates without any centralized interference and has been working well since 2009, but it is likely that the network has become oversecured in the meantime. This is due to the fact that the incentives for mining increase proportionally to the evaluation of bitcoin in fiat money, while the incentives for attacking the network do not. The question thus arises as to whether we have long surpassed the amount of energy that is needed to reasonably secure the Bitcoin network.

#### 4.2.1. Motivation for attacks

The next question regards the motivation for an attack on the Bitcoin network, and the answer depends on the respective perspective. An attacker might be motivated by (a) potential financial gains that can be made from a successful attack, (b) the removal of an unwanted rival to the existing financial system, or (c) simply enjoying the reputation of having destroyed the first and most prominent cryptocurrency. Obviously, the subjective appeal of these respective benefits cannot easily be quantified. Furthermore, breaking Bitcoin is not like breaking into Fort Knox. Instead of reaping the rewards in gold, a successful Bitcoin attacker could either purposefully destroy the network and/or spend a transaction twice (“double spending”). However, the attacker will not be able to steal bitcoins (i.e., UTXOs) from other users in the network unless the underlying cryptography can be broken, and the successful breaking would more or less destroy Bitcoin’s value. To stretch the Fort Knox analogy, this is the equivalent of successful intruders seeing the gold vanish in front of their eyes. Such attacks have happened before with other cryptocurrencies, for example, in the 2012 attack of the Eligius mining pool on a short-lived project called CoiledCoin. This attack was primarily motivated by the mining pool owner’s belief that CoiledCoin was a scam and was executed such that days’ worth of CoiledCoin’s transaction histories were reversed and a chain with empty blocks was mined, which finally caused users to abandon the cryptocurrency [158].

#### 4.2.2. Types of attacks

It is also necessary to clarify how Bitcoin can be attacked in the first place. The underlying cryptography Bitcoin uses to create digital signatures—the Elliptic Curve Digital Signature Algorithm (ECDSA) with the elliptic curve *secp256k1*—cannot be cracked with brute force mining power. Consequently, bitcoins (i.e., UTXOs) cannot be stolen, but recent transactions could potentially be reversed by a successful 51% attack, which is known as double spending [159]. As outlined in the previous paragraph, such attacks might also be used to demonstrate the vulnerability of a blockchain with the purpose of destroying it. Of course, rather than targeting the whole network, attackers might target an individual’s wallet, try to isolate individual nodes (Sybil attack), or execute a Denial of Service (DoS) attack. Another scenario, one that is beyond the capability of any human, is a global power outage that shuts down the Internet, potentially caused by a solar storm, in which case Bitcoin would most likely be a lesser concern.

Bitcoin proponents argue that new hardware (i.e., ASICs) makes energy use more efficient (i.e., more hashes per second are created) and consequently the network becomes more secure. ASICs merely convert energy into the likelihood of generating new blocks, and the competition is ultimately determined by the cost of energy. Since ASICs are publicly available, an increased hashrate will not automatically make the network more secure, as a potential malicious hacker also has the opportunity to acquire this improved hardware to attack the network. As mining equipment becomes increasingly more efficient over time [160], the level of competition rises proportionally and results in a higher hashrate rather than a drop in energy consumption.

#### 4.2.3. Potential attackers

Finally, it is important to clarify who the potential adversaries of Bitcoin are that could use energy to take over the network. Could it be public entities such as governments or central banks? This seems unlikely since (a) national authorities could use regulation to ban Bitcoin (of course this would not get rid of the global network and might lead to the occurrence of underground mining) and (b) it would be hard for any state (especially for the more democratic ones) to justify the humongous use of resources needed to destroy Bitcoin. Most importantly, the financial gains from destroying Bitcoin would be negligible in comparison to the required effort. Private organizations and individuals, on the other hand, routinely do not have the resources to launch a successful attack, while existing mining pools (a few of which taken together could control more than half of the network) have sufficient incentives not to destroy the network into which they have invested so much money. In addition, mining pools do not control the hashrates of the individual miners they are composed of, and the miners are incentivized to join another pool if they observe malicious behavior in their current pool. In summary, this does not mean that Bitcoin is not being attacked (different types of attacks are frequently being carried out) but rather that coordinated attacks from powerful entities such as governments or mining pools are rather unlikely. In summary, the question remains unanswered: How much energy would suffice for Bitcoin?

#### 4.3. Positive effects

In the following sections, I list several postulated energy-related advantages of Bitcoin. I loosely split them into environmental as well as economic and political benefits even though numerous overlaps exist. At times, it was hard to draw a boundary between those benefits that are related to energy and those that are not. It is noteworthy that I provide data and arguments as presented in the respective publications and that the verification or refutation of all claims need to be done through rigorous research and data collection.

##### 4.3.1. Environmental

Any analysis of Bitcoin’s environmental impact needs to also consider the scope and usefulness of Bitcoin’s realized and envisioned use cases and the respective alternatives. As of early 2023, Bitcoin’s role in the worldwide financial system is marginal (although Bitcoin maximalists might dispute that). Most applications in decentralized finance (DeFi) are based on other blockchains (mostly Ethereum), while Bitcoin is predominantly used as a store of value and a speculative asset. Yet, several authors compare Bitcoin with the banking system and the financial industry in general and highlight its potential to partially or fully substitute inefficient incumbents, which is based on the underlying assumption that Bitcoin has not yet reached its full potential. Since the focus of this paper is on energy consumption, I will briefly exemplify this viewpoint with a couple of studies and their reasoning. Rybarczyk et al. [117] scrutinized different assumptions regarding Bitcoin, ranging from beliefs that it has no value at all to those who see it as a future global monetary standard. It is especially adherents to the latter position who use comparisons of the energy consumption of Bitcoin (113.89 TWh) to that of gold (240.61 TWh) and the total banking system (263.72 TWh). Similarly, Khazzaka [161] found that Bitcoin uses 56 times less energy than the classical [payment] system and argued that a single PoW transaction is one to five times more energy efficient than its classical counterpart. Saylor [162] focused on Bitcoin’s current utility and argued that the Bitcoin network already has approximately a trillion USD of assets under management that are secured by 2 billion dollars’ worth of energy per year, pointing out that the costs for securing the network amount to only 20 basis points (i.e., 20/100 of one percentage point). Following such arguments, proponents of this view posit that a replacement of existing systems by Bitcoin will lead to reductions in energy use and, consequently, CO<sub>2</sub> emissions as well.

Apart from making existing applications more energy efficient, many Bitcoin proponents postulate that Bitcoin actually provides a strong incentive for using renewable sources. In general, miners face substantial competitive pressure and need cheap energy sources and efficient mining equipment to become or stay profitable [163]. Consequently, the question that arises is which resources provide the cheapest energy and in which cases competition might even be distorted due to substantial fossil-fuel subsidies that are common in countries such as China, Kazakhstan, and Iran [132]. Bitcoin proponents occasionally point out that “green energy is available for free”, and it is only the harvesting process that needs to be optimized [164]. One of the few academic approaches that postulates causal relationships comes from Sandner et al. [11] and is called the “Green Bitcoin Theory”. According to their reasoning, the architecture and incentive mechanisms of the Bitcoin network are conducive to increasing research and development investments in renewables. They argued that mining companies’ demand for low-cost energy requires suppliers and engineering companies to build and use efficient electricity-supplying facilities. Upstream investments in these facilities will allow mining companies to create profits downstream. In the case of a declining bitcoin price, they contend that those miners who mostly rely on conventional energy sources such as oil or gas will be forced to shut down.

The logic of the previous paragraph can be further extended to cases in which Bitcoin mining is the only economically viable option for using natural gas or even preventing the practice of flaring (i.e., burning of gas) [165]. The harvesting of natural gas often requires pipeline infrastructure, which frequently makes it unprofitable in remote regions, yet Bitcoin miners might exploit this opportunity by using mobile shipping containers that can be placed, for example, near an oil well [166]. The Bitcoin Clean Energy Initiative [167] stressed that Bitcoin miners are unique in that they offer a “highly flexible and easily interruptible load” (p. 1). Furthermore, they postulated that Bitcoin mining fosters the use of renewables and the search for novel energy storage solutions.

#### 4.3.2. Economic and political

As envisioned by Bitcoin maximalists, a novel monetary system can offer numerous advantages. Again, it is difficult to draw a boundary between the environmental and economic impacts of Bitcoin mining, but the basic assumption is that greater general economic efficiency will result in *indirect* environmental benefits. For example, Ammous [20] went so far as to claim that a non-inflationary monetary system could end or at least reduce wars since governments cannot easily print money for their warlike activities. It goes without saying that this would have a huge positive environmental impact. While not easy to quantify, such considerations are worthwhile to include in economic and political discussions related to Bitcoin due to their sheer importance.

When it comes to the financial industry, Saylor [162] argued that Bitcoin provides an energy-efficient alternative to secure assets. Tao et al. [168] took a look at the positive effects of Fintech development in general and concluded that “the higher the level of financial innovations in a country, the lower will be the carbon emissions after controlling for exports, GDP and capital formation” (p. 6). Of course, all such considerations assume that the current system will be replaced by a system based on Bitcoin and that Bitcoin does not continue as a mere add-on to an unchanged existing system.

In this respect, the location independence of Bitcoin miners is of particular importance, which is enabled by the relative ease with which mining equipment can be moved from one place to another. This has led to the claim that the proliferation of industrial Bitcoin mining might even be a driver of countries’ energy independence [169]. This is enabled by the relative ease with which Bitcoin mining can be done and the equal distribution of energy, especially of renewable resources such as solar energy, wind energy, and hydropower, across the planet. This not only fosters research on how to best use these renewables but might also have a democratizing effect [170].

The geographical flexibility of Bitcoin mining might incentivize the

use of either renewables or otherwise stranded resources. As mentioned in the previous section, this might have a direct positive environmental effect. However, given that miners are driven by monetary incentives, it is also crucial to consider the expected financial benefits that result from their decisions. Stranded gas is either flared due to limited pipeline capacity or comes from non-exploited wells due to logistical or economic reasons [133]. From a purely economic perspective, this is a waste of resources that could potentially fulfill an economic purpose. In this regard, Bitcoin gives economic meaning to otherwise “stranded or unwanted energy”. To make her case, Alden [148] provided examples of stranded hydroelectric power and natural gas that are vented or flared into the atmosphere because they cannot be used for economic reasons. The latter is primarily released as methane, which is an even stronger greenhouse gas than CO<sub>2</sub>. Similarly, Carter [100] mentioned the waste of renewable hydro energy in the Chinese provinces of Sichuan and Yunnan, which occurs simply as a result of differences in capacity between the dry and wet seasons. Rodríguez [171] provided the specific case of a Costa Rican hydropower plant that was on the brink of being shut down because of the country’s surplus of renewable energy. In this case, Bitcoin mining helped to sustain its operations and secure the employment of workers. McDonnell [172] reported that gas flaring is responsible for at least 1% of global carbon emissions and estimated that it wastes hundreds of millions of dollars per year. Gas companies that expect a regulatory crackdown to eliminate this practice are investigating alternative ways to use the energy, and Bitcoin mining is one of the more feasible options.

As outlined in the previous paragraphs, a major prerequisite to exploit stranded and curtailed resources is flexibility in regard to both location and operation. The general logic is that the use of Bitcoin’s flexible data centers incentivizes the use of renewable resources. Fridgen et al. [173] proposed an integrated energy system that connects plants, electricity markets, data centers, and sales markets. In such a system, monetary and information flows between all parties, especially data centers and renewable energy sources, help to ensure energy flexibility and stabilize the grid. In its memorandum, the Bitcoin Clean Energy Initiative [167] noted that Bitcoin miners are unique in that they offer a load that is flexible and easily interruptible, indicating that such miners can easily shut down in case more important demand arises. In this respect, Rhodes et al. [130] strived to quantify the impacts of large flexible data center loads in West Texas on the carbon emissions of the Texas electricity grid. They concluded that an additional data center load can not only incentivize more wind and solar energy but also that the flexible operation of such data centers can result in a net reduction of carbon emissions. Furthermore, the grid becomes more resilient since demand can be reduced during high-stress times. Pan [174] documented the reality of such scenarios, noting that nearly all industrial-scale miners in Texas shut off their equipment during a heat wave that pushed the state’s power grid to its limit. However, Carter and Connell [175] warned against overly optimistic expectations that Bitcoin mining could prevent a grid meltdown caused by black swan weather events. Instead, they argued that only better planning can help to avoid such situations. Nevertheless, they concluded that Bitcoin is an extremely suitable energy buyer for renewable grids due to its properties of interruptibility, attenuation (i.e., reducing use on a fractional basis), unconstrained location agnosticism, and scale independence (i.e., Bitcoin mining is fractionalizable).

According to the laws of thermodynamics, energy can be neither created nor destroyed. Accordingly, the mining equipment for cryptocurrencies creates a substantial amount of heat. As Chambers [99] noted, this energy can be used for heating instead of burning fossil fuels for this purpose. Practical applications are given by Hall [176], who reported the case of a Bitcoin miner using generated heat to dry wood and described an application where Bitcoin was mined in a greenhouse, which gives the farmers free heat for growing their crops. While the reuse of energy might actually drive the hashrate up since mining will become more profitable, it will also put inefficient miners who do not use their heat waste economically out of business [103]. Another positive side effect of

Bitcoin mining could be merge mining (alternatively: merged mining), which designates the process of simultaneously mining on two or more chains, a process that is also called Auxiliary Proof of Work (AuxPoW). This practice has become popular among Bitcoin miners and offers the possibility of receiving rewards for mining on an alternative chain [177]. Another positive aspect comes from Baur and Oll [178], who focused on Bitcoin's carbon impact from an investment perspective. They find that the addition of Bitcoin to a diversified equity portfolio can reduce the portfolio's aggregate carbon output while simultaneously enhancing its risk-return relationship. The underlying rationale for this is that Bitcoin investments can be less carbon-intensive than standard equity investments.

