blockchains

Review

Bitcoin and Renewable Energy Mining: A Survey

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Abstract: Bitcoin, the most valuable and energy-consuming cryptocurrency, has recently been at the center of a heated debate over its environmental impact. This controversy has caught the public's attention, prompting us to investigate the energy consumption of Bitcoin. In this paper, we have conducted a review of the literature on various aspects of Bitcoin mining, including its mechanisms, energy consumption, mining sites, and the potential for renewable energy use. Our findings reveal that the power consumption of Bitcoin is bound to increase with the continued adoption of the proof-of-work (PoW) consensus algorithm. Nonetheless, the growing availability of affordable renewable energy sources worldwide brings hope that Bitcoin mining will shift towards cleaner energy in the near future.

Keywords: blockchain; cryptocurrency; renewable energy; bitcoin mining

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1. Introduction

Satoshi Nakamoto introduced Bitcoin in 2008 and has recently gained a lot of public attention due to its skyrocketing price in 2021. Unlike traditional currencies and payment systems, Bitcoin allows transactions to occur without the need for a third party. The Bitcoin network is supported by nodes in a P2P format distributed globally. To ensure the integrity of transaction data, all virtual currencies require a consensus algorithm, and Bitcoin uses proof-of-work (PoW) based on cryptographic hash functions, which require a large amount of computing resources.

Given the growing interest in Bitcoin's environmental impact, this paper aims to consolidate existing research on Bitcoin mining and energy consumption from various sources such as journals, technical reports, and conference presentations. While many research papers have focused on blockchain technology and mechanisms, we summarize all concepts related to Bitcoin mining and energy consumption for readers interested in the topic.

This paper covers various aspects of Bitcoin mining, including cryptographic hash functions, PoW, proof-of-stake (PoS), distribution of mining sites globally, Bitcoin energy consumption, renewable energy and Bitcoin mining, Bitcoin mining in China, and Bitcoin mining and renewable energy in Texas USA. While technical aspects of blockchain are not discussed in detail, the concepts related to Bitcoin mining are covered comprehensively.

The main contribution of this paper is to provide a single survey summarizing the concepts of mining and providing practical technical details, saving readers time and effort in their investigation of mining and its impact on the environment. This review summarizes the current literature on the following key aspects of Bitcoin mining: the consensus mechanism of proof-of-work, the energy consumption and carbon footprint of mining, the geographical distribution of mining operations, and the potential for renewable energy sources.

Studies were selected through searches on Google Scholar and IEEE Xplore using relevant terms like 'Bitcoin mining', 'energy consumption', and 'renewable energy'. Criteria for inclusion were papers published from 2015–2022 in peer-reviewed journals and conferences. The literature was evaluated based on factors like rigor of analysis, sample size, recency, and impact.

The authors found that China, which accounted for a significant share of the world's Bitcoin mining before July 2021, had introduced renewable energy sources such as hydropower and solar power in the areas where mining was active before the ban. All studies suggest that Bitcoin's energy consumption is increasing each year. However, the authors note that renewable energy, which is cheaper than fossil fuels, is increasingly available, and clean Bitcoin mining using renewable energy can be expected in the future.

The rest of the paper is organized as follows: Section 2 summarizes the latest trends in Bitcoin, the history of mining, and introduces the environmental implications of Bitcoin mining. Section 3 explains the mechanics and principles of the hash functions needed for PoW. Section 4 explains how the consensus algorithm PoW works. Section 5 explains PoS, an alternative consensus algorithm to PoW. Section 6 discusses the distribution of Bitcoin miners and energy consumption in detail. Section 7 discusses renewable energy and its availability, as well as the impact and background of the Bitcoin mining ban in China. The final section provides a conclusion to the paper.

2. Background

Cryptocurrencies, such as Bitcoin, continue to attract attention from people all over the world. The price of Bitcoin was less than $1 in 2010 but hit a new high of $68,000 in 2021 [1]. Blockchain technology posts all transaction records to the transaction ledger at regular intervals. The data is stored in a distributed way across the internet and all transactions that occurred during the period should have consistency. Miners validate transactions, store and broadcast them to the blockchain. By contributing to the system, miners can receive 6.25 BTC for incentives in 2023. The initial mining reward was 50 BTC per block in 2009. However, Bitcoin has a fixed supply, and the mining reward becomes halved roughly every 4 years. It was reduced to 25 BTC in 2012, then 12.5 BTC in 2016, and 6.25 BTC in 2020. This halving of rewards will continue approximately every 4 years until the total supply reaches 21 million [2]. Satoshi [3] stated that the incentive was for nodes to support the network and that the network initially distributed Bitcoins to the community. Although other cryptocurrencies that use proof-of-work consensus algorithms have appeared, Bitcoin miners accounted for more than 80% of the mining fees paid by the major proof-of-work Blockchains [1].

In order to be competitive in Bitcoin mining, miners need powerful hardware and much electricity. For hardware, GPU, FPGA, and ASIC are used intensively among miners [4]. Initially, Satoshi might expect miners to use the CPUs that every computer has, but as time went on, miners discovered they could gain more mining power from GPU, mainly used for PC gamers. Although mining with GPU is no longer competitive in Bitcoin mining, the market value of GPU grew significantly from 2018 to 2021 [5].

According to Bedford Taylor [6], after the appearance of mining software, Python OpenCL for GPU in October 2010, the first open-source FPGA Bitcoin miner implementations were brought in June 2011. FPGA mining has some advantages, such as higher performance and a better cooling system than GPU mining. In 2013, Canaan Creative (Beijing, China) released the first set of ASICs, which stands for Application-Specific Integrated Circuit for Bitcoin mining [7]. Since then, it has been difficult to win the mining competition with ordinary computers. Serious Bitcoin miners invest heavily to prepare many ASICs. Choosing efficient hardware is also essential when it comes to energy consumption. If all miners continue to use their CPU hardware for mining, Bitcoin mining will consume more energy than combined in the United States and China [8].

Back in early 2010, it was possible to mine on a home with an ordinary PC. However, with the advancement of mining machines equipped with ASICs and the increasing difficulty of mining calculations, it became almost impossible to make a profit from solo mining at home. Miners no longer make profits alone, and thus, they join the group called the mining pool. Miners participate in the pool to find blocks together via a mining pool. After they successfully find a block, they split the rewards among the participants in proportion to their contribution. Proportional and pay-per-share are the two simple reward systems. In a propositional way, when the pool finds the block and receives a reward, the reward is distributed among the miners in proportion to the miners' shares during the round. Pay-per-share, participants receive the reward immediately after submitting shares regardless of the finding of blocks. The operator obtains all the rewards for blocks found by the entire pool [9].

Before we discuss Bitcoin mining and environmental issues, we need to consider the Paris Agreement. The Paris Agreement is an international framework for post-2020 climate change and successor to the Kyoto Protocol in 1997. The long-term goal is to keep the global average temperature increase well below 2 degrees Celsius compared to pre-industrial levels and limit it to 1.5 degrees Celsius [10]. One of the most revolutionary aspects of the Paris Agreement among climate change agreements is that it is a framework that requires all participating countries, including developing countries, to reduce their emissions equally. Countries need to report the actions and mitigation progress against climate change from 2024 [11]. They are supposed to verify the contribution of each other. About 68% of the world's total emissions are accounted for by a small number of countries around the world [12]. Since those countries are economic powerhouses, they value international credibility, and hence countries need to deal with Greenhouse gas emissions seriously.

Energy consumption is not equal to greenhouse gas emissions, but Bitcoin technology does consume a lot of energy. Cambridge estimates 124.22 TWh on 7 December 2021, more than the Philippines and Kazakhstan [13]. Mora et al. estimated Bitcoin emissions alone could push global warming above 2 degrees Celsius [14]. The study is controversial in some aspects. First, the hardware for Bitcoin mining keeps updating, which enables miners to process efficient mining with low power consumption compared to old hardware. Second, the study did not consider the rapid growth of renewable energy usage. China, which dominated Bitcoin mining in 2017 [15], is accelerating its move toward renewable energy to achieve carbon neutrality by 2060. As for the numerical targets by 2025, the plan calls for an 18% reduction in carbon dioxide (CO_2) emissions per unit of GDP and a 13.5% reduction in energy consumption per unit of GDP [16].

