Energy Consumption of Bitcoin Mining

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After its introduction in 2008, increasing Bitcoin prices and a booming number of other cryptocurrencies lead to a growing discussion of how much energy is consumed during the production of these currencies. Being the most expensive and the most popular cryptocurrency, both the business world and the research community have started to question the energy intensity of bitcoin mining. This paper only focuses on computational power demand during the proof-of-work process rather than estimating the whole energy intensity of mining. We make use of 160 GB of bitcoin blockchain data to estimate the energy consumption and power demand of bitcoin mining. We considered the performance of 269 different hardware models (CPU, GPU, FPGA, and ASIC). For estimations, we defined two metrics, namely; minimum consumption and maximum consumption. The targeted time span for the analysis was from 3 January 2009 to 5 June 2018. We show that the historical peak of power consumption of bitcoin mining took place during the bi-weekly period commencing on 18 December 2017 with a demand of between 1.3 and 14.8 GW. This maximum demand figure was between the installed capacities of Finland (~16 GW) and Denmark (~14 GW). We also show that, during June 2018, energy consumption of bitcoin mining from difficulty recalculation was between 15.47 and 50.24 TWh per year.

Energy Consumption of Bitcoin Mining

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ABSTRACT

After its introduction in 2008, increasing Bitcoin prices and a booming number of other cryptocurrencies lead to a growing discussion of how much energy is consumed during the production of these currencies. Being the most expensive and the most popular cryptocurrency, both the business world and the research community have started to question the energy intensity of bitcoin mining. This paper only focuses on computational power demand during the proof-of-work process rather than estimating the whole energy intensity of mining. We make use of 160 GB of bitcoin blockchain data to estimate the energy consumption and power demand of bitcoin mining. We considered the performance of 269 different hardware models (CPU, GPU, FPGA, and ASIC). For estimations, we defined two metrics, namely; minimum consumption and maximum consumption. The targeted time span for the analysis was from 3 January 2009 to 5 June 2018. We show that the historical peak of power consumption of bitcoin mining took place during the bi-weekly period commencing on 18 December 2017 with a demand of between 1.3 and 14.8 GW. This maximum demand figure was between the installed capacities of Finland (~16 GW) and Denmark (~14 GW). We also show that, during June 2018, energy consumption of bitcoin mining from difficulty recalculation was between 15.47 and 50.24 TWh per year.

Keywords: bitcoin; mining; blockchain; energy; consumption

JEL Classification: P18; Q47

1. Introduction

Cryptocurrencies and their energy consumption have become a popular subject of discussion over the last couple of years. Bitcoin, the most well-known and most expensive cryptocurrency, was first introduced by Satoshi Nakamoto, a pseudonym of an author or group of authors, in 2008. There are significant differences in bitcoin's energy consumption estimations since there are too many unknowns in the process, such as which type of hardware is used in the mining and for how long. This ambiguity necessitates an extensive analysis that will cover all bitcoin transactions from 2009 until today.

Bitcoin mining is a decentralized computational process, where transactions are verified and added to the public ledger, known as the blockchain. Nakamoto explains the working principles of bitcoin mining in detail in his paper [1]. Bitcoin networking started in 2009 with its unique currency bitcoin or BTC. The bitcoin network is a peer-to-peer, distributed network. In this network, all nodes are treated as equal peers. The process of making bitcoins is called mining, and the participants are called miners. All transactions are carried out and stored in a distributed ledger: the blockchain. The historic transaction data are contained in the blockchain. A signature between the new block and the previous block is needed for adding a new block to the blockchain. This is done via finding a nonce value that will satisfy the cryptographic hash function, Secure Hash Algorithm 256-bit (SHA-256). The nonce starts with 0 and is incremented by 1 by the miner until the hash of the block is less than or equal to the target value. Once a node finds a hash that satisfies the required number of zero bits, it transmits the block it was working on to the rest of the network. The other nodes in the network then express their acceptance by starting to create the next block for the blockchain using the hash of the accepted block. The finder of the block is rewarded for their efforts with a special transaction. Creators of a block are currently allowed to send 12.5 newly created coins to an address of their choosing. This is a fixed reward that halves every four years (210,000 blocks). On top of the fixed reward, a variable amount of transaction fees is received as well. The reward provides an incentive to participate in this type of network. To keep the flow of rewards stable, the network self-adjusts the difficulty of hash calculations, so new blocks are only created once every 10 min on average. Cryptography takes an important place in Bitcoin transactions with private and public keys. Private keys in the Bitcoin network are 256-bit long numbers that are created randomly in wallet creation. These randomly generated numbers provide security for Bitcoin transactions as they are infeasible to crack. Private keys are used to sign transaction messages and provide authenticity for the messages as only the owner of the bitcoin address knows the private key. Public keys are complementary to Private keys and allow checking of the authenticity of messages. Public keys are 512-bit long numbers that are derived from Private keys. Unlike Private keys, Public keys are shared in the Bitcoin network and are available to every node. Figure 1 shows a simple diagram how bitcoin mining is completed.