Finally, the fact that Bitcoin mining is mostly conducted in centralized and large-scale mining pools poses an opportunity to actually enforce the regulation of an inherently decentralized system. Antonopoulos [179] argued that the current mining processes concentrate energy production and demand and therefore facilitate regulation. In this regard, CoinShares [132] advised Western governments against banning Bitcoin mining from their jurisdictions since this would drive miners into regions with subsidized fossil fuels. Table 3 summarizes all previous arguments.

#### 4.4. Negative effects

Following the structure of the previous section, I seek to spark an informed discussion by providing the most popular arguments regarding the energy-related disadvantages of Bitcoin, as put forward by practitioners and academics. I also split them into environmental and economic/political impacts, even though the distinction is hard to make.

##### 4.4.1. Environmental

The most striking feature of Bitcoin's energy use is the sheer amount of electricity that is currently used by the network. Tovanich et al. [181] made it clear that bitcoin price increases further incentivize miners and force them to "compete in a prisoner's dilemma to upgrade their hardware continuously" (p. 869) and added that this emergent property of the network violates the original idea of Nakamoto: that one CPU should have one vote. Jones et al. [182] conducted a comprehensive economic analysis and concluded that between 2016 and 2021, the creation of each 1 USD in bitcoin market value caused 0.35 USD in global climate damage.

**Table 3**  
Energy-related advantages of Bitcoin.

Argument(s)	Exemplary literature
<i>Environmental</i>	
Energy efficiency (as compared to other systems)	Rybarczyk et al. [117], Khazzaka [161], Saylor [162]
Incentive for renewable energy sources	Das and Dutta [163], CoinShares [132], Sandner et al. [11]
Use of damaging energy, flare mitigation	Benson [165], Mitchelhill [166]
Utility-scale energy storage	Bitcoin Clean Energy Initiative [167]
<i>Economic and Political</i>	
Efficient monetary system	Ammous [20], Saylor [162], Tao et al. [168]
Location independence	Newar [169], Vukolić [170]
Stranded and curtailed resources	Blandin et al. [133], Alden [148], Carter [100], Rodríguez [171], McDonnell [172]
Flexible loads, baseload balancer, grid stability	Rhodes et al. [130], Moura [180], Fridgen et al. [173], Bitcoin Clean Energy Initiative [167], Pan [174], Carter and Connell [175]
Heating	Chambers [99], Hall [176], Sztorc [103]
Efficiency gains through merge(d) mining	BitMEX [177]
Reduced carbon emissions in portfolios	Baur and Oll [178]
Transparency, regulatory enforcement through concentration	Antonopoulos [179], CoinShares [132]

Based on its environmental impact, they compare Bitcoin with crude oil burned as gasoline. Using a systematic approach that takes into account not only the impact of CO<sub>2</sub> but also fine particulate matter (PM<sub>2.5</sub>), nitrogen oxides (NO<sub>x</sub>), and sulfur dioxide (SO<sub>2</sub>), Goodkind et al. [183] estimated that the creation of 1 USD in Bitcoin value was responsible for 0.49 USD in health and climate damages in the US and 0.37 USD in China. The authors also considered the geographical flexibility of cryptomining to be a challenge for regulators. Newberry [184] summarized the existing criticisms of Bitcoin's energy use, pointing out that a single Bitcoin transaction uses the same amount of energy that an American household uses in two months and that renewable energy accounts for less than 40% of Bitcoin's needs.

The energy composition that underlies Bitcoin mining is also a major topic among environmentalists, but, not surprisingly, their assessment of the energy mix is less favorable than that of Bitcoin proponents. According to the Bitcoin critics, the cryptocurrency's high valuation leads to a greater demand for energy created from natural gas or coal power plants [137]. For example, de Vries et al. [136] reported that environmentalists warn of the resurrection of 30 fossil-fuel power plants in the state of New York alone. De Vries [185] also warned that renewable energy will not solve Bitcoin's sustainability problem according to the argument that, especially in China, huge seasonal variability exists in hydropower and that these fluctuations are usually balanced out by using coal to generate electricity. De Vries et al. [136] outlined that mining projects that use flare gas would only yield a positive climate effect if their electricity replace electricity generated from higher carbon fuels or if they reduce waste gases, rather than supplementing them. Accordingly, Schinckus [186] doubted that a mining industry that is fueled by renewables will make PoW operations greener.

The total environmental impact of Bitcoin is determined not only by its operations but also by the costs that arise from the production, shipping, and disposal of its hardware. As outlined above, the ASICs used for Bitcoin mining are application-specific and cannot be used for any other purposes apart from mining. Therefore, critics argue that miners not only compete in energy use but also in acquiring the newest and fastest machinery, which results in a problem with e-waste. According to estimates from de Vries and Stoll [187], Bitcoin's e-waste adds up to 30.7 kilotons annually on May 2021. They developed a system dynamics e-waste generation cycle in which an increasing hashrate leads to declining profitability, which causes unprofitable devices to be disposed of and new types of more efficient devices to be developed, which, in turn, drives the hashrate up even more. This can be explained by the Jevons paradox, which postulates that a resource's improved efficiency generates more demand, which ultimately results in an increase rather than a decrease in its usage [188]. According to the Digiconomist platform operated by de Vries, the amount of e-waste has reached 61.06 kilotons as of June 2023 [189].

As mentioned in the previous section, heat is a byproduct of electricity consumption, and it can potentially be put to good use. However, this heat often poses a problem, which is proportional to the ambient temperature of the respective mining site and requires the use of additional resources or specific techniques (e.g., water cooling, immersion cooling) to cool the equipment. Cho [190] reported a case from a former coal power plant that converted to natural gas and started Bitcoin mining. To ensure the necessary cooling, it takes water from a nearby plant and releases it back into Seneca Lake (New York), endangering the lake's ecology and wildlife.

##### 4.4.2. Economic and political

As is the case with Bitcoin mining's postulated benefits, it is hard at times to draw a clear line between its environmental implications and its political and economic implications. A problem that definitely belongs to

the latter category is the global shortage of chips. Again, it is de Vries [191] who pointed out that an increased demand in the wake of the COVID-19 crisis resulted in chip shortages and manufacturing delays.<sup>4</sup> The increasing demand for Bitcoin mining equipment also negatively affects the production of electric vehicles, which are needed to meet global climate change goals.

Numerous case studies already exist that also highlight Bitcoin mining's negative impact on a local level. For example, Bacchi [193] reported that in Abkhazia's outdated energy system, cryptocurrency mining resulted in outages and overloaded power stations, which caused them to catch fire. In Kosovo, regulatory actions were taken after energy blackouts that affected millions of people. Bitcoin mining in Kosovo was especially attractive since several regions were exempt from electric bills [194]. Similar stories are reported from Iran, where officials partially blamed Bitcoin mining for power outages in Tehran and other large cities [195]. Howson and de Vries [196] emphasized that it is often low-income communities that experience the detrimental effects of Bitcoin mining and conflicts over resources. They provide the example of the Democratic Republic of Congo, where bitcoin miners outcompete locals when it comes to accessing cheap energy. Additionally, the strong incentive to make money can result in unsafe mining activities that might lead to accidents [197].

Finally, it is worthwhile to investigate whether the energy used for Bitcoin mining would truly be otherwise stranded, as discussed in the previous section, or whether it could be used for alternative purposes. Importantly, this also includes the question of whether the renewable energy used for Bitcoin mining needs to be substituted by more dirty energy for alternative uses. In this regard, Swanson [198] criticized the mantra of Bitcoin proponents who maintain that the need for cheap electricity will foster efforts for renewables and compared it to the logic of leaving a car running to incentivize the search for alternative power sources. Bitcoin also tends to exploit countries' inefficiencies that are caused by interventionist economies. Squires [199] provided the case of Argentina, where government-subsidized electricity allows miners to reap outside returns. Table 4 summarizes all previous arguments.

#### 4.5. Proposed solutions

Any discussion of proposed solutions to reduce Bitcoin's energy use needs to consider a potential transition from PoW to PoS. Since this topic has been discussed a lot in the context of Ethereum's transition, I mention it here without going into significant detail. A modification of the consensus mechanism would substantially alter the nature of the underlying consensus model, and Bitcoin proponents fear that this might compromise its level of decentralization [201]. It must be taken into account, however, that on the mining level, the Bitcoin network is already highly centralized. As of June 2023, the combined (monthly average) hashrate of the three largest pools (i.e., Foundry USA, AntPool, and F2 Pool) exceeded 65% of the global hashrate [202]. From a game-theoretic perspective, however, the mining pools possess a strong incentive not to cheat since any crash in the bitcoin price would devalue their previous investments. In case of misbehavior, the individual members of a cheating pool would be likely to direct their hashrate to other mining pools anyway. Another fundamental suggestion is pre-mining, a process that necessitates major involvement from a central authority and would mean even more substantial changes to the existing system [203]. As outlined above, these fundamental changes are therefore unlikely to happen on Bitcoin's base layer. However, this does not mean that an open debate is not warranted, particularly in light of the information and experience that was gained from Ethereum's transition.

Technical suggestions (BIPs) also exist on how to modify Bitcoin's

<sup>4</sup> In April 2023 Intel announced the discontinuation of its Bitcoin mining chips production [192], illustrating that is up to the manufacturers to decide which chips they produce.

**Table 4**  
Energy-related disadvantages of Bitcoin.

Arguments	Exemplary literature
<i>Environmental</i>	
Carbon footprint, transaction costs, lack of renewable energy	Tovanich et al. [181], Jones et al. [182], Goodkind et al. [183], Newberry [184], Schinckus [186]
Reactivation of fossil-fuel power plants	The White House [137], De Vries et al. [136], Spegele and Ostroff [200]
Energy composition	De Vries [185], de Vries et al. [136]
E-waste, need for new hardware	De Vries and Stoll [187], Digiconomist [189]
Wildlife impact through water heating	Cho [190]
<i>Economic and political</i>	
Global shortage of chips	De Vries [191]
Negative local impact (e.g., power outages/energy shortages/dangerous mining activities)	Bacchi [193], Bratanic [194], Turak [195], Howson and de Vries [196], Rustgi [197]
Inefficiency, opportunity costs, alternative uses	Swanson [198], Squires [199]

underlying PoW mechanism. One example includes the use of silicon photonic chips that use laser light and therefore demand less energy and function without heat waste [204]. Jacquet and Mans [205] are among those who concentrate on PoW and suggested a solution that suppresses the nonce field with the goal of achieving scalability without using much energy. Lasla et al. [206] proposed a system that relies on two mining rounds and labeled their suggestion Green-PoW. In contrast to traditional PoW, only selected runners-up of the first round are allowed to create the next block, thus reducing energy consumption by 50%. They also validate their proposed solution with respect to security, fork occurrences, censorship attacks, and mining centralization.

A creative suggestion on how to benefit from Bitcoin mining's flexibility comes from the Bitcoin Clean Energy Initiative [167]. As mentioned previously, the authors proposed that developers of utility-scale storage (i.e., large batteries with a storage capacity of up to hundreds of MWh) augment their battery offerings with Bitcoin miners such that they can use excess energy and improve returns for investors. The assumed flexibility of data centers is also the starting point for Rhodes et al. [130], who did not explicitly focus on Bitcoin but who argued that operating data centers in a flexible manner (i.e., by adding flexible load shed capabilities) can result in a net reduction of carbon emissions, which holds equally for the operation of Bitcoin.

As can be gleaned from the ongoing discussions, the fronts are hardened between Bitcoin proponents and opponents. Therefore, data are needed to be able to assess the impact of the measures that have been taken thus far. To create transparency, major players in the field have joined forces and launched a solar-powered mining project that also publishes metrics on a dashboard, which allows the public to assess its feasibility [207]. To facilitate carbon emission offsetting, Mullen and Finn [208] suggested the use of oracles (i.e., approved data sources for the outside world), which can provide independent and immutable emission data. In combination with government-sanctioned carbon credits, this could undergird a system in which miners are forced to offset their emissions or one that benefits those using environmentally friendly solutions [203]. Of course, such solutions require global coordination. If not, Bitcoin's mining flexibility would turn into a curse and drive miners into those regions where they can avoid such measures. In regard to regulation, Antonopoulos [179] argued that in cases where governments regulate and tax carbon, the demand for bitcoin supports and incentivizes the installation of renewable energy. Taken together, Howson and de Vries [196] considered four pathways, namely: the voluntary commitment of the private sector to use only renewable energy; a system of voluntary carbon offsetting; the application of existing financial regulation and tax frameworks; and finally, the globally coordinated ban of cryptocurrency mining. The authors concluded that the fourth option is likely to be the most effective. In light of a dawning energy crisis, the

**Table 5**  
Proposed solutions.

Solution	Source
<i>Technical solutions</i>	
Alternative consensus mechanisms (e.g., PoS, pre-mining)	Jha [201], Schmidt [203]
Improvements to PoW	Foxley [204], Jacquet and Mans [205]
Acknowledging the efforts of runner(s)-up	Lasla et al. [206]
Utility-scale storage	Bitcoin Clean Energy Initiative [167]
Flexible data centers	Rhodes et al. [130]
<i>Economic incentives and legislation</i>	
Renewable energy	Thomas [207]
Using oracles for carbon emission offsetting, carbon credits, or fees	Mullen and Finn [208], Schmidt [203]
Regulation and Taxation	Antonopoulos [179], Howson and de Vries [196], Campbell [210], European Commission [209], The New York State Senate [211]
<i>Interest groups and peer pressure</i>	
Crypto Climate Accord	<a href="https://cryptoclimate.org/accord/">https://cryptoclimate.org/accord/</a>
Bitcoin Clean Energy Initiative	<a href="https://bitcoin.energy/">https://bitcoin.energy/</a>
Bitcoin Mining Council	<a href="https://bitcoinminingcouncil.com/">https://bitcoinminingcouncil.com/</a>
Satoshi Action Fund	<a href="https://www.satoshiaction.io/">https://www.satoshiaction.io/</a>
Crypto Carbon Ratings Institute	<a href="https://carbon-ratings.com/">https://carbon-ratings.com/</a>

European Commission [209] has already announced in a recent plan that if “there is a need for load shedding [...] the Member States must also be ready to stop crypto-assets mining”. A more selective approach is the (regional) banning of fossil-fuel power plants for cryptocurrency mining and especially Bitcoin [210]. An example of this is Assembly Bill A7398C, which imposes a two-year moratorium on new PoW mining in New York. Miners that use renewables are exempt from this restriction [211].