After the Chinese government made it clear in May 2021 that it would tighten its control over Bitcoin, local governments began shutting down mining sites [17]. As a result, the situation surrounding Bitcoin mining has changed.

3. Cryptographic Hash Function

The concept of cryptographic hash functions is an integral part of Bitcoin itself and the mining process. In the Bitcoin network, the cryptographic hash function can be used to detect changes in transaction data. If someone tries to rewrite the transaction data, it will be noticed by someone who has verified the hash of the rewritten data [18]. As Yasuda and Sasaki [19] suggested, the cryptographic hash function has three features that keep it secure. First, collision resistance: it is hard to find two different inputs that have the same hash. Second, pre-image resistance: it is difficult to find the input from the hash value. Third, second-pre-image resistance: given an input and a hash value, it is difficult to find a different input that outputs the same hash value. Thus, the cryptographic hash function is a one-way function, and the only way to find the input value of a hash function is through brute force. This is why the proof-of-work algorithm for Bitcoin mining requires a great deal of computing power. Bitcoin uses a hash function called SHA256. The SHA256 compression process is illustrated in Figure 1.

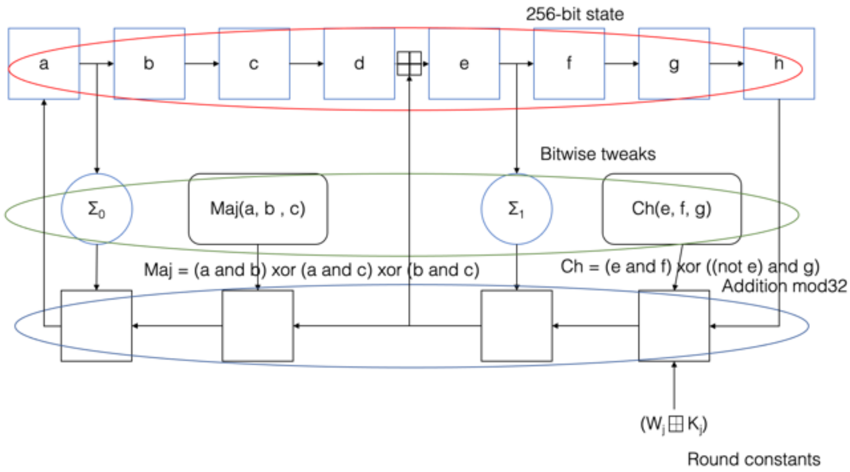

Figure 1. The SHA256 compression process [20].

Figure 1 explains the mechanism of SHA256 for the compression process. First, initialize the variables a through h, making each the same as the current hash value. In the next step, a compression loop is performed 64 times to mutate the values of a to h [21].

Developers use various mining algorithms in other cryptocurrencies such as Scrypt, EtHash, X11, and CryptoNight [22]. Mining efficiency varies depending on the hashing algorithm used by the cryptocurrency [23].

4. Proof-of-Work

A paper published by Landauer in 1961 showed the principle that a logically irreversible transformation of classical information requires the consumption of a minimum of (kT ln 2) joules [24]. Narayanan et al. referred to Bitcoin mining and Landauer's principle [20]. In other words, the hash function used in Bitcoin mining is irreversible, so energy consumption is inevitable in Bitcoin mining [20].

Miners who contribute to the verification of transactions in the blockchain will be given incentives. The verification is achieved by continuously assigning nonce (number only used once) to a hash function, repeating the operation, and looking for a number where the resulting hash is equal to or less than a given target value [25]. O'Dwyer and Malone use the following equation to describe the task of finding the nonce [26].

$$H(B.N) < T$$

where B represents the previous transaction, N is the nonce value, T is the target and . is the concatenation operator. H is the Bitcoin hash function: SHA256.

Without miners, new transactions are not added to the public ledger, and Bitcoin cannot function. The Bitcoin network adjusts the difficulty of mining a range of nonces so that a new block is added every 10 min [27]. The reason why Bitcoin and other cryptocurrencies use protocols such as proof-of-work is to prevent double-spending. Legal currencies have sort of fraud prevention technologies that can be visually verified, such as watermarks and serial numbers. Cryptocurrencies would be easily copied and double-spent without such fraud prevention technologies, and thus, proof-of-work is worked as a fraud prevention system [28].

If the difficulty of a block is D, the difficulty of block $N1$ can be calculated by the following formula [29].

$$D(N_1) = \frac{T_0}{T(\omega(N1))}$$

T_0 is the hex target of the genesis block, whereas $N0$ is the genesis block that has 1 value as a difficulty level. $T_0 = T(\omega(N0))$.

The difficulty of mining needs to be adjusted as many Bitcoin miners have been investing their computing resources in mining. Therefore, as part of Bitcoin's consensus rules, there is a difficulty adjustment algorithm that increases the difficulty when blocks are discovered too frequently and decreases the difficulty when blocks are discovered too infrequently [30].

Figure 2 shows the network difficulty and market price of Bitcoin mining from November 2013 to October 2021. Network difficulty is a relative measure of the difficulty of discovering nonce and generating new blocks. The higher the difficulty, the more computing power is required to mine Bitcoins. The dramatic increase in computational resources being poured into mining means that the difficulty of mining is increasing accordingly, as Figure 2 shows.

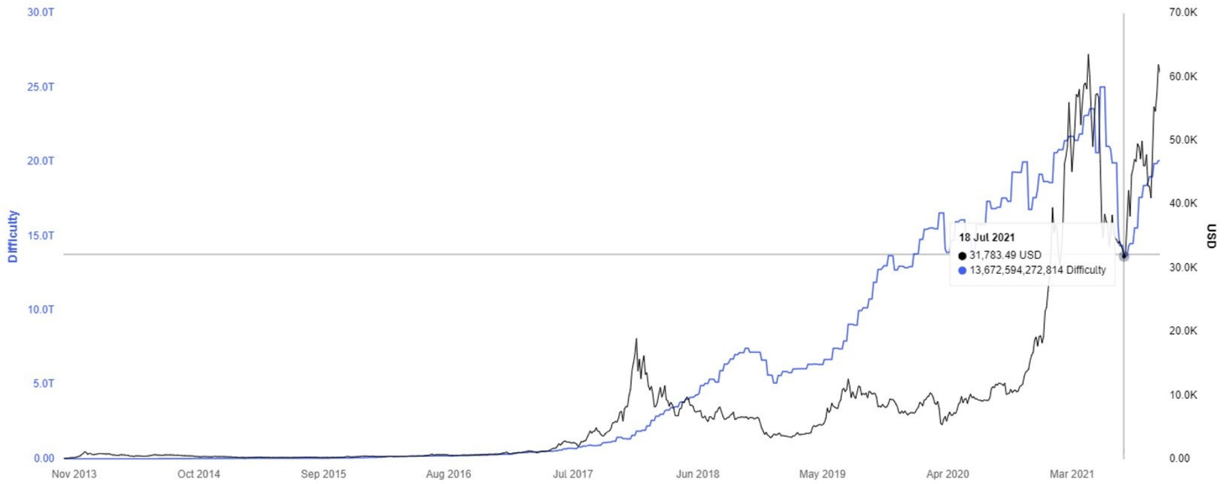

Figure 2. Network Difficulty and market price between 2013 and early 2022 based on the source [31].