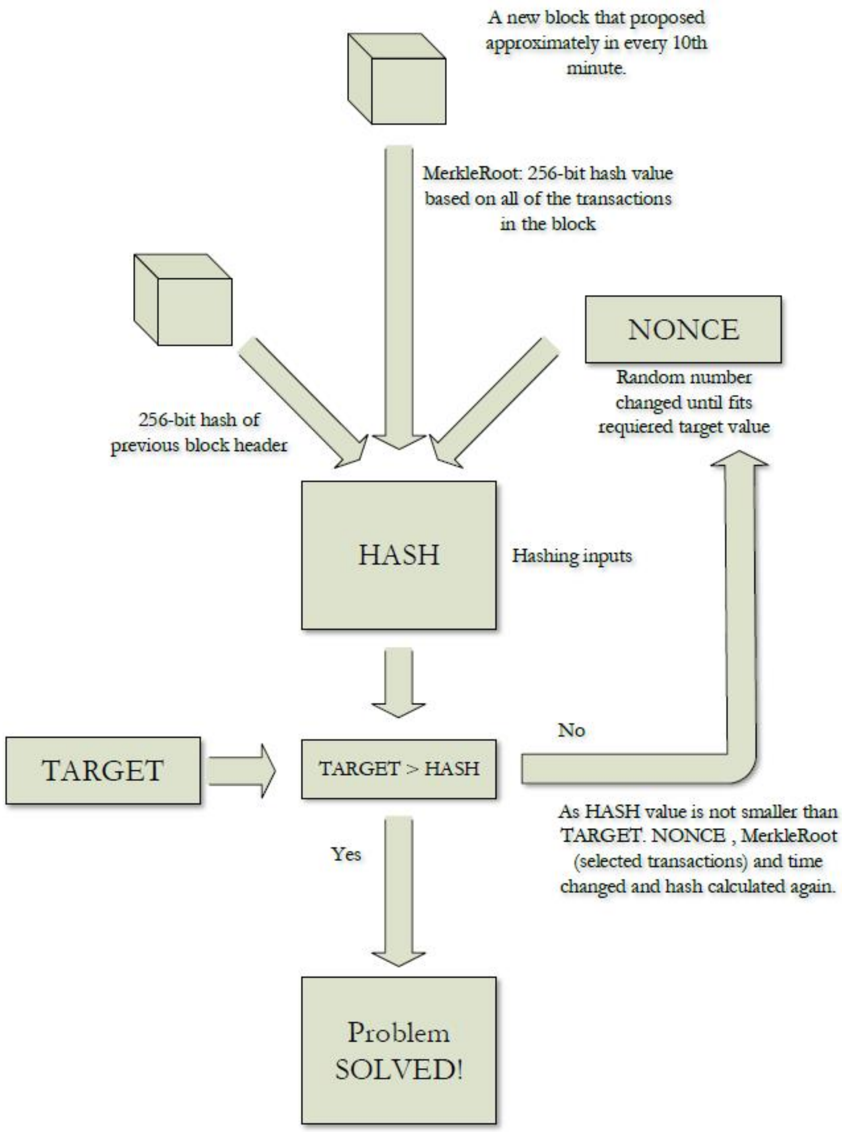

Figure 1. Bitcoin mining process.