Finally, it must be noted that the problem and its accompanying negative publicity have been recognized by the industry itself. Interest groups such as the Crypto Climate Accord, the Bitcoin Clean Energy Initiative, or the Bitcoin Mining Council strive to reduce the harmful environmental impacts of the industry through self-regulation. Additionally, the so-called Satoshi Action Fund was set up with the goal of “informing the policymakers and regulators about the benefits of Bitcoin mining”, and the Crypto Carbon Ratings Institute provides real-time data on the electricity consumption and carbon emissions of numerous

blockchain networks. Table 5 provides a summary of several proposed solutions and relevant interest groups.

4.6. Assessment of bitcoin mining

Drawing on the arguments outlined above, I suggest two frameworks in this section that can be used as starting points to investigate Bitcoin and its energy use in a rigorous manner. The first framework highlights the relevance of various perspectives—economic, technical, and political/legal—as different issues might be put on the agenda depending on the respective viewpoints and their underlying assumptions. The second framework goes into more detail and combines the topics discussed in the previous sections into a nomological network. The accompanying research questions are intended to guide research activities toward incremental knowledge gains.

4.6.1. Perspectives

In Fig. 3, I present a framework that combines different high-level perspectives (i.e., economic, technical, political, and legal), illustrating the reciprocal relationship between Bitcoin and its energy use as well as positive and negative environmental impacts. It further shows how the Bitcoin protocol incentivizes and determines the use of energy to create the blockchain. The valuation of bitcoin increases or decreases the amount of energy that is being used. The intended side effect is the security of the network, which deters potential attackers. As I have previously outlined, numerous positive and negative side effects can arise from the energy use.

Fig. 3 also illustrates various perspectives that can be taken into account when investigating (from a research perspective) or changing (from a technical, business, or legal perspective) the existing system. Let us start with the overarching question from an economic perspective of whether Bitcoin should be promoted, restricted, or stopped. This includes all the current or envisioned positive effects, many of which are extremely hard to assess in monetary terms (e.g., under the assumption that Bitcoin fosters financial inclusion, how much carbon would be generated by one additional person?), as well as the negative impacts expressed in economic terms. Investigating Bitcoin mining from an economic perspective one also needs to consider that current energy markets are distorted (e.g., due to subsidies) and that important negative externalities (e.g., CO<sub>2</sub> emissions) are not adequately priced. Thus, the

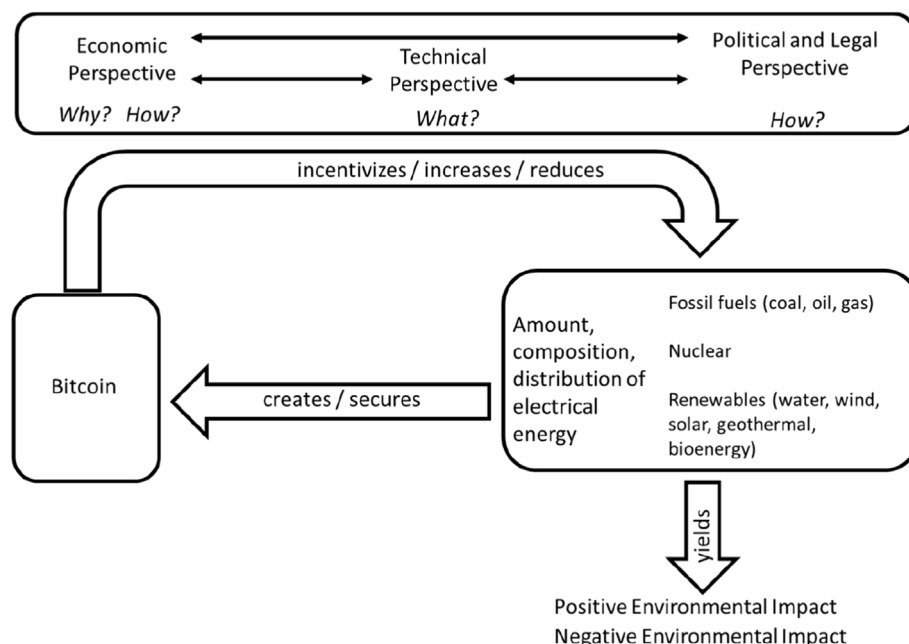


Fig. 3. Perspectives on Bitcoin’s energy consumption.

**Table 6**  
High-level research agenda.

Research Question
<i>Economic</i>
Why should Bitcoin be supported?
Alternatively: Why should Bitcoin be stopped?
How can economic incentives make Bitcoin more energy-efficient?
<i>Technical</i>
What technical measures can be taken to make Bitcoin energy efficient?
<i>Political and legal</i>
How can political and legal measures make Bitcoin more energy efficient?

questions arise *why* Bitcoin should be supported or stopped and *how* economic incentives can be applied such that a worldwide, decentralized ledger can be optimized in an energy-efficient manner. From a technical perspective, it is important to investigate *what* measures can be taken such that energy is used wisely and the protocol continues to function with less CO<sub>2</sub> output without compromising Bitcoin's underlying functionality and security level. In light of Bitcoin operating as a global system, research from a political and legal perspective needs to carefully investigate *how* political and legal measures impact the sum total of all negative externalities. Finally, all three perspectives are closely interconnected, such that regulatory measures also need to consider technical feasibility and economic impact. These broad research questions are summarized in Table 6.

#### 4.6.2. Research framework

In this subsection, I develop in a stepwise manner a detailed research framework pertaining to Bitcoin's energy use and suggest several research propositions. The first proposition naturally revolves around the nature of Bitcoin, its current use cases, and those that it might enable in the future. This includes the important question of whether Bitcoin can and will replace existing financial systems (such that Bitcoin's energy use can be directly compared with alternative uses) or whether it will continue to function more as an add-on, perhaps enabling additional uses that do not currently exist and are therefore difficult to compare. As outlined above, it might be hard to quantify Bitcoin's foreseen intangible benefits such as financial inclusion or enabling a libertarian economy by acting as a currency that cannot be artificially inflated. If instead the focus is on the functions of Bitcoin as a store of value and a medium of exchange, it can legitimately be contrasted with existing payment and monetary systems and potentially also the use of precious metals as a store of value. However, it is necessary to openly disclose the features and impacts of the respective systems to avoid potentially misleading comparisons. Importantly, it is only fair to also include potential future scenarios since Bitcoin is relatively new and might not yet have reached its full potential. Therefore, I suggest the first three research questions using "[...]" as a placeholder.

- RQ1a: What is the difference in functionality between Bitcoin and [...]?  
 RQ1b: How can/will Bitcoin change [...]?  
 RQ1c: What is the difference in functionality between Bitcoin and [...] in a future scenario?

As soon as the counterparts of the comparison are determined and their functionalities adequately described, the question arises as to how much energy goes into the respective solutions. Research questions 2a and 2b therefore consider various determinants of energy input. The focus of the framework is predominantly on fiat money, but it can easily be modified to also consider the energy input that is needed, for example, for gold mining. The resulting research questions are.

- RQ2a: What is the total energy input that goes into Bitcoin?  
 RQ2b: How much energy is needed to enable a specific Bitcoin use case?

RQ2c: How can the energy input for a specific Bitcoin use case be optimized (reduced)?

RQ2d: What is the total energy input that goes into [...]?

As soon as the energy demands for the respective counterparts are determined, it is possible to estimate their environmental impacts. As outlined above, the amount of CO<sub>2</sub> emissions cannot be directly deduced from the amount of energy that goes into Bitcoin mining since it is crucial to also consider the composition of the energy. Any rigorous research project therefore needs to take into account of the flexibility of this composition, while action research designs may wish to investigate appropriate measures to reduce this demand.

- RQ3a: How high is the environmental impact of Bitcoin mining?  
 RQ3b: How can the environmental impact of Bitcoin mining be optimized (reduced)?  
 RQ3c: How high is the environmental impact of [...]?

Apart from the intended main effects, numerous unintended consequences may arise from a more widespread adoption of Bitcoin. Therefore, any comprehensive investigation of a Bitcoin implementation also needs to openly disclose and discuss the consequences that accompany its introduction and compare them to those of its respective counterparts.

- RQ4a: What are the positive and negative side effects of Bitcoin?  
 RQ4b: What are the positive and negative side effects of [...]?

Fig. 4 summarizes the research questions in a nomological network. Importantly, many effects, whether they are intended or side effects, are intangible and hard to assess. This includes, for example, subjective valuations of privacy and monetary independence as well as beliefs in various economic philosophies. All of these topics have already been discussed in relation to Bitcoin, but it is fair to say that the jury is still out.

## 5. Discussion and implications

The starting point for this paper was the seemingly straightforward question of whether the energy that goes into the creation (i.e., mining) of bitcoin is actually wasted. The plethora of existing opinions and the heated debates surrounding this topic indicate that the answer might in fact be fairly complex, so the problem arises as to how to resolve the discussion deadlocks without shooting too many messengers. Therefore, is Bitcoin worth the energy use? On a superficial level, the answer is straightforward and mostly depends on one's (a) perceived value (benefit) of Bitcoin and (b) the way in which Bitcoin uses energy. However, things get complicated once a comprehensive assessment is done, which has to be performed on a global scale since Bitcoin is a worldwide network. Furthermore, a future outlook must be incorporated, given that Bitcoin's energy use is not stable and might increase or decrease over time and that the composition of its energy use (i.e., renewables vs. non-renewables) is also in flux. Therefore, a more thorough investigation of the topic uncovers many open questions that need to be approached by academics and practitioners alike.

### 5.1. Theoretical implications

A recommended starting point for academia would be to reach a consensus on the "true nature of Bitcoin", which entails the elimination of widespread misconceptions. In this paper, I have given my two cents on this question and highly appreciate critical comments. In regard to general perceptions of Bitcoin, three schools of thought can be roughly distinguished: Obviously, there are those who think that Bitcoin is a prime example of energy waste; a second group perceives Bitcoin as an inherently dirty technology that has some potential to go green [212]; and finally, a third group proposes that Bitcoin is already a driver for efficiency and the increased use of renewables [11]. By contrasting

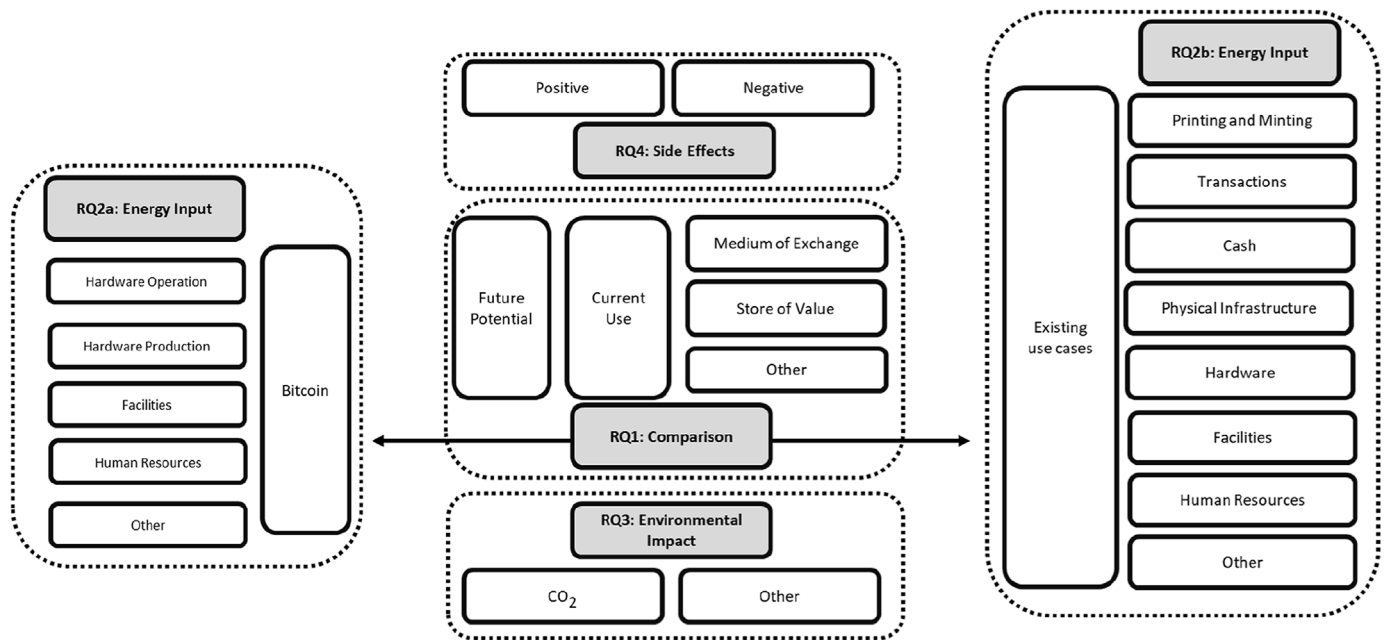


Fig. 4. A research framework for Bitcoin.

conflicting opinions on the subject, I found that the assessment of Bitcoin mining has an *absolute* and a *relative* perspective. The absolute perspective focuses on current amounts of energy or, more precisely, electricity or, even more precisely, the amount of CO<sub>2</sub> emissions, while the relative perspective contrasts the costs of Bitcoin with its (expected) benefits. The current discussion on this matter and the available information are indeed confusing. For example, Goodkind et al. [183] estimated that \$1 of bitcoin value was responsible for \$0.49 in health and climate damages in the U.S. and \$0.37 in China. Compare this with the results from Ante and Fiedler [213], who focused on the use of Bitcoin and wrote that “For every Dollar settled on the Bitcoin network in early 2021, between \$0.000065 to \$0.000097 (or 0.065%–0.0097%) are caused in environmental damages due to CO<sub>2</sub> emissions” (p. 9). Such disputes need to be resolved to provide a solid basis for all future assessments.