The difficulty of mining Bitcoin has fluctuated up and down to the present, but the decline in July 2021 is remarkable. This is because miners in China began to shut down operations in response to the mining and trading ban imposed by Chinese regulators in May [32]. According to Park et al., the Bitcoin network has about 8500–23,000 full-node peers, distributed around the world, mainly in the US [33]. Not all the full nodes participate in mining, but they can be used as an indicator of the geographical distribution of Bitcoin miners. This means that the general adoption of Bitcoin is already so widespread that individual countries and regions do not have the power over the Bitcoin community that they used to. After the Chinese government banned Bitcoin mining in China, the difficulty of mining temporarily decreased, but then increased again as Bitcoin miners in other countries and regions compensated for the reduced computing power.

5. Proof-of-Stake

Peercoin was the first virtual currency to adopt proof-of-stake in 2012. Peercoin's PoS is achieved through coinage, which is calculated by multiplying the amount of currency held by the amount of time it is held [34]. Like Bitcoin, peer coins use PoW, but the difficulty of mining is inversely proportional to the amount of coinage consumed [34]. In other words, the more considerable the amount of coinage consumed, the easier it is to discover blocks. The difference between PoS and PoW can also be seen in the difference in block reward. In PoS, all miners have the advantage of holding native coins, so even a lower block reward will work towards maximizing the value of their native coin holdings [35]. In PoW, on the other hand, there is no benefit for miners to hold native coins, so lowering the block reward will undermine the incentive to participate in block verification.

It is possible to use less power and computing machinery to verify cryptocurrencies using PoS since the amount and duration of coin holdings determine the mining reward. Platt et al. show that Bitcoin's overall and per-transaction electricity consumption is at least three orders of magnitude higher than cryptocurrencies employing the most consuming PoS systems [32]. In addition, we see that there is a difference in power consumption among cryptocurrencies that use PoS [32]. This may be due to the number of nodes engaged in mining and the architecture of the cryptocurrency affecting the power consumption.

6. Bitcoin and the Environment

6.1. How to Analyze Energy Consumption

Narayanan et al. described two methods for estimating the energy consumption of Bitcoin: one is a top-down method that estimates the electricity cost from the mining revenue, and the other is a bottom-up method that estimates it from the hash rate [20]. The top-down method infers the power used by the miner from the mining reward. It converts the current mining reward into legal tender and divides that value by the electricity usage price of the miner's location [20]. Although the miner does not spend all of the mining revenue on electricity, it gives an upper bound on the electricity used. In the bottom-up method, electricity usage is inferred from the network's hash rate and the mining hardware's mining efficiency. It can be obtained by the following formula [36].

$$P = H * e * P \cup E$$

where P is power consumption, h is hash, e is the energy efficiency of the hardware, and $P \cup E$ is power usage effectiveness.

6.2. Geographical Distribution of Miners

It is essential to consider the geographic location of Bitcoin miners when considering carbon emissions since the main methods of power generation vary from place to place. Bitcoin miners tend to be in similar regions.

Table 1 shows the determinants of location for Bitcoin miners when operating a new mining facility. Since mining requires a large amount of electricity, we can see that the most critical indicators for Bitcoin miners are access to electricity and the price of electricity.

Table 1. Determinant of location for small and large miners to set up new mining facilities [37].

Assessment Factors	Small Miners	Large Miners
Stable political environment	4.37	4.63
Friendly regulatory environment	4.37	4.75
Presence of skilled labor	3.32	3.75
Cold climate	3.11	4.25
Good internet connectivity	4.32	4.38
Easy access to a substantial electricity supply	4.37	4.88
Low electricity cost	4.47	4.88
Cheap land	3.58	3.75
Special incentives for mining-related activities Low crime rate	3.95	4.13
Low crime rate	3.63	3.88

The mining sites have relatively small populations and hilly or mountainous areas with powerful rivers flowing through them. This means that minorities will move to places where electricity rates are meager. According to an estimate by the University of Cambridge, the global mining rate as of April 2021 was as shown in Figure 3 [15].

This figure shows which countries are doing what percentage of Bitcoin mining globally. At this point, China accounted for almost half of the total, followed by countries such as the United States, Kazakhstan, and Russia.

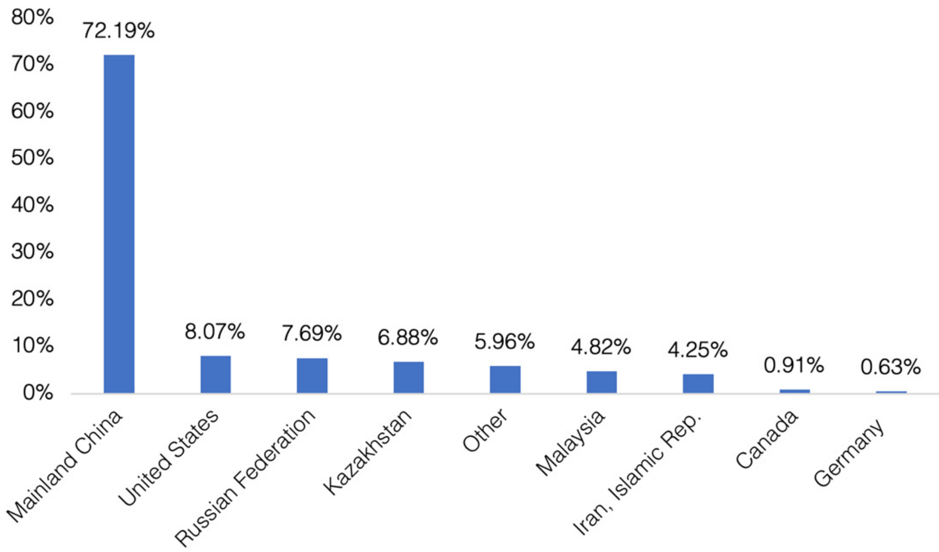

Figure 3. Country share of Bitcoin mining in April 2021 based on reference [13].

6.3. Difficulty in Estimation

There are three reasons why it is difficult to measure the energy consumption of Bitcoin accurately. The first is that some mining sites have seasonally varying drive rates, as observed in China. In the dry and rainy seasons, mining operations tend to shift between locations in response to fluctuations in renewable energy production, according to CBECI [13]. In other words, miners will increase or decrease their mining capacity depending on the time of year. The second reason is that the hardware used in mining cannot be identified. There is a gap in power efficiency between older hardware and newer ones. For example, if we compare the energy efficiency of the ASIC devices AntMiner S1 [500 Mhash/J] and AntMiner S9 [10,182 Mhash/J], the difference is more than 20 times [38]. Mhash/J stands for millions of hashes per joule. Most methods for estimating energy consumption assumed the cost of electricity for mining and then estimated it by excluding less profitable devices from the estimation. However, in reality, the acquisition cost of older-generation mining devices is low, and miners may continue to use older devices today. Therefore, it cannot be said in general that Bitcoin miners are using state-of-the-art devices with high energy consumption efficiency [39].

The third reason is that the price of Bitcoin has a direct impact on the energy consumption of Bitcoin. Huynh et al. stated that the price of bitcoin has a dynamic relationship with its energy consumption and found that a rapid decline in the price of bitcoin triggers high connectivity in energy usage [40].

In addition to the above factors, it is also difficult to accurately grasp the factors associated with mining, such as the cooling of mining hardware.

6.4. Energy Consumption

Table 2 shows the estimated energy consumption of Bitcoin by various studies [39,41–45]. Energy consumption is presented in megawatts (MW). The calculation method for each study is as follows.

- Vranken: The study in 2017 by Vranken stated that the lower bound of energy consumption was 45 MW if Bitcoin miners were estimated to have used the latest ASIC devices, and the energy consumption of Bitcoin was 500 MW if estimates were based on profits from mining. His study concluded that Bitcoin's energy consumption ranges from 100–500 MW.
- Bevand: Bevand's study, conducted between February 2017 and January 2018, calculated Bitcoin's energy consumption based on the energy efficiency of mining machines.

In other words, Bevand estimated the energy consumption for each case where all miners were using either old or modern mining machines.

