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Energy consumption of cryptocurrency mining: A study of electricity consumption in mining cryptocurrencies

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A B S T R A C T

Cryptocurrency is a relatively new combination of cryptology and currency in financial areas and is increasingly frequently used worldwide. Blockchain applications are expected to reshape the renewable energy market. However, there is a lack of studies covering the power usage of digital currencies. Therefore, this study ran experiments on mining efficiency of nine kinds of cryptocurrencies and ten algorithms. A comparison of statistical analysis of data in a benchmark and experiment results of Monero mining was conducted. Thereafter, this study provided an estimation of global electricity consumption of the Monero mining activity. The results indicated that the hashing algorithm mainly determines the mining efficiency. Data analysis and experiments and estimated Monero mining electricity consumption in the world and its carbon emission in China as a case study. In 2018, Monero mining may consume 645.62 GWh of electricity in the world after its hard fork. The Monero mining in China may consume 30.34 GWh and contribute a carbon emission of 19.12–19.42 thousand tons from April to December in 2018. Although cryptocurrency mining and blockchain technology are promising, their influence on energy conversation and sustainable development should be further studied.

1. Introduction

1.1. Background and motivation

Although cryptocurrency is a relatively new form of currency in financial areas, it has become more frequently used in towns and cities around the world in recent years. Currently, the value of all bitcoins is about $157.7 billion, and a volume of $8.9 billion every 24 h [1,2]. Statistically, the emerging market has at least 1587 kinds of coins representing a market capability of $432 billion [1]. After developing rapidly during the past few years, there has been a shifting but expanding marketplace for bitcoin, as well as a recognition of other cryptocurrencies. The value of bitcoin and other cryptocurrencies is assessed legitimately. (see Fig. 6)

The existing literature of cryptocurrencies can be grouped into two categories. The studies in the first category include technologies that support digital currencies. For instance, Khan and Salah [9] stressed the importance of blockchain in solving security issues in the Internet of Things (IoT) and future directions combining realities with the internet. Huh et al. [10] discussed deploying smart contracts to control and configure IoT devices. Some scholars are particularly interested in applying smart contracts to monitor the temperature of the indoor environment [11]. The second category characterized cryptocurrencies through various analysis. For instance, Phillip et al. [12] measure the nature of 224 different cryptocurrencies to evaluate their investability. Gkillas and Katsiampa [13] concluded that Bitcoin and Litecoin were the least risky of 5 dormant cryptocurrencies.

These studies provide insights into the dynamics of cryptocurrencies of their technological advancements. Using hashing algorithms, nodes of the network will validate a block and its transactions under a decentralized environment [14]. Transactions of cryptocurrencies work without an exchange center. For instance, transaction records of Bitcoin are validated and added to the blockchain by anyone with access to the internet and suitable hardware. Mining, as defined in Table 1, is the process that transactions are verified and added to the blockchain. The devices for the calculation are miners. Other mainly used keywords were explained in Table 1.

Miners can generate new blocks after completing all of the data in the block. Each block contains the transaction information of the last block. Thus, each block has a chain of blocks that together

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Table 1
Definitions of mainly used cryptocurrency keywords.

Mainly used Keywords	Descriptions
Mining	Mining is the process of validating computations. The process adds transaction records to the public ledger of past transactions or blockchain [3].
Hashrate	The hashrate is the unit of the processing power of the cryptocurrency network per second [4]. The unit varies depending on the coin, usually seen as H/s.
Hard fork	A hand fork is a change to the blockchain protocol that makes previously invalid blocks/transactions valid [5]. A hard fork requires all nodes in the community to upgrade their tools.
Blockchain	The blockchain a peer-to-peer network that sits on top of the internet [6]. It is a public record of all transactions in order.
Monero	Monero (XMR) is an open-source cryptocurrency that focuses on privacy, security, and decentralization [7].
Mining efficiency	The mining efficiency of a mining device was the ratio of the number of hashes in a second, divided by the power is consumed [8]. The unit varies depending on the coin, usually seen as J/H.