Academic research thus has numerous starting points for contributing to the current discourse. The first is technical and includes the investigation of whether there are viable alternatives to PoW and how they would impact Bitcoin’s offerings. A comprehensive comparison of consensus mechanisms was undertaken by Xiong et al. [214], who detailed the respective benefits and shortcomings of numerous mechanisms. They concluded that the most promising PoW alternatives for public chains include PoS, DPoS, PoH (Proof of History; proving that an event has occurred at a specific point in time), and CW-PoW (Compute and Wait; placing restrictions on successful nodes’ participation in the next round), although none of them is superior to PoW in every aspect.

From an economic and business perspective, Bitcoin mining can be considered a waste of energy if its negative aspects outweigh its benefits. While Bitcoin proponents praise its potential to lay the foundation for a just and fair economic order, its critics go so far as to state that “Bitcoin would be a calamity, not an economy” [215]. The logic underlying this criticism mostly follows Keynesian thinking, namely, that governmental and central bank interferences are needed in times of crisis since markets are not able to restore themselves in case of disturbances. For a hardcore Keynesian, Bitcoin provided a solution for a problem that does not exist. This is exactly what followers of a libertarian view (e.g., the Austrian School of Economics) vehemently dispute. They see Bitcoin as a decentralized alternative to central banking with the power to solve many economic problems caused by public intervention that have plagued economies for centuries [20]. The advantages and disadvantages of bitcoin were contrasted in great detail with gold, paper currency, and the

banking system in Badea & Mungiu-Pupăzan [216]. In any economic discussion, Bitcoin’s valuation is based on an underlying (implicit) philosophy and it can be far more than a mere means of payment. If one starts from a given economic worldview, it is only consequential that the assessment of an enabling technology such as Bitcoin will result in outcomes that are consistent with the underlying axioms of the respective view. In other words, Libertarians are likely to appreciate Bitcoin, while Keynesians might be inclined to view the technology as useless or even dangerous. From a personal point of view, I find it noteworthy that the same Western societies that promote free market economies and freedom of choice are vehemently opposed to an alternative currency or monetary system that they claim is inferior. By the logic of free markets, an inferior solution would succumb to its superior counterpart anyway. In this respect, several scenarios of how Bitcoin could coexist and compete with traditional fiat money have already been investigated by Schilling and Uhlig [217].

Governments’ ability to interfere with Bitcoin via regulation and taxation also opens up a broad research area for those who are interested in how the amount of energy used can potentially be steered by regulatory and fiscal approaches [218]. Such measures can also be economically justified by the need to internalize all costs and constitute a so-called Pigouvian tax on mining activities that prices in negative external impacts [219]. Podhorsky [220] suggested a microeconomic model with a focus on Bitcoin’s difficulty adjustment mechanism and claimed that these adjustments result in welfare losses for miners and users. She also showed that taxing the price of bitcoin can impact electricity costs.

Numerous research opportunities arise for behavioral researchers who are more interested in individual decision-making rather than macroeconomic implications. Chances are that the average person on the street does not know how Bitcoin/blockchain operates but that (s)he has an opinion that is mostly shaped by media coverage. Previous research has shown that it is relatively easy to change these opinions [221]. From an end user perspective, properties such as (perceived) privacy and their relevance for individual decision-making also constitute important antecedents for Bitcoin adoption. In the spectrum between total control and total anonymity, Bitcoin does not constitute an endpoint (despite this regularly being implied by those who postulate that it can enable illegal activities) since it is actually less anonymous than Monero or shielded transactions in Zcash, for example.

Apart from investigating end users who use bitcoin as a store of value or a medium of exchange, research is also needed on the behavior of miners, whose decisions ultimately determine the amount of energy use. De Vries [114] warned that higher mining profits incentivize market participants to make decisions that lead to suboptimal power efficiency in the network. A thorough investigation is also needed of how Bitcoin’s price volatility and mining affect the underlying energy markets and utility companies [222]. One of the few causal approaches in the field is the aforementioned “Green Bitcoin Theory” from Sandner et al. [11]. They postulated complex interactions between energy suppliers, Bitcoin mining companies, the Bitcoin network, and engineering companies. Models such as theirs provide a fruitful starting point for further confirmatory research.

From a methodological viewpoint, research on the implications of Bitcoin will benefit from applying a wide range of approaches and theoretical backgrounds. Apart from technical research that investigates improvement opportunities at the protocol level, researchers interested in the business and economic implications of Bitcoin can build on a strong repository of previous findings. In addition to well-established qualitative and quantitative approaches, tools such as scenario techniques have been proposed to combine academic rigor with practical relevance [223]. Previous examples in this direction stem from Zade et al. [224], who used scenarios to estimate the power demand of different cryptocurrencies, as well as Köhler and Pizzol [113], who presented scenarios that contrast technological change and miners’ location flexibility with a business-as-usual scenario. Fig. 5 summarizes the suggested theoretical implications for academia and also highlights the importance of specifying a given timeframe, since the environmental impact of Bitcoin might change over time, as might the range and the use of its possible applications.

5.2. Practical implications

Bitcoin mining and its use of energy is a topic of great practical relevance. Governments, central banks, and especially regulators all around the globe are currently considering how to best deal with blockchain technologies and cryptocurrencies, particularly Bitcoin. The suggested approaches range from officially adopting Bitcoin as a legal tender to completely banning it. Acknowledging the complexity and multidimensionality of the subject, the White House Office of Science and Technology Policy (OSTP) calls for transparency and encourages crypto-asset industry associations, including equipment manufacturers and mining firms, to “publicly report crypto-asset mining locations, annual electricity usage, GHG [greenhouse gases] emissions using existing protocols, and electronic waste recycling performance”. It also calls for further research to “improve understanding and innovation” with the goal of increasing the accuracy of estimates [137] (p. 8).

Additionally, numerous pressure groups seek to influence decision-making in their desired direction. Bitcoin is predicted to have significant macroeconomic implications, either for better or for worse, and much of this depends on its method for achieving decentralized

consensus and its demand for electricity. Responsible energy use and sustainable resources are of paramount importance in the current environmental crisis, and nobody can claim that we have not been warned. Almost four decades ago, Georgescu-Roegen [15] had already concluded that “all waste of energy - by overheating, overcooling, overspeeding, overlighting, etc. - should be carefully avoided, and if necessary, strictly regulated” (p. 378).

It is the goal of this paper to sketch numerous opinions on Bitcoin mining. For this reason, I have included articles and reports from public media to avoid purely academic introspection, which is an approach that is warranted by the topic’s great public relevance. Research is clearly needed that breaks out of academic ivory towers and helps policy makers worldwide base their decisions on unbiased investigations and data rather than on filtered information and hearsay. In this regard, it is astounding how many misconceptions about Bitcoin are still in circulation. However, the amount of electricity that goes into Bitcoin is undeniably substantial. From a practitioner’s point of view, and assuming that Bitcoin has beneficial use cases, there are two overarching questions that need to be investigated: (1) Is the amount of energy that goes into Bitcoin justified? and (2) Can the amount of energy that goes into Bitcoin be reduced without compromising its (beneficial) functionality?

Numerous conflicting opinions exist regarding not only the economic consequences of Bitcoin adoption but also the extent to which it can be regulated and what kind of environmental consequences the different approaches might have [135]. Of course, there are those who favor simply banning Bitcoin. However, previous experiences have shown that this approach could lead to an exodus of miners into jurisdictions that are less regulated, and the idea of reaching a global agreement on Bitcoin is, as with any other topic, rather wishful thinking. Another approach includes the taxation of carbon emissions, which would make dirty energy more expensive and therefore less attractive for Bitcoin. The underlying idea of this approach would be to enforce the shift toward renewables. Then, there are those who prefer a site-regulation policy to change the energy use structure of mining activities [3]. Finally, other authors advocate a mix of regulatory and economic measures, such as increasing the price of cryptocurrency mining, taxation of cryptocurrencies, carbon offset mandates, and bans on dirty mining procedures [225]. To support the general public and policy makers, academics are called upon to use their repository of available theories and methods to rigorously and independently investigate these approaches (and others) as well as their expected implications.

6. Conclusion, limitations, and future research

Investigating the relationship between Bitcoin and its energy use from a narrow and biased perspective is easy. Accordingly, many mass media outlets cannot withstand the temptation to create catchy headlines by comparing Bitcoin’s energy use with those of selected countries and seasoning their stories with references to money laundering or drug dealing. Conversely, Bitcoin maximalists describe Bitcoin as a full replacement for the current financial system that substantially reduces

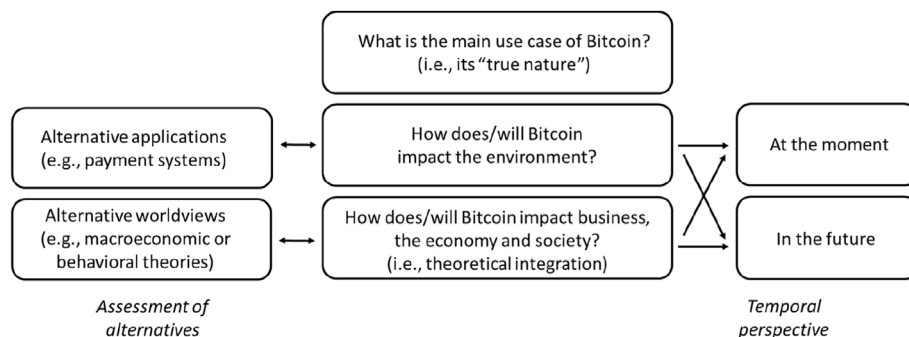


Fig. 5. Theoretical perspectives on Bitcoin.

energy use and fosters renewable resources. However, once one dives deep enough, the topic of Bitcoin's energy use and its resulting environmental impact is of stunning complexity. The mining process itself and its economic purpose are frequently misunderstood, as is its connection to network security, cryptography, and economic incentives. Energy use is not the main problem, but it is the production of CO<sub>2</sub> that causes major concerns, which depends greatly upon the way in which electricity is produced. It is therefore an oversimplification to refer to Bitcoin's energy use without taking into account the means of its production, the resulting environmental impact, alternative energy uses, and the substitution of existing use cases, all of which also need energy. Misconceptions and simplifications aside, numerous proponents and opponents provide plenty of arguments for their respective viewpoints. Therefore, who is correct? Presumably, this mostly depends on one's underlying assumptions and, importantly and frequently neglected, Bitcoin's future development.

A rational and fair discussion needs to weigh the benefits of a solution against its costs. In the case of Bitcoin, this needs to be done on a global level. It cannot be expected that those who are directly threatened by Bitcoin—mostly incumbents from the financial sector—will sing its praises, nor that those who benefit from its appreciation and mining operations will condemn its application. As I argue in this paper, a reasonable starting point would be to put the responsibility for energy use on the shoulders of those who actually use it, namely, the miners. The abstract entity that is Bitcoin just provides the game-theoretic incentive structure, but it is the miners who decide on the type of energy they use and whether they are willing to shut down their equipment in times of alternative demand.

From an academic perspective, it is only fair to listen to both sides and assess their arguments. In a first and crucial step, numerous errors and misconceptions pertaining to Bitcoin's mining process, often propagated by prestigious institutions and reputable academic outlets, need to be eliminated. Wrong assumptions and erroneous numbers that are disguised as facts must be removed from the public discussion, which includes the popular comparisons of Bitcoin to systems to which it is only loosely related. It is also crucial to discuss potential modifications of current financial and monetary systems and to consider the impact of regulatory and legal changes. While this might not resonate well with hardcore libertarians, it is only fair to argue that negative externalities such as CO<sub>2</sub> emissions are not adequately priced in the current economic system, which constitutes a market failure and calls for more regulation.

A substantial amount of research on blockchain fundamentals is done in technical communities, and I encourage academics working in areas such as economics, business, and the social sciences to put a greater emphasis on design science as well as action research approaches with a focus on solving pending problems and propagating objective knowledge. Much too often, the focus in these communities is on post hoc confirmatory studies that showcase academic rigor but only marginally contribute to existing debates.

To inform future discussions, I collected information from various sources pertaining to the amount, composition, and geographical distribution of Bitcoin's energy use. Carefully scrutinizing these data provides a solid starting point for debating more sophisticated arguments. This includes the questions of what the true nature of Bitcoin is (i.e., what purpose it can fulfill) and how much energy would be needed to sustain the network. More in-depth discussions are also needed pertaining to the numerous positive and negative effects that are attributed to Bitcoin by its followers and critics alike. The research framework that I present along with numerous research questions is intended to inspire and guide future research such that existing discussion deadlocks regarding the usefulness and true costs of Bitcoin can be uncovered and hopefully resolved.

I am aware that this paper, which is primarily based on existing literature and my personal opinions, might suffer from several limitations. First, given the ranges in values from different sources, at least some of the numbers reported herein have to be wrong. Furthermore,

even those that are correct will change over time. This obviously includes the total amount of energy that is used by Bitcoin but also the composition and geographical location of the energy that is used. Second, I might have missed important arguments either in favor of or against Bitcoin's energy use. Third, the arguments that I listed might be out of proportion. What I mean by this is that some of them might be highly important, while others might yield only marginal outcomes.