- De Vries: In his 2018 study, when calculating the lower bound, he assumed that the miner was using a state-of-the-art mining machine. For the upper bound, on the other hand, he estimated energy consumption by assuming that Bitcoin miners would mine until their marginal cost equaled their marginal productivity.
- McCook: He estimated the power consumption assuming that the manufacturer of the mining machine forms the majority of the hash power.
- Krause and Tolaymat: They estimated the energy consumption of Bitcoin based on the energy efficiency of the mining machines, like Bevand's study.
- Stoll et al.: The lower limit of energy consumption in their study assumed that bitcoin miners were using state-of-the-art mining machines, while the upper limit was calculated by the break-even point between revenue and electricity costs. For the best guess number, they followed the lower limit approach considering the anticipated energy efficiency of the network and the extra energy loss from cooling and mining hardware.

Table 2. Bitcoin Energy Consumption Estimates 2017–2020.

Study	Publication Year	Lower Bound (MW)	Upper Bound (MW)	Best Guess (MW)
Vranken [41]	January 2017	45	500	100–500
Bevand [42]	February 2017	325	774	470–540
	July 2017	640	1248	816–944
	January 2018	1620	3136	2100
De Vries [46]	March 2018	2550	7670	
McCook [43]	June 2014			150
Krause and Tolaymat [44]	November 2018			948
Stoll et al. [45]	December 2016			345
	December 2017			1637
	December 2018			5232

Unlike precious metals such as gold, which can only be mined in specific locations, Bitcoin can be mined anywhere there is power, an internet network, and hardware. Therefore, the environmental impact depends on the primary energy source used [44]. As illustrated in Table 2, the energy consumption of Bitcoin mining varies from study to study. In addition, different estimation methods, such as those that take into account the various energy consumptions at mining facilities, could significantly increase the estimated energy consumption of Bitcoin [47].

There are challenges in accurately estimating Bitcoin's energy consumption due to differences in data sources. Some studies like [41] rely on self-reported data from miners on their energy use while others like [42] extrapolate energy use based on miner revenues. Each approach has limitations in terms of potential bias, inaccuracies, and variability over time [39]. Furthermore, estimates often focus solely on mining while overlooking other aspects of Bitcoin infrastructure like cooling and hardware waste [47]. More research is needed to provide transparent and rigorous data on Bitcoin's total energy footprint.

In terms of annual consumption, Cambridge estimated 117.9 TWh on 4 December 2021, while Digiconomist estimated its amount as 200.6 TWh [13,48]. One thing the two estimates have in common is that Bitcoin's energy consumption continues to increase. Köhler and Pizzol estimated the Bitcoin network consumed 31.29 TWh in 2018 [49]. Bevand estimated 18.4 TWh as of 11 January 2018 [42]. Stoll et al. estimated 45.8 TWh as of 2018 [45]. De Vries estimated 87.1 TWh as of September 2019 [39]. The study by Onat et al. estimated the data of annual consumption of bitcoin for five years from 2015 to 2020, with values of 0.15, 1.23, 4.98, 22.46, 38.91, and 55.58 TWh, respectively [50]. The results are shown in Figure 4.

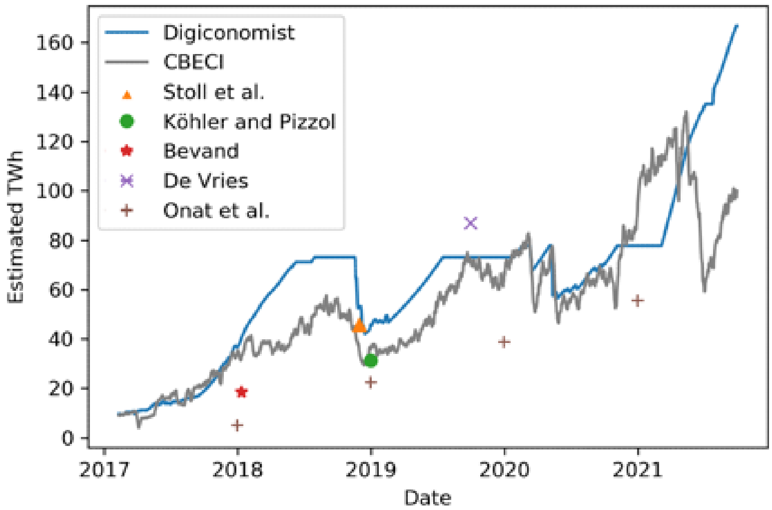

Figure 4. Annual electricity consumption of bitcoin by each study (TWh) [13,39,42,45,48–50].

6.5. Carbon Footprint

A study by Stoll et al. performed a carbon footprint of Bitcoin based on the location of the mining pool and the IP address of the mining device. According to their study, the annual global carbon footprint of Bitcoin in 2018 was 22.0–22.9 MtCO2 [45]. Compared to the world's annual carbon emissions ranking for 2018, that number is more extensive than Guatemala and smaller than Sri Lanka [51]. When compared to the 2018 global annual carbon emissions of 36,441 MtCO, Bitcoin's emissions are less than 0.06% of the total [51]. In a study by Köhler and Pizzol, Bitcoin emitted 17.29 MtCO2 in 2018 [49] and Digiconomist estimated that Bitcoin emitted 95.38 MtCO2 on 6 December 2021 [48]. Onat et al. estimated that bitcoin emitted 0.21, 0.95, 3.26, 18.30, 31.6, and 48.51MtCo2 between 2015 and 2020, respectively. The results are shown in Figure 5.

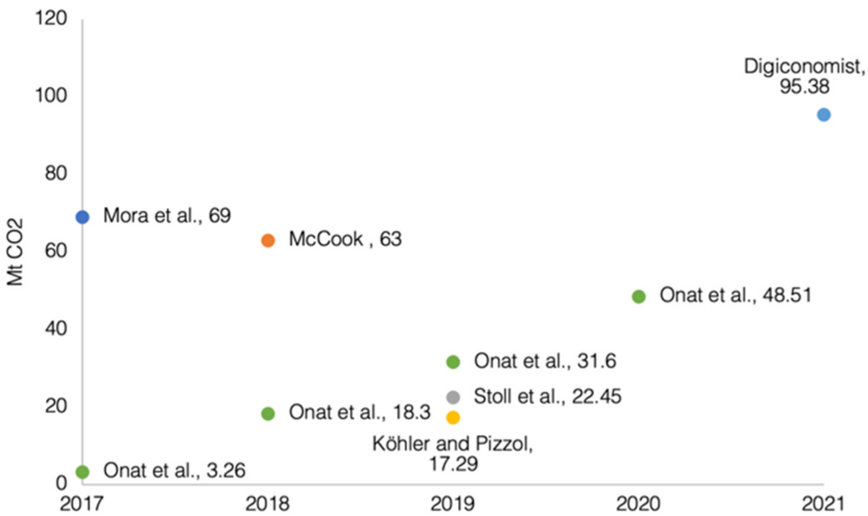

Figure 5. Annualized carbon footprint of Bitcoin [14,45,48–50,52].

6.6. Hardware Waste

In addition to the hardware disposal that occurs when newer, more efficient mining devices replace older mining devices, there are many cases where the mining devices themselves are worn out and discarded. Based on Koomey's Law, which states that the amount of computation per unit of energy consumed doubles every 1.57 years [53] and that only the most cost-effective machines are economically viable for mining, de Vries et al. estimated the lifespan of Bitcoin mining equipment to be less than 1.29 years [54]. As a result, the study estimated that the Bitcoin network generates 30.7 metric tons of waste annually [54].

6.7. Comparison

Bitcoin has been criticized for its power consumption, however, a study by Rybarczyk et al. shows that the existing financial system, banks, consume 238.92 TWh/year, more than twice as much power as Bitcoin [55].

Figure 6 shows the power consumption of the world banking system, the gold industry, and the Bitcoin network over the course of a year. The power consumption of Bitcoin at the time of comparison is based on data from CECBI. The bank's energy consumption data is derived from the power consumption of the world's banks from information about bank data centers, bank branches, ATMs, and card network data centers [55]. Song and Aste suggested that the operation and maintenance costs are enormous compared to the Bitcoin network, considering the energy consumed by the infrastructure and employees in the traditional financial system [56]. In addition, Bitcoin does not incur the cost of creating and maintaining the transit itself as legal tender does [56].