include a tremendous amount of work [15]. Changing a block requires regenerating all successors and redoing the work they carry. The process needs a massive amount of hash rate and consequently makes the blockchain difficult from tampering. For instance, Bitcoin uses the hashcash proof of work (PoW) as the mining core for block generation. The most widely used hashing algorithms are based on SHA-256 and it is introduced as a part of Bitcoin [6]. Some other algorithms are used for PoW [15], Table 1 shows some of them. Most coins can only be mined with one algorithm. However, some of them are compatible with many hashing algorithms. For the concern of decrease in block incentives, many other schemes are developed to enhance the network security. These schemes include Proof-of-Activity (PoW/PoS-hybrid), Proof-of-Burn (PoB), Proof-of-Validation (PoV), Proof-of-Capacity (PoC or Proof-of-Storage), Proof-of-Importance (PoI), Proof-of-Existence (PoE), Proof-of Elapsed Time (PoET), Ripple Consensus Protocol and Stellar Consensus Protocol (SCP). Despite the advancements of these new schemes, they have their concerns, including nothing-at-stake problem of PoS, excessive centralization of DPoS, and Difficult in building network effects of PoB [16]. Currently, the PoW and PoW/PoS hybrid schemes are mostly used by cryptocurrencies [1].

All the calculations of PoW and PoW/PoS hybrid schemes including mining the coins and maintaining the system are completed by electronic devices. Correspondingly, the use of cryptocurrencies relies on the consumption of electricity. However, the number of studies covering the power usage of digital currencies is relatively minor. There is a significant need for the analysis of electricity consumed by this technology.

1.2. Previous work on electricity consumption of cryptocurrencies

The known estimations of electricity consumption are mainly about Bitcoin. After the creation of the first block in 2009, the network difficulty of Bitcoin was only one [17]. CPUs and GPUs were used for mining. The mining performance of different devices was compared by mining efficiencies. Garcia et al. [18] used an average mining efficiency of 2 MH/J to estimate a fundamental value of one Bitcoin. Later, technologists developed Application Specific Integrated Circuit (ASIC) miners to increase the mining efficiency. Hayes [19] estimated the cost of electricity was close to the market value of Bitcoin with an assumed number in 2017. However, the ASIC miners have side-effects. Because of the outstanding hash rate, ASIC miners decreased the decentralization of Bitcoin by making 51% attack possible [20]. To stable the network, others will have to increase their hash rate, which in the end causes higher energy consumption.

The commonly seen figures of electricity consumption are based on assumptions. For instance, Digiconomist used the portion of mining revenues being spent on electricity costs for the estimation [21], the estimated annual electricity consumption of Bitcoin is 63.99 TWh in 2018. Also, Ethereum had an assumption of 18.09 TWh as the second largest cryptocurrency [22]. Digiconomist's results were also used in a report by Bank for International Settlements (BIS) in June 2018. In the report by BIS, they indicated that pursuing decentralized trust could become an environmental disaster [23]. While Bevand [24] assessed the value with the energy efficiency of miners, Bevand expected the annual electricity consumption in 2018 ranging from 14.19 TWh to 27.47 TWh. The results varied greatly. Prediction of Bevand was less than half the result of Digiconomist. Another report in August 2018 doubted results of Digiconomist. Imran [25] believed it was inappropriate to compare Bitcoin's per transaction energy usage with VISA because Bitcoin's energy is used to protect all transactions dating back to 2010. The mining process could help promote energy reallocation and the development of renewable energy [25]. However, there are currently no precise methods to estimate energy consumption of mining cryptocurrencies. The only specific number is the absolute minimum energy consumption using the product of network hash rate and energy efficiency of the most efficient miner. In this case, considering the average network hash rate of Bitcoin since January this year is around 27235.27 PH/s [26], the current most efficient miner has a mining efficiency of 10.2 GH/J [24], the current minimum annual electricity of Bitcoin mining is 23.38 TWh. The estimation of overall electricity used for Bitcoin mining is enormous.

Moreover, the mining activity includes other altcoins beside Bitcoin and Ether. Many altcoins [27] are created for these devices that can hardly mine Bitcoin or Ether. The altcoins can be traded for Bitcoin and Ether at the exchange centers. Behind the growing cryptocurrency market is the massive energy consumption. In the meantime, studies and investments have started applying blockchain to develop renewable energy because of its ability to accumulate and manage resources. Projects about metering, trading, and transportation of renewable energy using blockchain technology have been carried out by groups in Europe, America, and Australia [28]. Adjeleian et al. [29] believed the application of blockchain could provide more people with access to renewable energy and reshape the renewable energy market. They presented examples of companies and discussed the major problems in data protection and storage. However, their works focused on the trading and managing strategies after using blockchain. The statistical details of blockchain in the energy industry were not presented. With the unknown mining costs and increasing expectation of blockchain, there is a need to find out the energy consumption of the maintenance of the blockchain network.

There are several challenges when estimating electricity usage. Firstly, the overall number of cryptocurrencies is uncertain. People can develop an altcoin with guidance online. The actual number of cryptocurrencies changes every day. The second challenge is the condition of miners. Any ordinary computer with proper software can join the mining activity. Thirdly, cryptocurrencies are designed to be untraceable. This uncertainty makes it extremely difficult to acknowledge the status of the mining activity.