As such, future research needs to take my proposed research framework as a starting point, and I highly recommend that other researchers extend and change it with the goal of eliminating weaknesses and adding important perspectives that I missed. All the relevant numbers need to be constantly updated, and the assumptions underlying Bitcoin's positive and negative impacts need to be openly discussed. Furthermore, all assumed causalities that I have roughly outlined in the framework need to be tested, and further drivers and enablers as well as contingency variables must be added to the model. In this regard, academia can contribute substantially to objectivizing the discussions surrounding Bitcoin and its energy use as well as to create solutions that balance economic and environmental interests.

## Funding

This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

## Author contribution

This is a single-authored paper.

## Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

## References

- [1] The Economist, Mining cryptocurrencies is using up eye-watering amounts of power, *Economist* (2018). <https://www.economist.com/technology-quarterly/2018/08/30/mining-cryptocurrencies-is-using-up-eye-watering-amounts-of-power>. February 4, 2022.
- [2] J. Huang, C. O'Neill, H. Tabuchi, Bitcoin uses more electricity than many countries. How is that possible? *N. Y. Times* (2021). <https://www.nytimes.com/interactive/2021/09/03/climate/Bitcoin-carbon-footprint-electricity.html>. February 4, 2022.
- [3] S. Jiang, Y. Li, Q. Lu, Y. Hong, D. Guan, Y. Xiong, S. Wang, Policy assessments for the carbon emission flows and sustainability of Bitcoin blockchain operation in China, *Nat. Commun.* 12 (2021) (1938), <https://doi.org/10.1038/s41467-021-22256-3>.
- [4] cleanupBitcoin.com Bitcoin. Change the code, not the climate, <https://cleanupBitcoin.com/index.html>, 2022. June 24, 2022.
- [5] U. Bindseil, J. Schaff, Bitcoin's last stand. <https://www.ecb.europa.eu/press/blog/date/2022/html/ecb.blog221130~5301eecd19.en.html>, 2022. February 1, 2023.
- [6] United Nations, Sustainability Solution or Climate Calamity? the Dangers and Promise of Cryptocurrency Technology, *UN News*, 2021. <https://news.un.org/en/story/2021/06/1094362>. February 14, 2022.
- [7] D. Moore, Crypto miners' energy, climate costs draw white House scrutiny, *Bloomberg Law* (2022). <https://news.bloomberglaw.com/environment-and-energy/crypto-miners-energy-climate-costs-draw-white-house-scrutiny>. June 24, 2022.
- [8] P. Davies, EU Votes Down Proposal Limiting PoW Cryptos but Sets New Draft Rules, *Euronews*, 2022. <https://www.euronews.com/next/2022/03/14/europe-to-vote-on-limiting-pow-crypto-mining-used-by-bitcoin-and-ethereum>. April 9, 2022.
- [9] M. Quiroz-Gutierrez, Crypto is fully banned in China and 8 other countries, *Fortune* (2022). <https://fortune.com/2022/01/04/crypto-banned-china-other-countries/>. June 25, 2022.
- [10] T. Herwig, N. Reichelt, Mostly false: Bitcoin's "rapidly increasing use of fossil fuels", *Eufactcheck.Eu* (2021). <https://eufactcheck.eu/factcheck/mostly-false-bitcoins-rapidly-increasing-use-of-fossil-fuels/>. February 14, 2022.
- [11] P. Sandner, D. Wingen, S. von Jan, A. Straub, The green Bitcoin theory: how are Bitcoin, electricity consumption and green energy related? *Medium* (2020). <https://philippsandner.medium.com/the-green-bitcoin-theory-how-are-bitcoin-electricity-consumption-and-green-energy-related-7d4e1c1e1e1e>

- ctricity-consumption-and-green-energy-related-b541b23424ab. February 14, 2022.
- [12] Bitcoin Mining Council, Global Bitcoin mining data review Q4 2021, Bitcoin Min. Council (2022). <https://Bitcoinminingcouncil.com/wp-content/uploads/2022/01/2022.01.18-BMC-Q4-2021.pdf>.
- [13] Y. Wang, B. Lucey, S.A. Vigne, L. Yarovaya, An index of cryptocurrency environmental attention (ICEA), *China Finance, Rev. Int.* 12 (2022) 378–414, <https://doi.org/10.1108/CFRI-09-2021-0191>.
- [14] A.R. Sai, H. Vranken, Promoting Rigour in Blockchains Energy & Environmental Footprint Research: A Systematic Literature Review, *ArXiv Prepr. ArXiv221011664*, 2022.
- [15] N. Georgescu-Roegen, Energy and economic myths, *South, Econ. J.* 41 (1975) 347–381, <https://doi.org/10.2307/1056148>.
- [16] A. Rejeb, Z. Suhaiza, K. Rejeb, S. Seuring, H. Treiblmaier, The Internet of Things and the circular economy: a systematic literature review and research agenda, *J. Clean. Prod.* 350 (2022) 131439, <https://doi.org/10.1016/j.jclepro.2022.131439>.
- [17] C. Bendiksen, What is Bitcoin? *CoinShares* (2020). <https://coinshares.com/insights/what-is-Bitcoin>. February 4, 2022.
- [18] K. Ashford, What is Bitcoin and how does it work? *Forbes Advis* (2021). <https://www.forbes.com/advisor/investing/cryptocurrency/what-is-Bitcoin/>. June 28, 2022.
- [19] S. Nakamoto, Bitcoin: a peer-to-peer electronic cash system., <https://Bitcoin.n.org/Bitcoin.pdf> (2008) 1–9.
- [20] S. Ammous, *The Bitcoin Standard: the Decentralized Alternative to Central Banking*, John Wiley & Sons, Hoboken, New Jersey, 2018.
- [21] A. Feign, How much energy does Bitcoin use?. <https://www.coindesk.com/business/2021/08/18/how-much-energy-does-Bitcoin-use/>, 2021. February 4, 2022.
- [22] H. Treiblmaier, What is coming across the horizon and how can we handle it? Bitcoin scenarios as a starting point for rigorous and relevant research, *Future Internet* 14 (2022) 162, <https://doi.org/10.3390/fi14060162>.
- [23] M. Pfister, N. Kannengießer, A. Sunyaev, Finding the right balance: technical and political decentralization in the token economy, in: M.C. Lacity, H. Treiblmaier (Eds.), *Blockchains Token Econ. Theory Pract.*, Palgrave Macmillan, London, Great Britain, 2022, pp. 53–86.
- [24] L. Ren, Analysis of Nakamoto consensus. <https://eprint.iacr.org/2019/943>, 2019.
- [25] N. Shanker, Securing the blockchain: how the blockchain prevents fraud, *HackerNoon* (2022). <https://hackernoon.com/securing-the-blockchain-how-the-blockchain-prevents-fraud>. July 25, 2022.
- [26] Crypto Carbon Ratings Institute, The Merge: Implications on the Electricity Consumption and Carbon Footprint of the Ethereum Network, *Crypto Carbon Ratings Institute, Dingolfing, Germany*, 2022. <https://carbon-ratings.com/>. February 2, 2023.
- [27] M. Wendl, M.H. Doan, R. Sassen, The environmental impact of cryptocurrencies using proof of work and proof of stake consensus algorithms: a systematic review, *J. Environ. Manag.* 326 (2023) 116530, <https://doi.org/10.1016/j.jenvman.2022.116530>.
- [28] J.P. Lowery, *Softwar: A Novel Theory on Power Projection and the National Strategic Significance of Bitcoin*, Independently published, 2023.
- [29] M. Platt, J. Sedlmeir, D. Platt, P. Tascas, J. Xu, N. Vadgama, J.I. Ibañez, Energy footprint of blockchain consensus mechanisms beyond proof-of-work, *ArXiv210903667 Cs* (2021). <http://arxiv.org/abs/2109.03667>. February 5, 2022.
- [30] Kraken Intelligence, Proof-of-Work vs. Proof-of-Stake: securing the chain, *Kraken Intellig.* (2022). <https://kraken.docsend.com/view/2gw6c4da9h5ccmh>. February 5, 2023.
- [31] International Telecommunication Union, Recommendation L.1317 : Guidelines on Energy Efficient Blockchain Systems, International Telecommunication Union, Geneva, Switzerland, 2021. <https://www.itu.int/rec/T-REC-L.1317-202111-1/en>. May 5, 2023.
- [32] I. Malakhov, A. Marin, S. Rossi, D. Smuseva, On the use of proof-of-work in permissioned blockchains: security and fairness, *IEEE Access* 10 (2022) 1305–1316, <https://doi.org/10.1109/ACCESS.2021.3138528>.
- [33] A. Urquhart, B. Lucey, Crypto and digital currencies — nine research priorities, *Nature* 604 (2022) 36–39, <https://doi.org/10.1038/d41586-022-00927-5>.
- [34] J. Connell, How much does it cost to run a full Bitcoin node? – Featured Bitcoin news, *Bitcoin News* (2017). <https://news.Bitcoin.com/cost-full-Bitcoin-node/>. May 5, 2023.
- [35] C. Dwork, M. Naor, Pricing via processing or combatting junk mail, in: E.F. Brickell (Ed.), *Adv. Cryptol. — CRYPTO' 92*, Springer, Berlin, Heidelberg, 1993, pp. 139–147, [https://doi.org/10.1007/3-540-48071-4\\_10](https://doi.org/10.1007/3-540-48071-4_10).
- [36] A. Back, Hashcash, 1997. <http://www.cyberspace.org/hashcash/>. July 25, 2022.
- [37] K. Erturk, On the Tobin tax, *Rev. Polit. Econ.* 18 (2006) 71–78, <https://doi.org/10.2139/ssrn.386963>.
- [38] H. Vranken, Sustainability of Bitcoin and blockchains, *Curr. Opin. Environ. Sustain.* 28 (2017) 1–9, <https://doi.org/10.1016/j.cosust.2017.04.011>.
- [39] Braiins, How much would it cost to 51% attack Bitcoin? *Braiins* (2021). <https://braiins.com/blog/how-much-would-it-cost-to-51-attack-Bitcoin>. July 26, 2022.
- [40] L. von Mises, *Theorie des Geldes und der Umlaufmittel*, Duncker & Humboldt, München und Leipzig, 1912. <https://mises.org/library/theory-money-and-credit>. June 28, 2022.
- [41] J. Tucker, Bitcoin and mises's regression theorem. <https://tucker.liberty.me/Bitcoin-and-mises-regression-theorem/>, 2014. January 27, 2021.
- [42] A. Narayanan, J. Clark, Bitcoin's academic pedigree, *Commun. ACM* 60 (2017) 36–45, <https://doi.org/10.1145/3132259>.
- [43] N. Kannengießer, S. Lins, T. Dehling, A. Sunyaev, Trade-offs between distributed ledger technology characteristics, *ACM Comput. Surv.* 53 (42) (2020) 1–42, <https://doi.org/10.1145/3379463>, 37.
- [44] Genesis DevCon, Draft: what are blockchain protocols and how do they work? *Medium* (2018). <https://medium.com/@genesishack/draft-what-are-blockchain-protocols-and-how-do-they-work-94815be5efa7>. June 30, 2022.
- [45] G. Dorfleitner, F. Muck, I. Scheckenbach, Blockchain applications for climate protection: a global empirical investigation, *Renew. Sustain. Energy Rev.* 149 (2021) 111378, <https://doi.org/10.1016/j.rser.2021.111378>.
- [46] River Financial, What is a Bitcoin improvement proposal (BIP)?, in: *River Learn Bitcoin Technology*, River Financ, 2022. <https://river.com/learn/what-is-a-Bitcoin-improvement-proposal-bip/>. February 14, 2022.
- [47] GitHub, Bitcoin Core integration/staging tree. <https://github.com/Bitcoin/Bitcoin/blob/3ce40e64d4ae941965855fd1fb250b93f52684a/doc/bips.md>, 2022. February 14, 2022.
- [48] M. Cepnik, G.J.F. Echaiz, T.B. Solari, R. Vergé, A New Look at the Bitcoin Blockchain, *Blockchain Research Institute*, Toronto, Canada, 2020. <https://www.blockchainresearchinstitute.org/project/a-new-look-at-Bitcoin/>. February 4, 2022.
- [49] J.J. Kearney, C.A. Perez-Delgado, Vulnerability of blockchain technologies to quantum attacks, *Array* 10 (2021) 100065, <https://doi.org/10.1016/j.array.2021.100065>.
- [50] R. Benkoczi, D. Gaur, N. Nagy, M. Nagy, S. Hossain, Quantum Bitcoin mining, *Entropy* 24 (2022) 323, <https://doi.org/10.3390/e24030323>.
- [51] A. Narayanan, Analyzing the 2013 Bitcoin fork: centralized decision-making saved the day. <https://freedom-to-tinker.com/2015/07/28/analyzing-the-2013-Bitcoin-fork-centralized-decision-making-saved-the-day/>, 2015. July 29, 2022.
- [52] B. Nibley, Proof of Stake: a process used to validate crypto transactions through staking, *Bus. Insid.* (2022). <https://www.businessinsider.com/personal-finance/proof-of-stake>. July 29, 2022.
- [53] K. Rees, What is an “ASIC-resistant” cryptocurrency? 5 examples, *MUO* (2022). <https://www.makeuseof.com/what-is-an-asic-resistant-cryptocurrency/>. July 29, 2022.
- [54] S.D. Lerner, A new mystery in Satoshi timestamps, *Bitslog* (2020). <https://bitslog.com/2020/06/22/a-new-mystery-in-satoshi-timestamps/>. July 29, 2022.
- [55] Bitcoin Mining Council, Global Bitcoin mining data review Q3 2021, Bitcoin Min. Council (2021). <https://Bitcoinminingcouncil.com/wp-content/uploads/2022/01/2022.01.18-BMC-Q4-2021.pdf>.
- [56] S. Polane, Is Bitcoin mining in trouble? History may have the answer.... <https://www.polaneconsult.com/2022/06/22/is-Bitcoin-mining-in-trouble-history-may-have-the-answer-how-it-works/>, 2022. August 2, 2022.
- [57] N. Brown, Bitcoin miner power consumption: how much energy do Bitcoin miners consume? *Kompulsa* (2021). <https://www.kompulsa.com/Bitcoin-miner-power-consumption-much-energy-Bitcoin-miners-consume/>. February 1, 2023.
- [58] NeoMam Studios, The cost of mining Bitcoin in 198 different countries, *Vis. Capital* (2022). <https://www.visualcapitalist.com/cp/the-cost-of-mining-Bitcoin-in-198-different-countries/>. August 11, 2022.
- [59] A. Jezard, Bitcoin will consume more power than the world does today, *World Econ.* (2020). *Forum.* (2017), <https://www.weforum.org/agenda/2017/12/Bitcoin-consume-more-power-than-world-2020/>. May 15, 2021.
- [60] C. Mora, R.L. Rollins, K. Taladay, M.B. Kantar, M.K. Chock, M. Shimada, E.C. Franklin, Bitcoin emissions alone could push global warming above 2°C, *Nat. Clim. Change* 8 (2018) 931–933, <https://doi.org/10.1038/s41558-018-0321-8>.
- [61] Statista, Daily Bitcoin transactions 2017–2021, *Statista* (2022). <https://www.statista.com/statistics/730806/daily-number-of-Bitcoin-transactions/>. June 26, 2022.
- [62] D. Held, PoW is efficient, *medium.* <https://danhd.medium.com/pow-is-efficient-aa3d442754d3>, 2018. August 6, 2022.
- [63] E. Masanet, A. Shehabi, N. Lei, H. Vranken, J. Koomey, J. Malmodin, Implausible projections overestimate near-term Bitcoin CO<sub>2</sub> emissions, *Nat. Clim. Change* 9 (2019) 653–654, <https://doi.org/10.1038/s41558-019-0535-4>.
- [64] J. Sedlmeir, H.U. Buhl, G. Fridgen, R. Keller, The energy consumption of blockchain technology: beyond myth, *Bus. Inf. Syst. Eng.* 62 (2020) 599–608, <https://doi.org/10.1007/s12599-020-00656-x>.
- [65] Strack, Expect more Bitcoin miners to go bankrupt in 2023, *Blockworks* (2022). <https://blockworks.co/news/more-crypto-miner-bankruptcy-2023>. May 5, 2023.
- [66] A. Munro, Bitcoin's energy consumption will grow, and it can't be stopped, *Finder.Com.Au.* (2018). <https://www.finder.com.au/Bitcoins-energy-consumption-will-grow-and-it-cant-be-stopped>. July 29, 2022.
- [67] C. Schinckus, C.P. Nguyen, F.C.H. Ling, Crypto-currencies trading and energy consumption, *Int. J. Energy Econ. Pol.* 10 (2020) 355–364.
- [68] J. Gonzalez-Barahona, Factors determining maximum energy consumption of Bitcoin miners, *ArXiv:2107.10634v1* (2021) 1–24.
- [69] Bitcoin Glassnode, Hash rate - Glassnode studio. [https://studio.glassnode.com/metrics?a=BTC&clid=00Q1100000LlQY8UAN&pm= mining.HashRateMean&pmScl=lin&pmSc=lin&pmRes=1month&pmU=1648850399&utm\\_campaign=&utm\\_medium=firstmover&utm\\_source=newsletters&utm\\_zoom=,](https://studio.glassnode.com/metrics?a=BTC&clid=00Q1100000LlQY8UAN&pm= mining.HashRateMean&pmScl=lin&pmSc=lin&pmRes=1month&pmU=1648850399&utm_campaign=&utm_medium=firstmover&utm_source=newsletters&utm_zoom=,) 2022. July 29, 2022.
- [70] BTC.com, Difficulty - BTC.com, *Bitcoin Diffic.* (2022). <https://btc.com/stats/diff>. July 29, 2022.
- [71] W. Foxley, Guesstimating the cost of moving Bitcoin miners out of China, *Newsroom - Compass* (2021). <https://compassmining.io/education/cost-Bitcoin-miners-leaving-china/>. July 29, 2022.
- [72] R. Browne, Bitcoin production roars back in China despite Beijing's ban on crypto mining, *CNBC* (2022). <https://www.cnbc.com/2022/05/18/china-is-second-biggest-Bitcoin-mining-hub-as-miners-go-underground.html>. July 29, 2022.