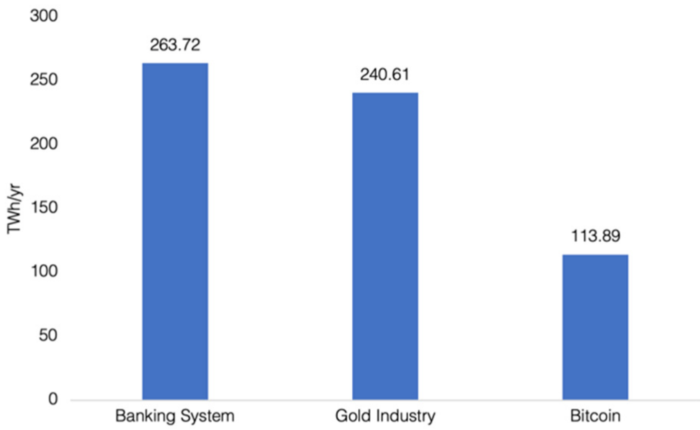

Figure 6. Comparison of energy consumption between banks, the gold industry, and Bitcoin (TWh/year) [55].

McCook calculated the contrast between the carbon footprint of the gold industry and Bitcoin, as shown in Figure 7 [52].

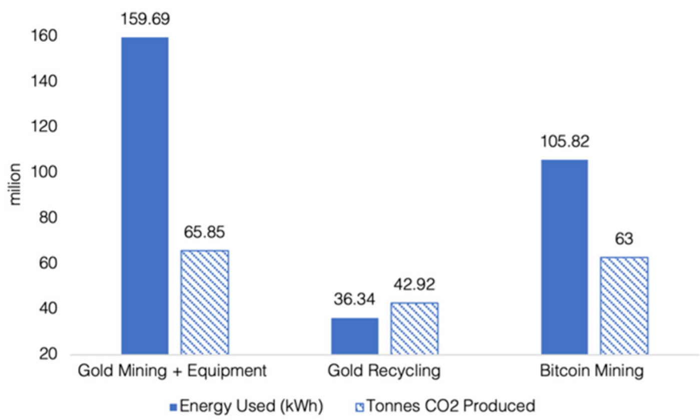

Figure 7. Comparing the carbon footprint of the gold mining industry and its equipment, gold recycling, and the Bitcoin network [52].

7. Renewable Energy and Bitcoin Mining

7.1. What Is Renewable Energy?

Not only determined by geological depletion but also by national resource policies, reserves of fossil fuels like oil, gas, and coal are all likely to peak by 2030 [57]. As a result, a shift to renewable energy is taking place around the world. Unlike fossil energy, which is a finite resource such as oil or coal, renewable energy does not emit greenhouse gases, such as solar, wind, and hydroelectric energy, which always exist in nature [58]. While renewable energy has significant environmental benefits, there are also reasons why it is challenging to implement. One of the issues is that the amount of power generated per unit area is smaller than that of thermal power generation, so huge facilities and sites are required. The second reason is that electricity is difficult to store in large quantities, so output and demand must be kept constant [59]. According to the IEA, the share of renewable energy in global power generation reached about 27% in 2019 [60].

7.2. Renewable Energy and Mining

Research on the use of renewable energy in Bitcoin mining, like energy consumption, has varied in result numbers from study to study. 2019 Research by CoinShare estimated renewable energy use in Bitcoin Mining at 73% in December 2019 [61]. On the other hand, Brandin et al. estimated the number as 39% in September 2020 [62]. The different survey methods used in the two studies may be the reason for the extensive range in the figures. While Brandin et al.'s study is based on a survey of miners, CoinShare multiplies the penetration of renewables in each Bitcoin mining region by the region's share of the global mining industry. They then use a method to calculate a weighted average [61,62]. China's share of the world's mining volume as of 2019 compared to 2020 is high. In addition, the low price of renewable energy due to the abundant water resources in Sichuan during the rainy season may have had a significant impact on the calculation results.

Malfuzi et al. stated that the profitability of mining with renewable-based SOFC power is lower than that of mining with the grid. However, considering the environmental issues and sustainability of grid-based mining, renewable energy-based mining is beneficial in the future [63]. Bitcoin miners need cheap power to generate profits. Therefore, if renewable energy sources become cheaper than fossil fuels, miners will inevitably start using renewable energy sources. In a study of the tail dependence of Bitcoin and green financial assets, Naeem and Karim found that clean energy is an effective hedging instrument for Bitcoin [64].

According to IRENA, solar and onshore wind power in 2020 will always be below the price of the cheapest coal-fired power, even without government funding. In addition, the operating costs of solar PV and onshore wind power are also lower than those of existing coal-fired power generation [65]. Roser stated that one of the reasons why solar power, one of the renewable energy sources, has become much cheaper to generate is because it had the advantage of being able to generate power in space, and production processes and technologies continued to improve for the purpose of powering satellites [66]. The study by Bastian Pinto et al. shows that the simultaneous construction of a wind farm and a Bitcoin mining site can reduce the risk of future electricity price fluctuations [67]. In other words, if the market price of electricity decreases, the electricity can be used for Bitcoin mining. Figure 8 shows the electricity prices in 2009 and 2019 for each generation facility method, respectively.

7.3. Bitcoin Mining in China

China had a dominant position in Bitcoin mining until the strict regulation. This was because of cheap electricity and technological development. The cost of industrial electricity in China in March 2020 was $0.098, compared to $0.109 in the U.S.; it is cheaper than U.S. [68]. As of 8 October 2021, the most profitable five ASIC hardware manufacturers were, from top to bottom, Bitmain, Innosilicon, Goldshell, iPollo G1, and StrongU, and four of these companies have their HQ in China [69]. In addition, the local government was assisting Bitcoin mining. For example, the local government of Ordos in China's Inner Mongolia Autonomous Region provided electricity to Bitcoin miners for $0.04 per kWh [70].

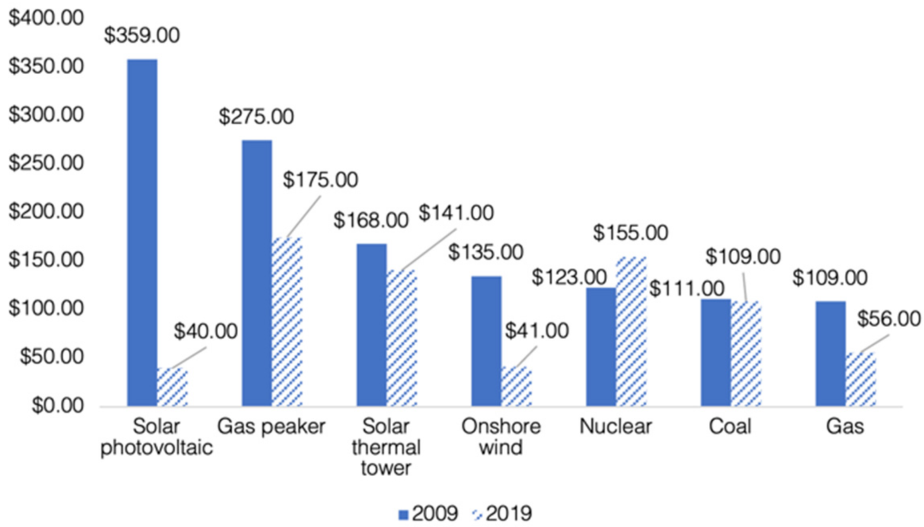

Figure 8. The price of electricity from new power plants [66]. This figure shows the electricity prices in 2009 and 2019 for each generation facility method, respectively.