Given the problems above, there is a lack of investigations into energy consumption of mining cryptocurrencies. Most encrypted digital currency report hardly covered the influence on energy. Therefore, this study discusses the status of energy consumption of cryptocurrency mining. The team quantitatively estimated electricity consumption of another cryptocurrency with theoretical and experimental results. The results could be used when designing digital currencies and calculate the performance of blockchain applications in the energy market.

2. Methodology

In this section, the method of this study is explained. Section 2.1 explains the research objects and their properties. Section 2.2 focuses on experimental facilities, conditions, and procedures. These are followed by a part that elaborates on the steps of this study. The steps are illustrated in Fig. 1. Experiments were firstly conducted on the digital coins other than Bitcoin. Then, the statistical analysis of data in a benchmark and experiment results of Monero mining were compared to validate the results. Finally, this study provided an estimation of global electricity consumption of the Monero mining activity.

2.1. Study object

This study used several encryption coins from Google search to make the test objects were reachable for everyone. The coins are classified according to their algorithms. The consensus mechanism of the coins was mainly POW or POW/POS hybrid. Table 2 shows altcoins in this study. All information of the coins in Table 2, including mining algorithm and total supply, can be traced in Announcements (Altcoins) of Alternate cryptocurrencies in Bitcoin.

Then, this study selected Monero for estimating electricity consumption during mining because of three factors. The first reason is the representativeness of Monero. Monero is recognized for its unlinkability and untraceability, which currently ranks 12th among cryptocurrencies with a market capitalization of more than $3.9 billion [1]. The second one is that Monero is still mineable. Monero conducted a hard fork to change its POW to resist ASIC miners in April 2018 [30], which makes the active miners in the world are CPUs and GPUs. Thirdly, there is a relatively available database for Monero. A benchmark was set up for Monero miners sharing their hash rate [31], which solves the absence of a central register with all active miners.

This study used three notebook computers and two desktop computers. Since these devices had not replaced their hard disks, the operating time of these devices was equal to the service time of hard disks. Each of them was tested by professional hardware identify software before experiments. Table 3 shows the detail information of the devices. The operating systems were Windows 10 professional. The mining software was xmr-stak, which can provide the same mining performance of CPUs and GPUs. RAM uses very