- [73] S. Kong, Why China's latest "Bitcoin ban" is bullish for DeFi, decrypt. <https://decrypt.co/82243/china-bans-Bitcoin-again-bullish-for-defi>, 2021. February 6, 2023.
- [74] D. Pan, Crypto lenders' woes worsen as Bitcoin miners struggle to repay debt, Bloomberg.Com (2022). <https://www.bloomberg.com/news/articles/2022-11-30/crypto-lenders-woes-worsen-as-Bitcoin-btc-miners-struggle-to-repay-debt>. January 31, 2023.
- [75] M. Cavicchioli, Bitcoin mining difficulty is still declining, Cryptonom. (2023). <https://en.cryptonomist.ch/2023/01/03/Bitcoin-mining-difficulty-decreasing/>. January 31, 2023.
- [76] Bloomberg, Bitcoin has a dirty, Dirty Secret, Fortune (2017). <https://fortune.com/2017/12/15/Bitcoin-dirty-secret-energy-use-pollution/>. August 8, 2022.
- [77] J. Hinsdale, Cryptocurrency's dirty secret: energy consumption, State Planet (2022). <https://news.climate.columbia.edu/2022/05/04/cryptocurrency-energy/>. July 30, 2022.
- [78] E. Wolff-Mann, "Only good for drug dealers": more Nobel prize winners snub Bitcoin. <https://finance.yahoo.com/news/good-drug-dealers-nobel-prize-winner-s-nub-Bitcoin-184903784.html>, 2018. June 30, 2022.
- [79] LibertyInOurTime, An interview with F. A. Hayek, 2018, <https://www.youtube.com/watch?v=s-kFc63tZl>, 1984. August 10, 2022.
- [80] Chainalysis, The 2022 Crypto Crime Report, Chainalysis Inc., New York, NY, USA, 2022.
- [81] A.B. Turner, S. McCombie, A.J. Uhlmann, Discerning payment patterns in Bitcoin from ransomware attacks, J. Money Laund. Control 23 (2020) 545–589, <https://doi.org/10.1108/JMLC-02-2020-0012>.
- [82] L.W. Cong, C.R. Harvey, D. Rabetti, Z.-Y. Wu, An Anatomy of Crypto-Enabled Cybercrimes, 2022. <https://papers.ssrn.com/abstract=4188661>. August 16, 2022.
- [83] A. de Vries, U. Gallersdörfer, L. Klaußen, C. Stoll, The true costs of digital currencies: exploring impact beyond energy use, One Earth 4 (2021) 786–789, <https://doi.org/10.1016/j.oneear.2021.05.009>.
- [84] J.L. Mackie, Causes and conditions, Am. Phil. Q. 2 (1965) 245–264.
- [85] G. Iacurci, Cryptocurrency poses a significant risk of tax evasion, CNBC (2021). <https://www.cnbc.com/2021/05/31/cryptocurrency-poses-a-significant-risk-of-tax-evasion.html>. August 7, 2022.
- [86] A. Goldstein, Crypto doesn't have to enable tax cheats, Bloomberg.Com. (2021). <https://www.bloomberg.com/opinion/articles/2021-08-26/crypto-doesn-t-have-to-enable-tax-cheats>. August 7, 2022.
- [87] N.X. Chen, T. Lehmer, Aggressive tax avoiders: U.S. Multinationals shifting domestic earnings to zero, Account. Rev. 96 (2021) 181–206, <https://doi.org/10.2308/TAR-2018-0419>.
- [88] A. Sabu, Reframing Bitcoin and Tax Compliance, Univ. Law J., St. Louis, 2020, p. 64. <https://scholarship.law.slu.edu/lj/vol64/iss2/4>.
- [89] J. Alm, Tax evasion, technology, and inequality, Econ. Gov. 22 (2021) 321–343, <https://doi.org/10.1007/s10101-021-00247-w>.
- [90] O. Versteegen, Standby power: what is it and how can you prevent it? Sensorfact (2022). <https://www.sensorfact.eu/standby-power/>. July 29, 2022.
- [91] International Energy Agency, The Future of Cooling: opportunities for energy-efficient air conditioning, in: International Energy Agency, 2018. Paris, Europe, <https://www.iea.org/reports/the-future-of-cooling>.
- [92] B. Neimark, O. Belcher, P. Bigger, US military pollution, Ecologist (2019). <https://theecologist.org/2019/jun/27/us-military-pollution>. June 24, 2022.
- [93] Transport & Environment, Private jets: can the super-rich supercharge zero-emission aviation? Campaign. Clean. Transp. Environ. (2021). <http://www.transportenvironment.org/discover/private-jets-can-the-super-rich-supercharge-zero-emission-aviation/>. February 19, 2022.
- [94] U.S. Environmental Protection Agency, From Farm to Kitchen: the Environmental Impacts of U.S. Food Waste, U.S. Environmental Protection Agency, Washington, D.C., 2021. [https://www.epa.gov/system/files/documents/2021-11/from-farm-to-kitchen-the-environmental-impacts-of-u.s.-food-waste\\_508-tagged.pdf](https://www.epa.gov/system/files/documents/2021-11/from-farm-to-kitchen-the-environmental-impacts-of-u.s.-food-waste_508-tagged.pdf).
- [95] UCLA, Sustainability in the Motion Picture Industry, California Integrated Waste Management Board, Sacramento, CA, 2006.
- [96] K. Hao, Training a single AI model can emit as much carbon as five cars in their lifetimes, MIT Technol. Rev. (2019). <https://www.technologyreview.com/2019/06/06/239031/training-a-single-ai-model-can-emit-as-much-carbon-as-five-cars-in-their-lifetimes/>. July 29, 2022.
- [97] Anurag, Is Bitcoin the climate savior?, coin repub, Cryptocurrency Bitcoin Ethereum Amp Blockchain News (2022). <https://www.thecoinrepublic.com/2022/05/10/is-Bitcoin-the-climate-savior/>. August 5, 2022.
- [98] C. Bustos, Irony: envisioned to Be fully decentralized, Bitcoin Today High Centr. (2021). <https://finance.yahoo.com/news/irony-envisioned-fully-decentralized-Bitcoin-170811070.html>. August 13, 2022.
- [99] C. Chambers, There's No need to worry about cryptocurrency and AI energy demands, Forbes (2019). <https://www.forbes.com/sites/investor/2019/03/04/theres-no-need-to-worry-about-cryptocurrency-and-ai-energy-demands/>. February 9, 2022.
- [100] N. Carter, How much energy does Bitcoin actually consume? Harv. Bus. Rev. (2021). <https://hbr.org/2021/05/how-much-energy-does-Bitcoin-actually-consume>. February 19, 2022.
- [101] M. Pehl, A. Arvesen, F. Humpenöder, A. Popp, E.G. Hertwich, G. Luderer, Understanding future emissions from low-carbon power systems by integration of life-cycle assessment and integrated energy modelling, Nat. Energy 2 (2017) 939–945, <https://doi.org/10.1038/s41560-017-0032-9>.
- [102] H. Treiblmaier, Do cryptocurrencies really have (no) intrinsic value? Electron. Mark. 32 (2022) 1749–1758, <https://doi.org/10.1007/s12525-021-00491-2>.
- [103] P. Sztorc, Nothing is cheaper than proof of work. <https://www.truthcoin.info/blog/pow-cheapest/>, 2015. June 6, 2023.
- [104] V. Smil, Energies: an Illustrated Guide to the Biosphere and Civilization, first ed., The MIT Press, Cambridge, Mass, 1998.
- [105] C. Edwards, The Energy Standard, Capriole, 2020. <https://medium.com/capriole/the-energy-standard-b726dede588>. February 4, 2022.
- [106] D. Held, Information theory of money, Bitcoin Times (2021). <https://medium.com/the-bitcoin-times/information-theory-of-money-36274aebdf1>. June 25, 2022.
- [107] I.L. Hatzis, Is Bitcoin energy money?, Fintech DeFi blockchain Web3 dly, News Finyear (2021). [https://www.finyear.com/is-Bitcoin-energy-money\\_a44368.html](https://www.finyear.com/is-Bitcoin-energy-money_a44368.html). July 30, 2022.
- [108] W.J. Luther, Bitcoin is not a battery | AIER. <https://www.aier.org/article/Bitcoin-is-not-a-battery/>, 2022. July 30, 2022.
- [109] M. Alizart, Cryptocommunist, Polity (2020). Cambridge, UK.
- [110] C. Edwards, Bitcoin value-energy equivalence, Capriole (2019). <https://medium.com/capriole/Bitcoin-value-energy-equivalence-6d00d1baa34a>. August 10, 2022.
- [111] H.F. Calvo-Pardo, T. Mancini, J. Olmo, Machine learning the carbon footprint of Bitcoin mining, J. Risk Financ. Manag. 15 (2022) 71, <https://doi.org/10.3390/jrfm15020071>.
- [112] S. Kifeoglu, M. Özkuran, Bitcoin mining: a global review of energy and power demand, Energy Res. Social Sci. 58 (2019) 101273, <https://doi.org/10.1016/j.erss.2019.101273>.
- [113] S. Köhler, M. Pizzol, Life cycle assessment of Bitcoin mining, Environ. Sci. Technol. 53 (2019) 13598–13606.
- [114] A. de Vries, Bitcoin's energy consumption is underestimated: a market dynamics approach, Energy Res. Social Sci. 70 (2020) 101721, <https://doi.org/10.1016/j.erss.2020.101721>.
- [115] K. Kononova, A. Dek, Bitcoin carbon footprint: mining pools based estimate methodology, in: 9th Int. Conf. Inf. Commun. Technol. Agric. Food Environ., HAICTA, Thessaloniki, Greece, 2020, pp. 265–273.
- [116] H. Fahmy, Assessing the carbon footprint of cryptoassets: evidence from a bivariate VAR model, in: T. Walker, F. Davis, T. Schwartz (Eds.), Big Data Finance, Palgrave Macmillan Cham, 2022, pp. 207–230, [https://doi.org/10.1007/978-3-031-12240-8\\_11](https://doi.org/10.1007/978-3-031-12240-8_11). February 1, 2023.
- [117] R. Rybarczyk, D. Armstrong, A. Fabiano, On Bitcoin's Energy Consumption: A Quantitative Approach to a Subjective Question, Galaxy Digital, New York, NY, US, 2021. [https://www.lopp.net/pdf/On\\_Bitcoin\\_Energy\\_Consumption.pdf](https://www.lopp.net/pdf/On_Bitcoin_Energy_Consumption.pdf). August 11, 2022.
- [118] O. Chershesnia, Environmental load from use of blockchain technology and cryptocurrency mining in Russia, InterCarto InterGIS 27 (2021) 238–248, <https://doi.org/10.35595/2414-9179-2021-1-27-238-248>.
- [119] H. McCook, Bitcoin Emits Less than 5% of the Legacy Financial Sector's Carbon Emissions, Bitcoin Mag. - Bitcoin News Artic. Expert Insights, 2021. <https://bitcoinmagazine.com/business/Bitcoin-vs-financial-sector-energy-use>. August 6, 2022.
- [120] P. Sandner, C. Lichti, C. Heidt, R. Richter, B. Schaub, The Carbon Emissions of Bitcoin from an Investor Perspective, Frankfurt School Blockchain Center and intas.tech, Frankfurt, Germany, 2021. <https://philippsandner.medium.com/study-the-carbon-emissions-of-Bitcoin-from-an-investor-perspective-4c90707474b8>. February 4, 2022.
- [121] MoneySuperMarket, Crypto energy consumption. <https://www.moneysupermarket.com/gas-and-electricity/features/crypto-energy-consumption/>, 2022. February 12, 2022.
- [122] M. Roeck, T. Drennen, Life cycle assessment of behind-the-meter Bitcoin mining at US power plant, Int. J. Life Cycle Assess. 27 (2022) 355–365, <https://doi.org/10.1007/s11367-022-02025-0>.
- [123] H. Tandy, Cryptocurrencies. <https://www.castlefield.com/news-media/blog/cryptocurrencies/>, 2022. April 9, 2022.
- [124] T. Knutson, Crypto energy consumption enormous but it needn't Be, congressional panel hears, Forbes (2022). <https://www.forbes.com/sites/tecknutson/2022/01/20/crypto-energy-consumption-enormous-but-it-needn-t-be-congressional-panel-hears/>. June 24, 2022.
- [125] Cambridge Centre for Alternative Finance, Cambridge Bitcoin Electricity Consumption Index, CBECI, 2022. <https://ccaf.io/cbeci/index>. February 9, 2022.
- [126] Cambridge Centre for Alternative Finance, Cambridge Bitcoin electricity consumption index. <https://ccaf.io/cbeci/index/comparisons>, 2023. August 6, 2022.
- [127] Digiconomist, Bitcoin energy consumption index, Digiconomist (2023). <https://digiconomist.net/Bitcoin-energy-consumption/>. February 12, 2022.
- [128] Cambridge Centre for Alternative Finance, Bitcoin Mining Map, 2022. [https://ccaf.io/cbeci/mining\\_map?utm\\_campaign=%3F%3F](https://ccaf.io/cbeci/mining_map?utm_campaign=%3F%3F). August 8, 2022.
- [129] Coinwarz, Bitcoin hashrate chart, BTC Hashrate 209.33 EH/s (2022). <https://www.coinwarz.com/mining/Bitcoin/hashrate-chart>. August 8, 2022.
- [130] J.D. Rhodes, T. Deetjen, C. Smith, Impacts of Large, Flexible Data Center Operations on the Future of ERCOT, IdeaSmiths LLC, Houston, TX, 2021. <https://lancium.com/press/>. February 12, 2022.
- [131] U.S. Energy Information Administration (EIA), Electricity Explained, 2022. <https://www.eia.gov/energyexplained/electricity/#:~:text=Electricity%20is%20both%20a%20basic,wind%20energy%2C%20into%20electrical%20power.> August 11, 2022.
- [132] CoinShares, The Bitcoin Mining Network: Energy and Carbon Impact, CoinShares International Limited, Jersey, Channel Islands, 2022. <https://coinshares.com/research/Bitcoin-mining-network-2022>. June 6, 2023.
- [133] A. Blandin, G. Pieters, Y. Wu, T. Eisermann, A. Dek, S. Taylor, D. Njoki, 3rd Global Cryptoasset Benchmarking Study, Cambridge Centre for Alternative Finance, Cambridge, UK, 2020. <https://www.jbs.cam.ac.uk/faculty-research/centres/alt>