Figure 9 shows the average monthly hash rate share for Mainland China based on geographic mining pool data in August 2019. The shade of the color represents the size of the hash rate. Mining was concentrated in Inner Mongolia, Xinjiang, Sichuan, and Yunnan.

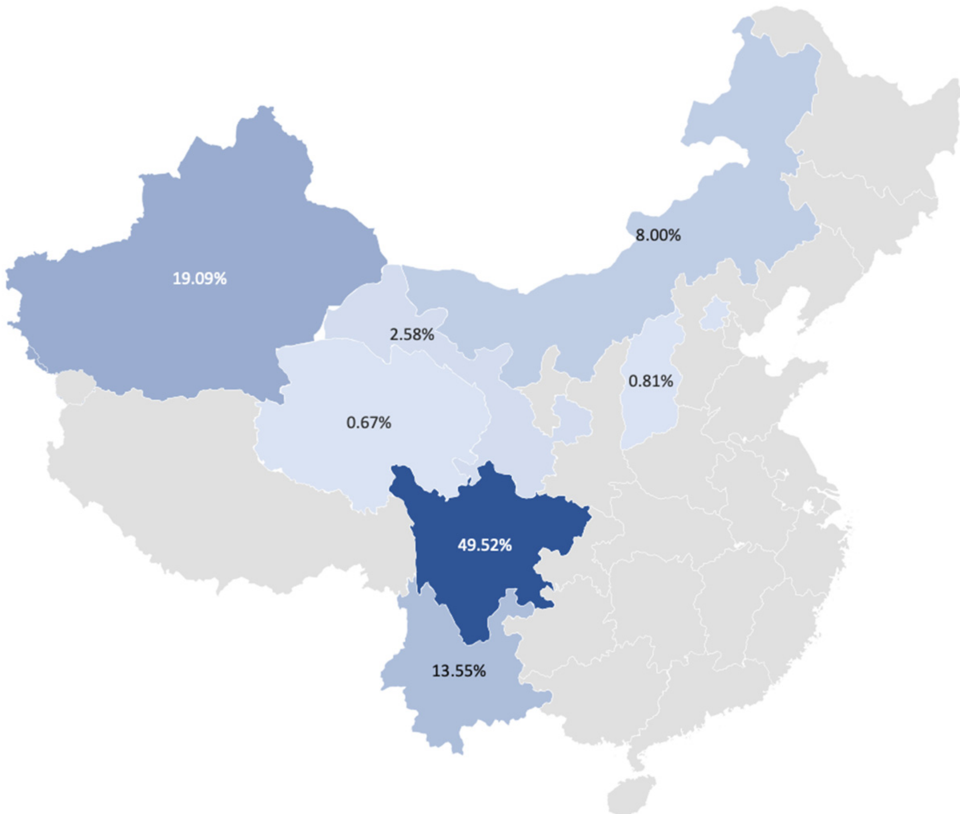

Figure 9. Distribution of Bitcoin mining in China based on the paper [13].

Large-scale thermal power generation is taking place in Xinjiang and Inner Mongolia, and hydroelectric power generation is flourishing in Sichuan and Yunnan, taking advantage of their abundant water resources and electricity supply is significantly greater than demand [71,72]. Therefore, Bitcoin mining was intensively conducted in the districts mentioned above.

7.4. Mining Ban in China

In May and June 2021, the local governments of Inner Mongolia, Qinghai, Xinjiang, Yunnan, and Sichuan issued a ban on Bitcoin mining [32]. On 24 September, the People's Bank of China issued a notice stating that business activities related to virtual currencies are illegal. In the notice, the People's Bank, in league with law enforcement agencies, explicitly notified local governments to monitor Bitcoin mining [73].

Figure 10 shows which countries in the world are mining Bitcoin and at what rate. At the moment, the United States accounts for nearly half of the total, followed by countries such as Kazakhstan, Russia, and Canada.

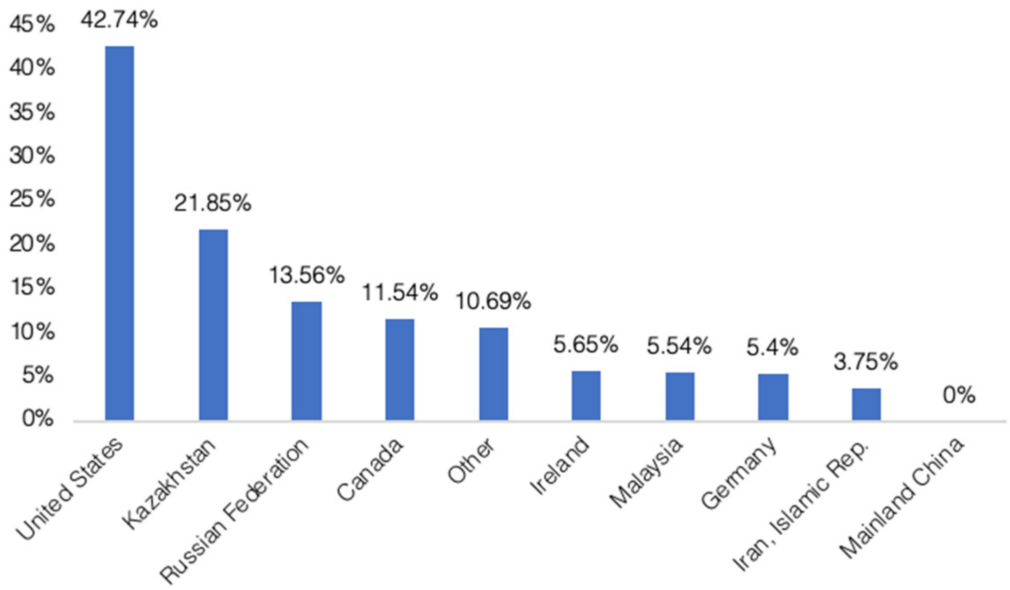

Figure 10. Country share of Bitcoin mining in August 2021 based on the paper [13].

One of the reasons China has regulated Bitcoin mining is because of environmental issues. Jiang et al. estimated that carbon emissions from Bitcoin operations will peak at 130.5 million tons per year in 2024, ranking in the top 10 among China's 182 county-level cities and 42 major industrial sectors and accounting for about 5.41% of China's power generation emissions [74]. In other words, the Bitcoin industry's carbon emissions were a threat to China's greenhouse gas emission reduction goals.

7.5. Renewable Energy in China

In places like Yunnan, Sichuan, and Inner Mongolia, the equipment usage rate for renewable energy is relatively high in China. The facility utilization rate is calculated by the following equation [75].

$$R(\%) = \frac{E}{C * 365\ days * 24\ hours} * 100$$

where R is annual equipment usage rate, E is annual power generation, and C is power generation capacity.

The average annual capacity utilization of wind and solar power in China as a whole is 24% and 13% [63]. Figures 11 and 12 show the utilization rate of wind and solar power facilities in each province of China.

Figure 11 shows the utilization rates of wind power facilities in 17 Chinese provinces and autonomous regions, listed in descending order of utilization rate. Yunnan, Sichuan, and Inner Mongolia, where Bitcoin mining was widespread, have higher usage rates than the Chinese average, and wind power was being used effectively.