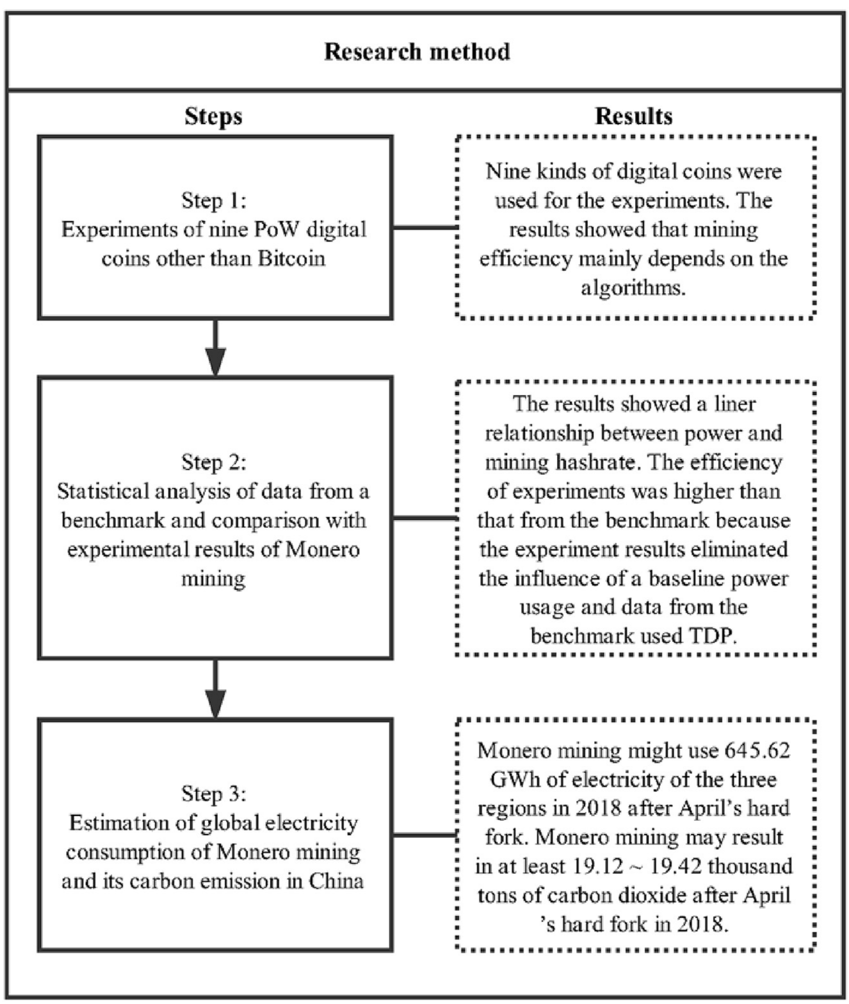

Fig. 1. Research method workflow.

Table 2
The cryptocurrencies tested in this study.

Cryptocurrency	Mining Algorithm	Consensus Mechanism	Total Supply/(Million coins)
Verge (VXG) [32]	Lyra2rev2 myr-groestl scrypt x17 blake2s	POW	16500
NevaCoin (NEVA) [33]	blake2s	POW/POS hybrid	26.28
TajCoin (TAJ) [34]	blake2s	POW/POS hybrid	36.9
Bulwark (BWK) [35]	nist5	POW/POS hybrid	6.54
Fexchange (FXC) [36]	nist5	POW	21
Yenten (YTN) [37]	yescryptr16	POW	84
Monero (XMR) [38]	Cryptonight V7	POW	18.4
Aeon (AEON) [39]	Cryptonight-lite	POW	18.4
Pirl (PIRL) [40]	Ethash	POW	12.1

Table 3
The configuration of computers used in this study.

Computers	CPU	GPU	RAM	Measured Power Usage Baseline (W)	Computer operating hours (h)
A	i7-4710MQ @ 2.50 GHz	NVIDIA GeForce GTX 860M 2 GB GDDR5	Samsung 8 GB DDR3L 1600 MHz	18	10394
B	i5-3230M @ 2.60 GHz	Nvidia GeForce GT 750M 1 GB GDDR5	Kingston 8 GB DDR3L 1600 MHz	16	7933
C	Xeon E5-2696 v3 @ 2.30 GHz (X2)	Nvidia Quadro K4200 4 GB GDDR5	Samsung 64 GB DDR3 2133 MHz	80	10
D	i5-4590 @ 3.30 GHz	Nvidia GeForce GTX 660 2 GB GDDR5	Kingston 16 GB DDR3 1600 MHz	48	9122
E	i7-4720HQ @ 2.60 GHz	Nvidia GeForce GTX 960M 2 GB GDDR5	Samsung 8 GB DDR3L 1600 MHz	17	2056

little power when working and has few effects on the mining process [41]. Thus, the measured power usage mainly comes from CPUs and GPUs.

2.2. Experimental facilities, conditions, and procedures

The team conducted the experiments in an experimental room (4.3 m × 2.7 m × 3.0 m) in April in a laboratory building of Hunan University, Changsha, China. The walls were insulated to reduce the influence of the outdoor environment, mainly heat from outside. Inside the room, there were four regular desks. Partitions (about 1.1 m high) situated in the center of the room. The layout of the experimental room is shown in Fig. 2. The computers were placed in the center of the desk.

The TR-72Ui meter temperature and humidity meter was put on the edge of the partition with no obstacles around the sensor. The air temperature was measured at 1.6 m above the floor at a measuring point. The room temperature was maintained at around 26 °C and a relative humidity of 60%. These setting are eliminating influences of indoor temperature on computers fans and providing a steady environment for the mining process. The devices are functioning normally and only run mining programs during experiments. Consequently, the results are the primary electricity consumption of mining. Computer power usage was measured with a power meter. Other vital parameters were also recorded in the room through the experiments. Table 4 presented the detail information of parameters and instruments.

When making the experimental procedures, this study referred to the study of Matthew [42]. Each test lasted for two hours of two steps. The computers firstly operated for an hour without running any tasks to obtain a baseline. Then, the computer power was measured when mining for another hour. This arrangement makes sure the mining energy is the minus of the two measures. The operating power and hash rate were recorded every minute.