- ernative-finance/publications/3rd-global-cryptoasset-benchmarking-study/. February 12, 2022.
- [134] Coinbase, Fact check: is Bitcoin mining environmentally unfriendly? Medium (2021). <https://blog.coinbase.com/fact-check-is-bitcoin-mining-environmentally-unfriendly-3559823af6f1>. February 12, 2022.
- [135] A. Neumueller, A deep dive into Bitcoin's environmental impact - news & insight, Camb. Judge Bus. Sch. (2022). <https://www.jbs.cam.ac.uk/insight/2022/a-deep-dive-into-bitcoins-environmental-impact/>. February 3, 2023.
- [136] A. de Vries, U. Gallersdörfer, L. Klaaßen, C. Stoll, Revisiting Bitcoin's carbon footprint, *Joule* 6 (2022) 498–502, <https://doi.org/10.1016/j.joule.2022.02.005>.
- [137] The White House, Climate and Energy Implications of Crypto-Assets in the United States, The White House, Washington, DC, USA, 2022.
- [138] J. Baltrusaitis, Bitcoin projected to become first monetary system to hit net zero emissions by 2024, *Finbold* (2022). <https://finbold.com/Bitcoin-projected-to-become-first-monetary-system-to-hit-net-zero-emissions-by-2024/>. February 3, 2023.
- [139] batcoinz, 50 landfills mining Bitcoin = A net zero emission Bitcoin network, *Batcoinz* (2023). <https://batcoinz.com/50-landfills-mining-Bitcoin-a-zero-emission-on-Bitcoin-network/>. February 3, 2023.
- [140] N. Carter, R. Stevens, Bitcoin net zero, *NYDIG* (2021). <https://nydig.com/Bitcoin-net-zero>. June 6, 2023.
- [141] Bitcoin Mining Council, Bitcoin mining Council survey confirms sustainable power mix, *Bitcoin Min. Council*. (2021). <https://Bitcoinminingcouncil.com/Bitcoin-mining-council-survey-confirms-sustainable-power-mix/>. February 14, 2022.
- [142] J. Geels, Electrical power consumption reduction in the Bitcoin mining process using phase change material, *Future Energy* 1 (2022) 12–15.
- [143] W. Sun, H. Jin, F. Jin, L. Kong, Y. Peng, Z. Dai, Spatial analysis of global Bitcoin mining, *Sci. Rep.* 12 (2022) 10694, <https://doi.org/10.1038/s41598-022-14987-0>.
- [144] M. Sigalos, China is kicking out more than half the world's Bitcoin miners – and a whole lot of them could be headed to Texas, *CNBC* (2021). <https://www.cnbc.com/2021/06/15/chinas-bitcoin-miner-exodus.html>. August 11, 2022.
- [145] S.L. Nández Alonso, J. Jorge-Vázquez, M.Á. Echarte Fernández, R.F. Reier Forradellas, Cryptocurrency mining from an economic and environmental perspective. Analysis of the most and least sustainable countries, *Energies* 14 (2021) 4254, <https://doi.org/10.3390/en14144254>.
- [146] M. Sigalos, Bitcoin mining isn't nearly as bad for the environment as it used to be, new data shows, *CNBC* (2021). <https://www.cnbc.com/2021/07/20/Bitcoin-mining-environmental-impact-new-study.html>. February 12, 2022.
- [147] N. Carter, It's the settlement assurances, stupid, *Medium*, [https://medium.com/@nic\\_carter/its-the-settlement-assurances-stupid-5dcd1c3f4e41](https://medium.com/@nic_carter/its-the-settlement-assurances-stupid-5dcd1c3f4e41), 2019. February 19, 2022.
- [148] L. Alden, Bitcoin's energy usage isn't A problem, Here's Why (2021). <https://seekingalpha.com/article/4452010-Bitcoin-energy-usage-isnt-a-problem-heres-why>. February 19, 2022.
- [149] Enerdata, Electricity consumption. <https://yearbook.enerdata.net/electricity/electricity-domestic-consumption-data.html>, 2022. August 8, 2022.
- [150] M.J. Krause, T. Tolaymat, Quantification of energy and carbon costs for mining cryptocurrencies, *Nat. Sustain.* 1 (2018) 711–718, <https://doi.org/10.1038/s41893-018-0152-7>.
- [151] Y. Elmandjra, Debunking Bitcoin myths for the institutional investment community, *ARK Invest* (2021). <https://ark-invest.com/articles/analyst-research/Bitcoin-myths/>. February 14, 2022.
- [152] U. Gallersdörfer, L. Klaaßen, C. Stoll, Energy Efficiency and Carbon Footprint of Proof of Stake Blockchain Protocols, *Crypto Carbon Ratings Institute* 2022, Dingolfing, Germany, 2022.
- [153] R. de Best, Bitcoin energy consumption 2022, *Statista* (2022). <https://www.statista.com/statistics/881541/Bitcoin-energy-consumption-transaction-comparison-via-sa/>. August 9, 2022.
- [154] V. Kohli, S. Chakravarty, V. Chamola, K.S. Sangwan, S. Zeadally, An analysis of energy consumption and carbon footprints of cryptocurrencies and possible solutions, *ArXiv:2203.03717* (2022) 1–16.
- [155] D. LeClair, S. Rule, Bitcoin is the world's most efficient value settlement network. <https://www.nasdaq.com/articles/Bitcoin-is-the-worlds-most-efficient-value-settlement-network>, 2021. April 9, 2022.
- [156] M. Garside, Distribution of gold demand worldwide by sector in 2021, *Statista* (2022). <https://www.statista.com/about-us/our-research-commitment/913/m-garside>. August 9, 2022.
- [157] CoinCarbonCap, Coin Carbon Cap: PoW currencies ranked by energy efficiency, *Coin Carbon Cap* (2022). <https://coincarboncap.com/>. April 9, 2022.
- [158] A. Narayanan, J. Bonneau, E. Felten, A. Miller, S. Goldfeder, *Bitcoin and Cryptocurrency Technologies: A Comprehensive Introduction*, Princeton University Press, Princeton, 2016.
- [159] M. Saad, J. Spaulding, L. Njilla, C.A. Kamhoua, D. Nyang, A. Mohaisen, Overview of attack surfaces in blockchain, in: S. Shetty, C. Kamhoua, L. Njilla (Eds.), *Blockchain Distrib. Syst. Secur.*, John Wiley & Sons, Ltd, 2019, pp. 51–66, <https://doi.org/10.1002/9781119519621.ch3>.
- [160] IEA, Efficiency of Bitcoin Mining Hardware – Charts – Data & Statistics, *IEA*, 2020. <https://www.iea.org/data-and-statistics/charts/efficiency-of-bitcoin-mining-hardware>. April 9, 2022.
- [161] M. Khazzaka, Bitcoin: cryptopayments energy efficiency. <https://doi.org/10.2139/ssrn.4125499>, 2022.
- [162] M. Saylor, Michael Saylor on the Bitcoin environment argument. <https://www.youtube.com/watch?v=TeVtScfCQ4>, 2021. July 30, 2022.
- [163] D. Das, A. Dutta, Bitcoin's energy consumption: is it the Achilles heel to miner's revenue? *Econ. Lett.* 186 (2020) 108530 <https://doi.org/10.1016/j.econlet.2019.108530>.
- [164] D. Wingen, Bitcoin's energy consumption is a necessity and has positive impact on the environment, *Value Bitcoin* (2018). <https://medium.com/value-of-bitcoin/bitcoins-energy-consumption-is-a-necessity-and-has-positive-impact-on-the-environment-752502288082>. January 31, 2023.
- [165] J. Benson, Bitcoin firm cruseo energy raises \$505 million to grow flare-gas mining business, *Decrypt* (2022). <https://decrypt.co/98424/Bitcoin-firm-cruseo-energy-a-raises-505-million-grow-flare-gas-mining-business>. July 30, 2022.
- [166] T. Mitchelhill, Oil giant ConocoPhillips reduces gas flaring emissions via Bitcoin mining, *Cointelegraph* (2022). <https://cointelegraph.com/news/oil-giant-conocophillips-reduces-gas-flaring-emissions-via-bitcoin-mining>. August 12, 2022.
- [167] Bitcoin Clean Energy Initiative, Bitcoin is key to an abundant, clean energy future, *Square* (2021).
- [168] R. Tao, C.-W. Su, B. Naqvi, S.K.A. Rizvi, Can Fintech development pave the way for a transition towards low-carbon economy: a global perspective, *Technol. Forecast. Soc. Change* 174 (2022) 121278, <https://doi.org/10.1016/j.techfore.2021.121278>.
- [169] B. Newar, Bitcoin mining could be good for US energy independence: research, *Cointelegraph* (2022). <https://cointelegraph.com/news/Bitcoin-mining-could-be-good-for-us-energy-independence-research>. April 9, 2022.
- [170] M. Vukolić, On the future of decentralized computing, *Bull. Eur. Assoc. Theor. Comput. Sci.* (2021). <https://research.protocol.ai/publications/on-the-future-of-decentralized-computing/>. February 4, 2022.
- [171] S. Rodríguez, Can cryptocurrency ever be environmentally friendly? *DW.COM* (2022). <https://www.dw.com/en/bitcoin-can-cryptocurrency-mining-ever-be-environmentally-friendly/a-60818440>. June 6, 2023.
- [172] T. McDonnell, The pandemic is turning fracking companies into Bitcoin miners, *Quartz* (2022). <https://qz.com/1988503/Bitcoin-miners-and-fracking-companies-are-working-together/>. July 30, 2022.
- [173] G. Fridgen, M.-F. Körner, S. Walters, M. Weibelzahl, Not all doom and gloom: how energy-intensive and temporally flexible data center applications may actually promote renewable energy sources, *Bus. Inf. Syst. Eng.* 63 (2021) 243–256, <https://doi.org/10.1007/s12599-021-00686-z>.
- [174] D. Pan, Bitcoin miners shut off rigs as Texas power grid nears brink, *Bloomberg.Com* (2022). <https://www.bloomberg.com/news/articles/2022-07-11/bitcoin-miners-shut-off-rigs-as-texas-power-grid-nears-brink>. July 30, 2022.
- [175] N. Carter, S. Connell, Miners are the optimal buyers: the data behind Bitcoin-led decarbonization in Texas, *Bitcoin Mag.* *Bitcoin News Artic. Charts Guid.* (2021). <https://Bitcoinmagazine.com/business/Bitcoin-mining-fits-texas-energy-grid>. April 9, 2022.
- [176] J. Hall, Flower powered: Bitcoin miner heats greenhouses in The Netherlands, *Cointelegraph* (2022). <https://cointelegraph.com/news/flower-powered-bitcoin-miner-heats-greenhouses-in-the-netherlands>. July 30, 2022.
- [177] BitMEX, The growth of Bitcoin merge mining, *BitMEX Blog* (2020). <https://blog.bitmex.com/the-growth-of-bitcoin-merge-mining/>. July 30, 2022.
- [178] D.G. Baur, J. Oll, Bitcoin investments and climate change: a financial and carbon intensity perspective, *Finance Res. Lett.* (2021) 102575, <https://doi.org/10.1016/j.frl.2021.102575>.
- [179] A. Antonopoulos, The real truth about Bitcoin's energy usage. <https://www.youtube.com/watch?v=xoEid1UEsG4>, 2021. July 30, 2022.
- [180] C. Moura, Why Bitcoin miners in Texas are getting paid not to mine Bitcoin, *BLOCK* (2022). <https://www.theblock.co/post/164376/why-bitcoin-miners-in-texas-are-getting-paid-not-to-mine-bitcoin>. February 1, 2023.
- [181] N. Tovanich, N. Soulié, N. Heulot, P. Isenberg, MiningVis: visual analytics of the Bitcoin mining economy, *IEEE Trans. Vis. Comput. Graph.* 28 (2022) 868–878, <https://doi.org/10.1109/TVCG.2021.3114821>.
- [182] B.A. Jones, A.L. Goodkind, R.P. Berrens, Economic estimation of Bitcoin mining's climate damages demonstrates closer resemblance to digital crude than digital gold, *Sci. Rep.* 12 (2022) 14512, <https://doi.org/10.1038/s41598-022-18686-8>.
- [183] A.L. Goodkind, B.A. Jones, R.P. Berrens, Cryptodamages: monetary value estimates of the air pollution and human health impacts of cryptocurrency mining, *Energy Res. Social Sci.* 59 (2020) 101281, <https://doi.org/10.1016/j.erss.2019.101281>.
- [184] E. Newberry, 4 facts that prove Bitcoin is still disastrous for the environment, *Motley Fool* (2021). <https://www.fool.com/the-ascent/cryptocurrency/article/s4-facts-that-prove-bitcoin-is-still-disastrous-for-the-environment/>. February 4, 2022.
- [185] A. de Vries, Renewable energy will not solve Bitcoin's sustainability problem, *Joule* 3 (2019) 893–898, <https://doi.org/10.1016/j.joule.2019.02.007>.
- [186] C. Schinckus, Proof-of-work based blockchain technology and Anthropocene: an undermined situation? *Renew. Sustain. Energy Rev.* 152 (2021) 111682.
- [187] A. de Vries, C. Stoll, Bitcoin's growing e-waste problem, *Resour. Conserv. Recycl.* 175 (2021) 105901, <https://doi.org/10.1016/j.resconrec.2021.105901>.
- [188] B. Alcott, M. Giampietro, K. Mayumi, J. Polimeni, *The Jevons paradox and the myth of resource efficiency improvements*, Routledge (2007), <https://doi.org/10.4324/9781849773102>. London.
- [189] Digiconomist, Bitcoin electronic waste monitor, *Digiconomist* (2022). <https://digiconomist.net/bitcoin-electronic-waste-monitor/>. June 6, 2023.
- [190] R. Cho, Bitcoin's impacts on climate and the environment, *Columbia Clim. School* (2021). <https://news.climate.columbia.edu/2021/09/20/bitcoins-impacts-on-climate-and-the-environment/>. February 12, 2022.
- [191] A. de Vries, Bitcoin boom: what rising prices mean for the network's energy consumption, *Joule* 5 (2021) 509–513, <https://doi.org/10.1016/j.joule.2021.02.006>.