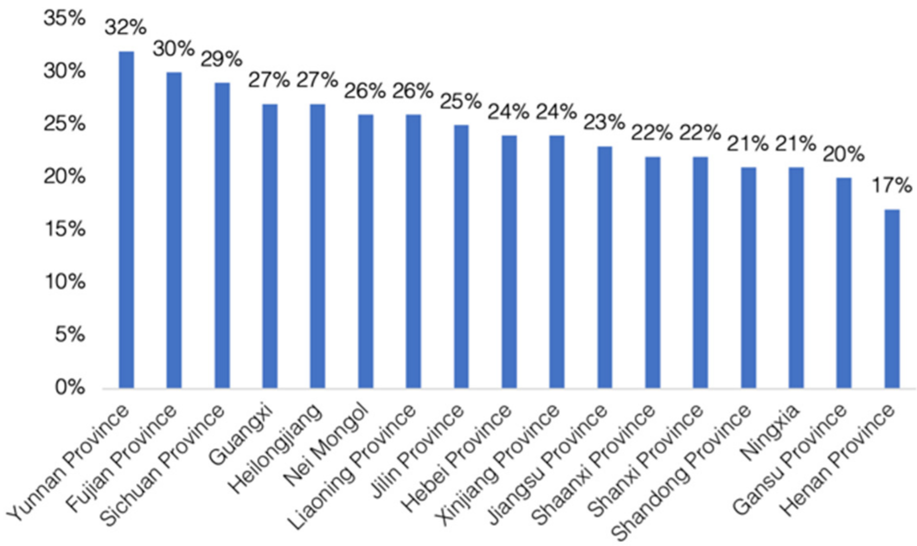

Figure 11. The utilization rate of wind power generation equipment in 2019, based on reference [75].

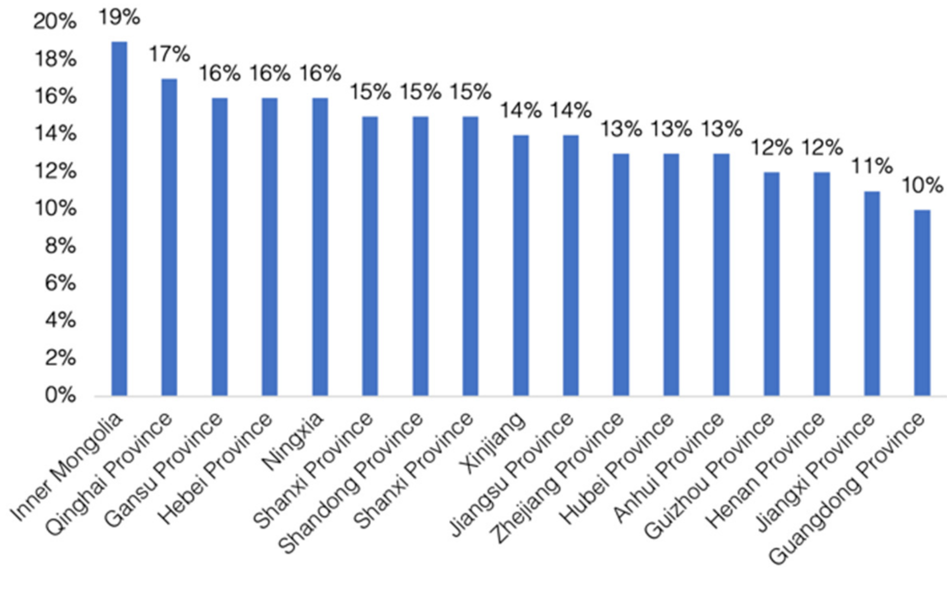

Figure 12. The utilization rate of solar power generation equipment in 2019, based on reference [75].

Figure 12 shows the utilization rates of solar power facilities in 17 Chinese provinces and autonomous regions, listed in descending order of utilization rate. In terms of the utilization rate of solar power generation equipment, the Inner Mongolia Autonomous Region ranks first with 19%, and Xinjiang Uygur Autonomous Region ranks fifth with 14%.

There were many Bitcoin miners using small-scale hydroelectric power development in Sichuan and Yunnan provinces [76]. The development of small hydropower in China has not only met local electricity demand but has also contributed to the local economy by selling surplus power to the power grid [77]. In addition, Yunnan and Sichuan provinces had become the latest hot areas for private investors to build more new small hydropower plants [77]. Miners were using the power from those plants to mine Bitcoins, so after the government banned Bitcoin mining, many small-scale hydroelectric plants were put up for sale [78]. Thus, we can see that the use of renewable energy has advanced in the region of China, where Bitcoin mining is popular.

In response to the Chinese mining ban, Bitcoin miners began moving to Kazakhstan and Texas for cheap electricity [79]. In Kazakhstan, coal accounted for about 70% of electricity generation in 2018, followed by natural gas at 20% [80].

Figure 13 shows the electricity production for each source in Kazakhstan in 2018. Renewable energy accounted for 10.4% of power generation in Kazakhstan in 2018. This was a low figure compared to China's 29.5% [16], which raised concerns about the negative environmental impact of fossil fuel-based Bitcoin mining in Kazakhstan.

7.6. Mining in Texas

After China banned Bitcoin mining altogether, the U.S. hash rate increased, accounting for 35.4% of the global hash rate at the end of August [13]. In other words, the U.S. has become the world's leading position in Bitcoin mining.

Figure 14 shows the Bitcoin hash rate by state, based on data from Foundry USA, the largest mining pool in the U.S. According to the Figure, 19.9% of the hash rate is in New York, 18.7% in Kentucky, 17.3% in Georgia, and 14% in Texas [81]. The deregulated power grid in Texas allows miners to buy cheap power from the power grid at a fixed price [82]. In other words, Texas tends to have the best economics for miners, which is why some miners from China moved their business to Texas. In addition to the cheap electricity, Texas is also making progress on cryptocurrency legislation. With bill HB4474, cryptocurrencies have been incorporated into the Commercial Code and recognized as valid for commercial transactions [83]. Considering the above factors, Texas is likely to increase its share of Bitcoin mining in the U.S. in the future.

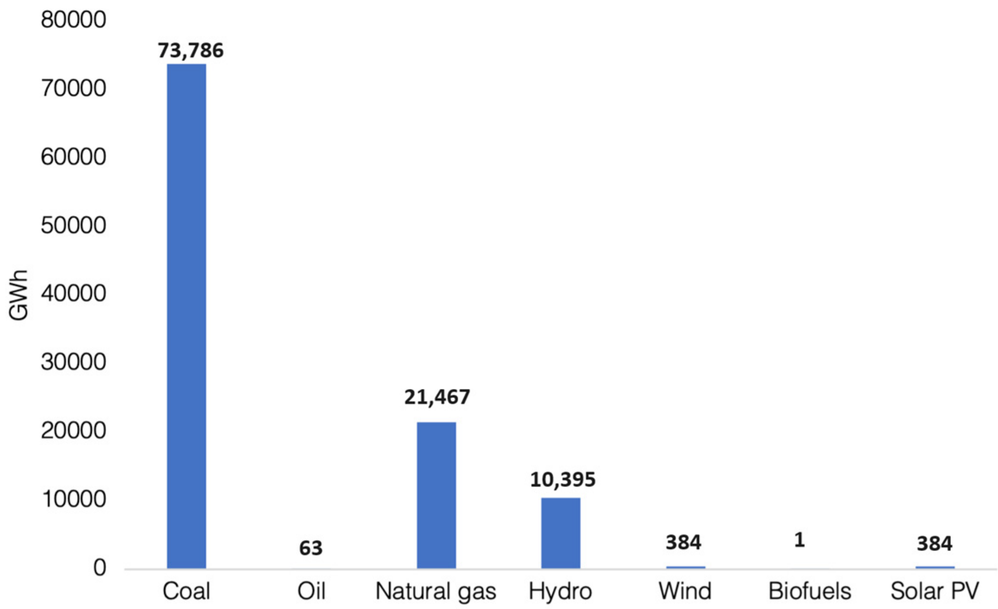

Figure 13. Electricity generation energy sources in Kazakhstan, based on reference [80].

7.7. Renewable Energy in Texas

Texas leads the nation in wind power generation, with wind accounting for nearly all of the electricity generated by renewable resources in Texas [84]. In addition, the state has made great strides in the adoption of solar power, becoming the second-largest producer of solar power in the country in 2020, behind only California [85].

Figure 15 shows the electricity production of each power source and the percentage of renewable energy in the total in Texas from 2010 to 2020. Renewable energy, especially wind power, continues to grow as its share of total electricity generation in Texas has increased from 8% in 2010 to 25% in 2020. The adoption of renewable energy in Texas is likely to proceed within the framework of a political push by the legislature and a competitive electricity market [86]. In the future, Bitcoin mining will become more environmentally friendly as cheap renewable energy is introduced in Texas.