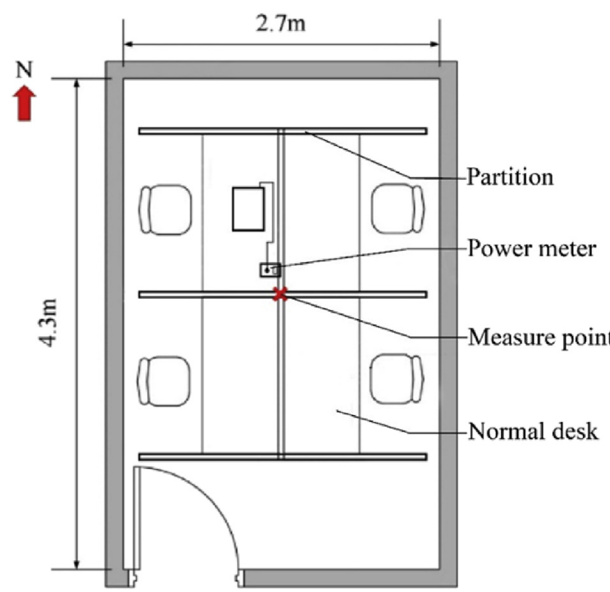

Fig. 2. The layout of the experimental room.

Temperatures of the two steps were measured with a FLIR C2 thermal camera.

2.3. Statistical analysis and comparative analysis

Statistical analysis was carried out to analyze data from the online database. The benchmark has hash rate and Thermal Design Power (TDP) of CPUs and GPUs shared by miners. Before analysis, data from the benchmark conducted a filtration using linear

Table 4
Information about instruments used in this study.

Instruments	Parameters	Measuring range	Accuracy
(UNI-T) UT230A-II	Power usage	Voltage (100.0 V–260.0 V)	±1%
		Voltage display (0.000 A–10.00 A)	±1%
		Wattage display (0.5 W–2200 V)	±1%
		Power (0.010 KWh~9999 KWh)	±1%
TR-72Ui temperature and humidity meter	Air temperature	Temperature (0–50 °C)	±0.3 °C
	Relative humidity	Humidity (10–95%RH)	±5%
FLIR C2	Computer temperature	Temperature (−10 °C–50 °C)	±2 °C

regression to eliminate the abnormal data because of possible incorrect input. The regression analysis brought a linear relationship for power usages of CPUs and GPUs. Since the two have the same mining performance, the two can be analyzed together. Meanwhile, The analysis of experimental results should provide a general relationship between hash rate and power. Another comparative analysis was conducted with shared results from the benchmark as a validation. The comparative experiment used devices in Table 3 under the same condition in Section 2.2. The hashrate and power usages of each device were recorded for two hours.

In this study, the former stage is also considered. A threshold is taken into consideration when measuring. If power is less than rated power, there should be no hash rates. The energy consumption of Monero mining is calculated as

$$H = \begin{cases} 0, & if\ P < P_e \\ k \cdot P + b, & if\ P \geq P_e \end{cases} \tag{1}$$

where H is the mining hash rate of the computer, P is the power usage, P_e is the rated power, k is the mining efficiency, and b is the constant of the formula. This method is proper because data from the two shall have a similar trend line if the relationship is correct. This study used IBM SPSS Statistics software and Python for statistical analysis.

2.4. Carbon emission estimation

The product of network hash rate and mining efficiency can be used to estimate electricity of Monero mining. Although IP addresses of miners are untraceable, the distribution of pools can provide a general geolocation distribution. Therefore, the carbon emission of the mining activity of different regions can be estimated. This study used the carbon intensity factor to calculate the emission amount. The carbon emission of Monero mining in China is calculated as

$$C = C_I \times H \times k^{-1} \tag{2}$$

where C is the estimated carbon emission, C_I is the estimated carbon intensity in China [43], k is the same in Eq. (1).

3. Results and discussions

3.1. Mining efficiency and algorithms

The coins in Table 2 were tested and recorded using computers in Table 3. To illustrate the mining efficiency of different algorithms, the reciprocal of mining efficiency was set as the y-axis and x-axis represented the devices. Fig. 3 shows the results. Based on the measurements, two features are noticed. The first feature is each hashing algorithm has a corresponding efficiency regardless of mining on the same coin or not. For instance, Verge (VXG) has five mining algorithms. Lyra2rev2, myr-groestl, scrypt, x17, and blake2s have different hashing efficiencies even though they were used for mining the same coin. While blake2s for hashing VXG, NEVA, and TAJ and nist5 of BWK and FXC were almost the same. The second feature is when using the same hashing algorithm, mining efficiencies of the five computers showed fluctuations. Most fluctuations of these algorithms are minor, while some of them are fluctuating around a particular value. These two features indicate that the mining efficiency is relative to the algorithm. However, the experimental results of five computers were insufficient for proving the second feature. Further analysis of the big data shared by miners worldwide was conducted.