- [192] Reuters, Intel ends its Bitcoin mining chip series, Reuters (2023). <https://www.reuters.com/technology/intel-ends-its-Bitcoin-mining-chip-series-2023-04-18/>. June 11, 2023.
- [193] U. Bacchi, Abkhazia's illegal Bitcoin miners face new threat from thieves, Reuters (2022). <https://www.reuters.com/markets/currencies/abkhazias-illegal-Bitcoin-miners-face-new-threat-thieves-2022-01-06/>. July 30, 2022.
- [194] J. Bratanic, Kosovo's Bitcoin miners selling equipment after government ban, Bloomberg.Com (2022). <https://www.bloomberg.com/news/articles/2022-01-17/kosovo-s-Bitcoin-miners-selling-equipment-after-government-ban>. August 5, 2022.
- [195] N. Turak, Iran bans Bitcoin mining as its cities suffer blackouts and power shortages, CNBC (2021). <https://www.cnbc.com/2021/05/26/iran-bans-Bitcoin-mining-as-its-cities-suffer-blackouts.html>. February 23, 2022.
- [196] P. Howson, A. de Vries, Preying on the poor? Opportunities and challenges for tackling the social and environmental threats of cryptocurrencies for vulnerable and low-income communities, Energy Res. Social Sci. 84 (2022) 102394, <https://doi.org/10.1016/j.erss.2021.102394>.
- [197] N. Rustgi, Bitcoin crashes after accident in Xinjiang, China halts mining operation, Crypto Brief (2021). <https://cryptobriefing.com/Bitcoin-crashes-accident-xinjiang-g-china-halts-mining-operation/>. February 5, 2023.
- [198] T. Swanson, Bitcoin and other PoW coins are an ESG nightmare, Gt. Wall Numbers (2021). <https://www.ofnumbers.com/2021/02/14/Bitcoin-and-other-pow-coins-are-an-esg-nightmare/>. June 24, 2022.
- [199] S. Squires, Crypto mining booms on cheap, subsidized energy in Argentina, Bloomberg.Com (2021). <https://search.ebscohost.com/login.aspx?direct=true&db=buh&AN=150591124&site=ehost-live>. August 16, 2022.
- [200] B. Spegele, C. Ostroff, Bitcoin miners are giving new life to old fossil-fuel power plants, Wall Str. J. (2021). <https://www.wsj.com/articles/Bitcoin-miners-are-giving-new-life-to-old-fossil-fuel-power-plants-11621594803>. July 30, 2022.
- [201] P. Jha, Eager to work: Bitcoin switch to proof-of-stake remains unlikely, Cointelegraph (2022). <https://cointelegraph.com/news/eager-to-work-Bitcoin-sw-itch-to-proof-of-stake-remains-unlikely>. June 6, 2023.
- [202] BTC.com, Pool distrib, in: Pool Stats - BTC.Com, 2023. [https://btc.com/stats/pool?pool\\_mode=month](https://btc.com/stats/pool?pool_mode=month). January 31, 2023.
- [203] J. Schmidt, Why does Bitcoin use so much energy? Forbes Advis (2021). <http://www.forbes.com/advisor/investing/Bitcoins-energy-usage-explained/>. April 9, 2022.
- [204] W. Foxley, Mining Bitcoin with lasers? Meet Optical Proof-of-Work (oPoW), Newsroom – Compass (2021). <https://compassmining.io/education/Bitcoin-mining-lasers-optical-proof-of-work/>. August 16, 2022.
- [205] P. Jacquet, B. Mans, Blockchain moderated by empty blocks to reduce the energetic impact of crypto-moneys, Comput. Commun. 152 (2020) 126–136, <https://doi.org/10.1016/j.comcom.2020.01.031>.
- [206] N. Lasla, L. Alshah, M. Abdallah, M. Younis, Green-PoW: an energy-efficient blockchain proof-of-work consensus algorithm. <https://doi.org/10.48550/arXiv.2007.04086>, 2020.
- [207] D. Thomas, Block and blockstream to create 100% solar powered mining farm using tesla technology in Texas, BeInCrypto (2022). <https://beincrypto.com/block-and-blockstream-to-create-100-solar-powered-mining-farm/>. June 24, 2022.
- [208] T. Mullen, P.D. Finn, Towards an evaluation metric for carbon-emitting energy provenance of Bitcoin transactions, in: Proc. Fourth ACM Int. Symp. Blockchain Secure Crit. Infrastruct., Association for Computing Machinery, New York, NY, USA, 2022, pp. 11–21, <https://doi.org/10.1145/3494106.3528673>.
- [209] European Commission, EU action plan on digitalising the energy system, Eur. Comm. - Eur. Comm. (2022). [https://ec.europa.eu/commission/presscorner/detail/en/QANDA\\_22\\_6229](https://ec.europa.eu/commission/presscorner/detail/en/QANDA_22_6229). February 1, 2023.
- [210] M. Campbell, Cryptocurrency miners may no longer be able to use fossil fuel-generated power in New York, Euronews (2022). <https://www.euronews.com/green/2022/06/07/cryptocurrency-miners-may-no-longer-be-able-to-use-fossil-fuel-generated-power-in-new-york>. August 15, 2022.
- [211] The New York State Senate, NY state assembly bill A7389C. <https://www.nysenate.gov/legislation/bills/2021/a7389/amendment/c>, 2021. February 5, 2023.
- [212] S. Tully, A. Bluestein, Can Bitcoin go green? Fortune 184 (2021) 76–80.
- [213] L. Ante, I. Fiedler, Bitcoin's energy consumption and social costs in relation to its capacity as a settlement layer, SSRN (2021). [https://papers.ssrn.com/sol3/papers.cfm?abstract\\_id=3910778](https://papers.ssrn.com/sol3/papers.cfm?abstract_id=3910778).
- [214] H. Xiong, M. Chen, C. Wu, Y. Zhao, W. Yi, Research on progress of blockchain consensus algorithm: a review on recent progress of blockchain consensus algorithms, Future Internet 14 (2022) 47, <https://doi.org/10.3390/fi14020047>.
- [215] J. Surowiecki, Bitcoin would be a calamity, not an economy, MIT Technol. Rev. (2018). <https://www.technologyreview.com/2018/04/10/3060/Bitcoin-would-be-a-calamity-not-an-economy/>. February 3, 2021.
- [216] L. Badea, M.C. Mungiu-Pupăzan, The economic and environmental impact of Bitcoin, IEEE Access 9 (2021) 48091–48104, <https://doi.org/10.1109/ACCESS.2021.3068636>.
- [217] L. Schilling, H. Uhlig, Some simple Bitcoin economics, J. Monet. Econ. 106 (2019) 16–26, <https://doi.org/10.1016/j.jmoneco.2019.07.002>.
- [218] J. Truby, Decarbonizing Bitcoin: law and policy choices for reducing the energy consumption of Blockchain technologies and digital currencies, Energy Res. Social Sci. 44 (2018) 399–410, <https://doi.org/10.1016/j.erss.2018.06.009>.
- [219] J. Thomson, Tragedy of the energy commons: how government regulation can help mitigate the environmental and public health consequences of cryptocurrency mining, Seattle J. Technol. Environ. Innov. Law. 11 (2020) 77–111.
- [220] A. Podhorsky, Taxing Bitcoin: Incentivizing the Difficulty Adjustment Mechanism to Reduce Electricity Usage, Department of Economics, York University, Toronto, Canada, 2022.
- [221] H. Treiblmaier, E. Gorbunov, On the malleability of consumer attitudes toward disruptive technologies: a pilot study of cryptocurrencies, Information 13 (2022) 295, <https://doi.org/10.3390/info13060295>.
- [222] S. Corbet, B. Lucey, L. Yarovaya, Bitcoin-energy markets interrelationships - new evidence, Res. Pol. 70 (2021) 101916, <https://doi.org/10.1016/j.resourpol.2020.101916>.
- [223] H. Treiblmaier, Exploring the next wave of blockchain and distributed ledger technology: the overlooked potential of scenario analysis, Future Internet 13 (2021) 183, <https://doi.org/10.3390/fi13070183>.
- [224] M. Zade, J. Myklebost, P. Tzscheuschler, U. Wagner, Is Bitcoin the only problem? A scenario model for the power demand of blockchains, Front. Energy Res. 7 (2019) 21.
- [225] S. Chamanara, A. Ghaffarizadeh, K. Madani, The environmental costs of mining Bitcoin, Earth Space Sci. Open Arch. ESSOAr. (2021), <https://doi.org/10.1002/essoar.10507153.1>.