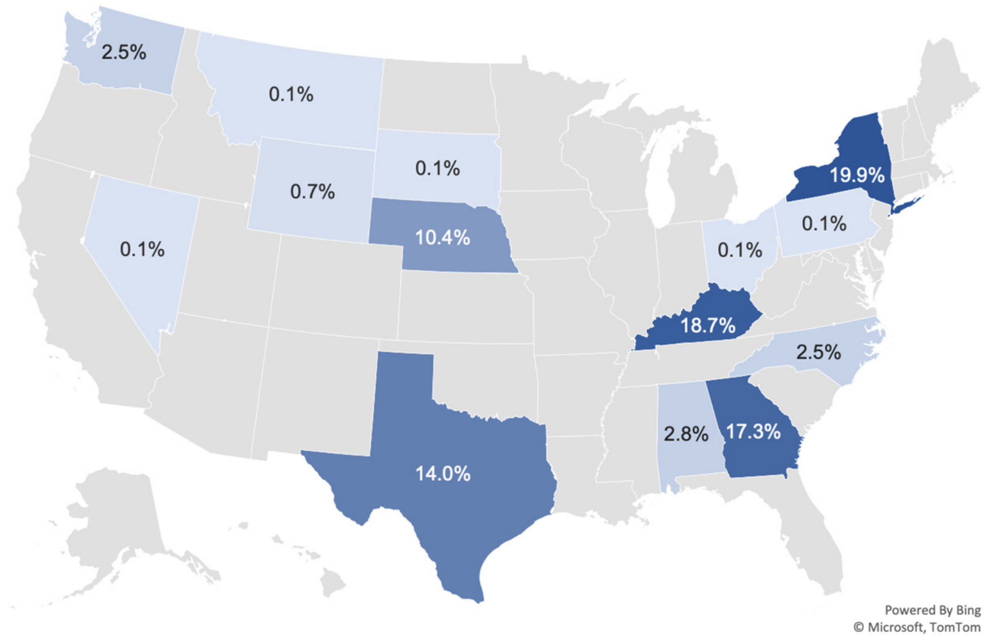

Figure 14. U.S. hash rate shared by the state at Foundry USA pool taken, based on reference [71].

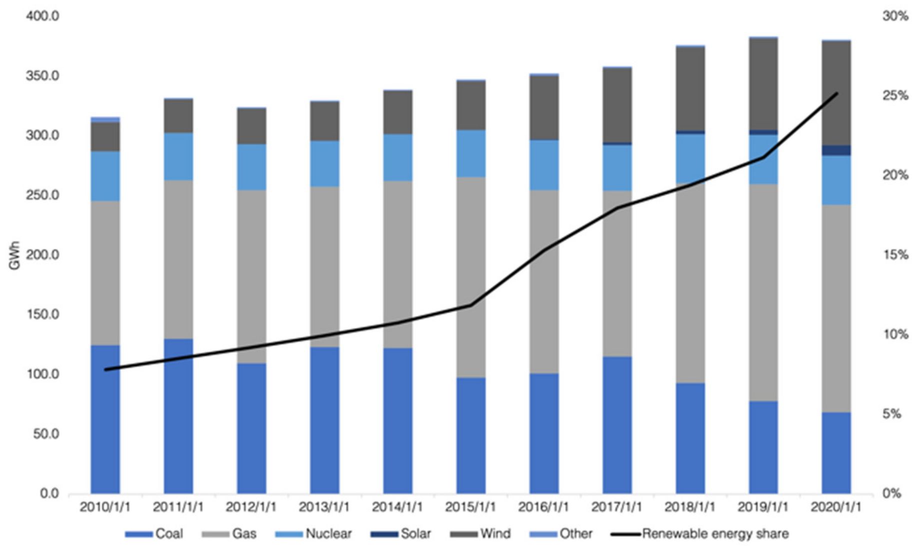

Figure 15. The renewable share of power generation in Texas, based on reference [84].

7.8. Environmental Initiatives by Industry

As a result of the growing debate on the environmental issues of Bitcoin and other cryptocurrencies, there has been a shift towards the creation of an environmental framework at the industry level. The Crypto Climate Accord is a private-sector initiative to achieve virtually zero greenhouse gas emissions by 2040 [87]. More than 150 cryptocurrency business-related companies, NGOs, energy, and climate experts participate in this initiative [87]. We can expect the initiative to make the crypto industry more sustainable.

8. Conclusions

This research paper contributed to the collection of editorials on Bitcoin and energy consumption and the use of renewable energy for Bitcoin mining. In particular, the banning of mining in China will have a significant impact on the future movement of Bitcoin mining sites.

With recent policymakers and society's increasing concern for the environment due to the Paris Agreement and other factors, the environmental impact of Bitcoin is gaining attention. This study identifies the environmental impacts and challenges of the Bitcoin network and mining process on the environment. This study serves as a review before more advanced research.

Bitcoin uses proof-of-work as its consent formation protocol. The reason why the Bitcoin network requires a lot of power to maintain is the PoW process; proof-of-work literally requires that computing power and power consumption be provided for the transaction verification work. The participants in the transaction verification work need to discover the nonce in the range through a hash function, and that work is called mining. Since the hash function is unidirectional, nonces can only be discovered by a brute-force attack with computing resources. Other cryptocurrencies, such as Peercoin, use proof-of-stake, which verifies transactions by the amount and duration of coins held, allowing the network to operate with less power and computing machinery than PoW.

Bitcoin miners tend to congregate in similar regions with stable access to electricity and low prices. Examples of such areas are relatively sparsely populated, hilly, or mountainous areas with strong rivers running through them.

The reason why it is difficult to accurately measure the energy consumption of Bitcoin is that miners increase or decrease their mining capacity depending on the time of year, and the power efficiency of the hardware used for mining varies. In addition, it is difficult to accurately grasp the power consumption related to mining, such as hardware cooling. For the reasons mentioned above, each paper has a range of figures for power consumption and carbon dioxide emissions even with the same estimation method. It is also necessary to take into account not only the energy consumption generated by mining but also the e-waste generated by the mining hardware. In Bitcoin mining, power prices are important to miners. Therefore, if the price of electricity from renewable energy sources becomes cheaper than the price of electricity from coal and other fossil fuel-based energy sources, miners will inevitably start using renewable energy sources.

China had long dominated the top spot in the hash rate of mining by country, but the total ban on mining in the country began and the hash rate rapidly declined. This was because the government was concerned about carbon emissions from Bitcoin operations. However, the areas of China where mining was popular have been adopting renewable energy, and it is thought that a not insignificant percentage of renewable energy was being used for mining.

After the Chinese mining ban, the miners moved to Kazakhstan and Texas. In Kazakhstan, where the adoption rate of renewable energy is extremely low, there are concerns about the negative impact of Bitcoin mining on the environment. In Texas, there is a congressional push for cryptocurrencies in addition to low electricity prices. Texas is likely to increase its share of Bitcoin mining in the US in the future. With the introduction of cheap renewable energy in Texas, Bitcoin mining will become more environmentally friendly. However, the environmental impacts of relocated mining will depend on the energy mix in these new mining hotspots. More research is needed to track the post-China shift in Bitcoin's energy footprint. There are also open questions about making crypto-mining more energy efficient through renewable energy, optimized hardware, and consensus protocols like proof-of-stake.

As a result of the increased discussion on the environmental issues of Bitcoin and other cryptocurrencies, efforts are being made to address the environmental aspects at the industry level. It is hoped that these efforts will make the crypto industry more sustainable. Moving forward, research should continue monitoring Bitcoin's energy consumption across changing regulatory landscapes. More investigation is needed into making cryptocurrencies environmentally sustainable through clean energy and optimized design. Additionally, robust life cycle analyses are needed to fully account for the environmental impacts of Bitcoin mining, including factors like hardware waste.

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