3.2. Hash rate and power usage

After obtaining the hash rate and thermal design power (TDP) from the benchmark, the team calculated the mining efficiency. This study deleted those with input errors. Thereafter, the regression analysis indicated that power had a significant influence on the hash rate. The absolute fraction of variance (R^2) was given to analyze the model accuracy. For TDP from the benchmark, $R^2 = 0.939$. The results show that the linear model fits the relationship between hash rate and TDP. Fig. 4 showed the linear relationship between hash rate and TDP with a mining efficiency of 7.42 J/H. Data in the benchmark indicated that miners were mainly mining with computers with low configuration. A few miners had a high hash rate with corresponding costs.

This linear relationship was validated by the experiments with a mining efficiency of 4.23 H/J. Fig. 5 shows the fitting line. The absolute fraction of variance (R^2) was given to analyze the model accuracy. For net power usage, $R^2 = 0.967$. The result show validation of the previous liner model. The efficiency of experiments was higher than that from the benchmark. Such results are because the experiment results eliminated the influence of a baseline power usage. Another reason is that data from the benchmark used TDP which is designed for CPUs and GPUs functioning at the maximum load (see Figs. 4 and 5).

3.3. Estimated electricity of Monero mining

With the mining efficiency from Fig. 5, the electricity consumption can be calculated. The team used the current hash rate [44] and Auto-Regressive and Moving Average Model (ARMA) to predict the hash rate in 2018. The calculation was conducted in Python. Fig. 6 shows the mining hash rate after the hard fork. From May to August, the predicted results showed no fluctuations comparing with actual values, and the overall trend is consistent with the actual hash rate. The rapid increase in Fig. 6 was caused by the encouragement of several influential news. After being regarded as the greatest price gainer with Bitcoin [45], Monero is attracting more investors and traders towards it. Due to the rapid increase in a short period of time, it is hard to predict the next trend. The original prediction was used in the following calculations.

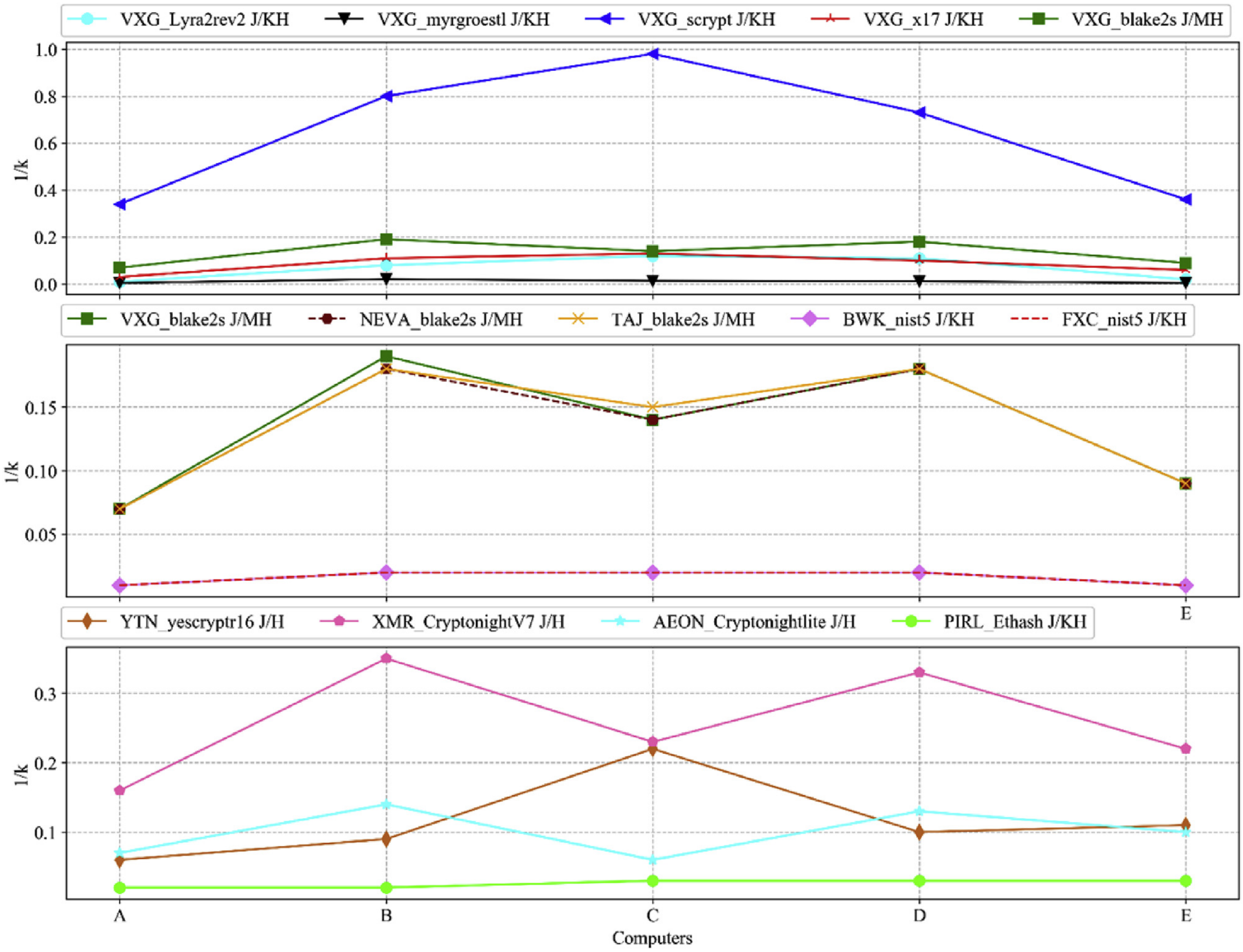

Fig. 3. The relationship between mining efficiency and algorithm.

The hash rate mainly comes from mining pools in the United States, Europe, and Asia [46]. Thus, Monero mining might use 645.62 GWh of electricity of the three regions in 2018 after April's hard fork. Among them, the fifth largest pool, F2Pool [47] is a Chinese mining pool with servers located in China and the U.S. As the earliest pool in China, many miners choose to connect F2Pool because of the network. Assuming all Monero miners in F2Pool are in China and considering a carbon intensity of 0.63–0.64 kg CO_2/KWh in China from Wu and Peng [43]. Monero mining may result in at least 19.12–19.42 thousand tons of carbon dioxide after April's hard fork in 2018.

4. Discussions

The experimental results and estimations are presented as above. The PoW mining of many digital coins other than Bitcoin continues electricity consumption. Monero mining activity was presented as an example.

4.1. Energy consumption of digital coins mining

Blockchain has been regarded as a potential method to reshape the renewable energy market [29]. Although there have been schemes that do not rely on mining as mentioned in Section 1.1, the PoW mining remains the major scheme and it consumes a large amount of energy. The experimental results indicated that the

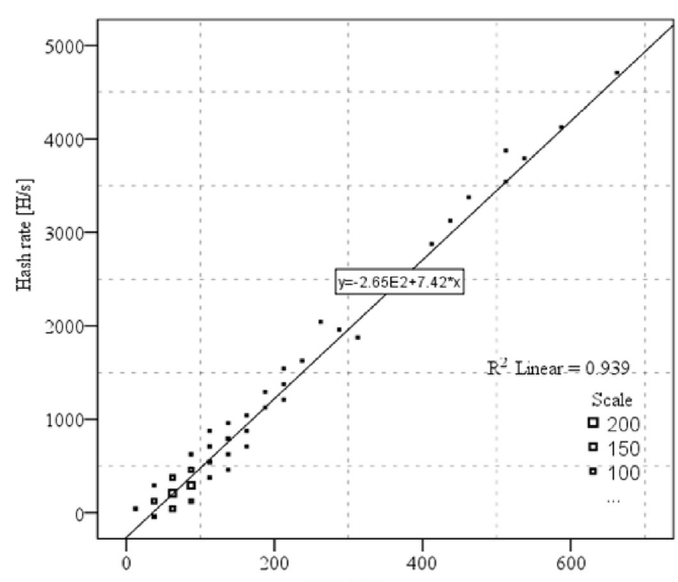

Fig. 4. The relationship between hash rate and TDP from the benchmark.

hashing algorithm mainly determined the mining efficiency. The

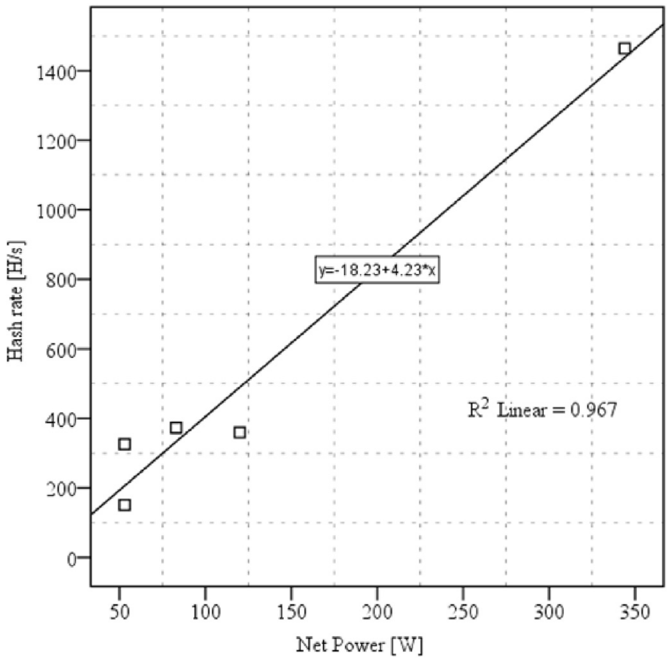

Fig. 5. The relationship between hash rate and net power usage.

differences in computer configurations may affect mining efficiency. The experiments and data analysis showed a significant relationship between the hash rate and power. The tested subjects are consistent with data distribution from the benchmark, where low configuration machines are in the lower-left corner, and high-performance computers are on the upper-right side.

Comparing with the works of Alex and Bevand [24,48], this study neglected equipment depreciation and profitability during mining because the mining activity does not necessarily need to consider equipment depreciation and profitability. The mining program can be implanted into websites and propagate over the internet. Any device can become miners when browsing web pages or being infected [49]. Thus, this study used an average mining efficiency for all devices to estimate energy consumption.

Furthermore, the estimation of energy consumption and carbon emission in China are minimum values. The Monero Coin in this study is Monero 7 after the hard fork. The actual mining activity is even higher than the estimation in this study. For instance, ASIC miners continued their mining on Monero Classic which is the version before the hard fork. The cryptocurrency Bitcoin Cash shares a similar fact. In this tendency, energy consumption will keep increasing. More energy efficient and environmentally friendly algorithms are needed in developing cryptocurrencies.

Moreover, the secondary energy consumption should be further studied. Energy consumed when mining is exhausted as heat into the indoor environment, which increases the cooling load of cooling systems. The next step of this research will continue experiments with more test subjects on more cryptocurrencies to improve the reliability. Meanwhile, research should move on to quantify the influence of cryptocurrency mining on cooling systems.

4.2. Limitations

Although this study quantitative estimated energy consumption and environmental effects, there are several limitations. First, due to the encryption of the currency, the real number of miners and the geolocations are anonymous. To have a general estimation, this study only assumed the miners only connect pools in their region and pools only have servers in their birthplaces. However, the mining activity does not have to be in the local pools. Miners in China may connect pools in America and Europe. American and European miners may do the same. Besides, pools may have servers in different countries and miners might connect oversea pools if available. Because of the above facts, the actual amount is hard to trace. In the future, works will be done on the improvements of accuracy. Second, the number of tested subjects is relatively small. Also, the time series prediction of network hash rate of the following eight months was lack of enough source data. A more accurate estimation will be carried out when more subjects become available. The team will attempt to improve the accuracy with adequate statics. Third, extra heat from the mining process is not monitored. A thermal camera is not accurate. Electricity Usage

Fig. 6. Monero network hash rate and time series prediction.

Monitors should be used in measuring extra cooling load caused by the mining process. Also, the influence over the network servers was not considered. Further studies are needed into the status of cooling loads and servers.

5. Conclusions

This study discussed the issue of energy consumption from cryptocurrency mining. This study has the following contributions:

1. This paper presented several previous works about the costs of electricity and benefits for the energy market. Many projects have started using blockchain for trading and managing renewable energy. Although the future of blockchain applications in energy market seems promising, the energy usage of this technology remains unknown.
2. The energy consumption of Bitcoin and Ether has been noticed by scholars around the world. There are a few studies focusing on energy consumption using PoW or PoW/PoS other than the above two kinds of coins. This study conducted experiments on mining efficiency of different encrypted digital coins. The hashing algorithm mainly determines the mining efficiency.
3. With data analysis and experiments, this study estimated electricity for Monero mining as a case study. Monero mining may consume 645.62 GWh of electricity in the world in 2018 after the hard fork. If there is 4.7% mining activity happening in China, the consumption is at least 30.34 GWh, contributing a carbon emission of 19.12–19.42 thousand tons this year.
4. The findings in this study will be useful for cryptocurrency management and blockchain development, especially for the energy policies concerning encrypted currencies. The results could be used for better quantifying the effects of blockchain applications.

Nonetheless, since there is no similar previous research, the uncertainties in Section 1.2 and limitations in Section 4.2 remain unclear. Therefore, it is suggested that more studies should be carried out on energy consumption from cryptocurrency mining and secondary loads on the cooling system.

Acknowledgments

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