During the mining process, the miner computes the hash of a block of transactions and the summary information of the previous block. The block has a 'nonce' value and the miner randomly chooses a nonce value so that the hash of the block is smaller than a target, which is periodically recalculated by the network. Random attempts for nonce values to find a valid hash is called as proof-of-work. This process needs computational effort, which is measured in Gigahashes per second. The more computational power a miner has, the bigger the share of all distributed rewards that go to that miner. This is the part where the energy consumption of bitcoin mining takes place. This paper aims to present a detailed analysis and estimation of the energy consumption of bitcoin mining by focusing on the use of computational power during the proof-of-work process, and hence the mining process only. In our study, we analyzed 160 GB of blockchain bitcoin data. We deliberately excluded the estimation for energy intensity of bitcoin mining more generally since it will include all processes including the use of external cooling systems and their energy consumption.

2. Studies Covering Energy Consumption of Bitcoin Mining

O'Dwyer and Malone used two hardware efficiencies; an efficient commodity hardware and a high efficiency ASIC machine [2]. Then they calculated the total power demand to be between 0.1 and 10 GW depending on what hardware was used in the mining. McCook calculated the energy consumption with a scenario where all mining was done with ASIC machines with the following models and ratios of the mining models: Bitfury BF3500, 35%, KnC Neptune, 25%, Cointerra TerraMiner IV, 20%, Antminer S2, 15%, Antminer S3, 5% of all hardware [3]. He calculated the yearly energy consumption as 3.64 GJ (around 1 MWh) for the year 2014. With minimum and maximum energy efficiencies of 0.8 J/GH and 1.5 J/GH, respectively, he calculated the power demand to be between 3.28 and 6.15 GW. Hayes assumed that if the marginal cost of bitcoin mining exceeded the bitcoin price, then the bitcoin mining would stop [4]. He calculated hypothetical upper boundaries for mining by taking the energy price as 13.952 c/kWh and the hardware efficiency as 1.15 J/GH. The Economist reported about a modern bitcoin mining facility of KnCMiner in Boden, Sweden, which uses high efficiency ASIC hardware, and it claims that if all miners in the world used the same hardware as in Boden, then the yearly energy consumption for the world would be 1.46 TWh [5]. Vranken calculated the power demand for mining to be between 400 MW (electricity price of 2 c/kWh) and 2.3 GW (electricity price of 3.5 c/kWh) [6]. He suggests that power demand for mining would be most likely in the range of 100–500 MW (which corresponds to 3–16 PJ per year). Gauer assumed an electricity price of 5 c/kWh, an average BTC price of $3524, and a reward for block of 12.5 BTC, and then calculated the total energy consumption to be 3.56 TWh and the power demand to be 3831 MW in 2017 [7]. Similarly, de Vries estimated the minimum power demand to be 2.55 GW and, in the future, the maximum consumption would be 7.67 GW [8]. Digiconomist estimated an energy use of 73.12 TWh/year with a minimum estimation of 59.55 TWh/year [9]. To calculate the minimum energy consumption, Digiconomist assumed only the hardware Bitmain’s Antminer S9 was used. Bevand estimated the minimum 1620 MW (14.19 TWh/year) and maximum 3136 MW (27.47 TWh/year) with a best guess of 2100 MW (18.40 TWh/year) [10]. Krause and Tolaymat reported estimations of 283 MW, 948 MW, and 3441 MW for the years 2016, 2017, and 2018, respectively [11]. The estimations vary considerably mainly due to the hardware efficiencies and the electricity prices used in the analysis process. It is quite hard to know exactly which models of hardware are used in the mining process during a given time span. Therefore, to be as precise as possible, in this paper we identified the hardware available in the market that could be used in bitcoin mining. Table 1 summarizes the power demand estimations of bitcoin mining.

Table 1. Power demand estimations of Bitcoin mining.

Source	min. (GW)	max. (GW)
O’Dwyer and Malone (2014) [2]	0.1	10
McCook (2014) [3]	3.28	6.15
Vranken (2017) [6]	0.4	2.3
Gauer (2017) [1] [7]	3.83	-
de Vries (2018) [8]	2.55	7.67
Bevand (2018) [10}	1.62	3.14
Krause and Tolaymat (2018) [1] [11]	3.44	-

[1] Average estimation.

3. Materials and Methods

This research was based on four different sources of data: Bitcoin’s Blockchain, the performance data of the devices that solves hash problems, historical Bitcoin prices, and power cost data. Bitcoin data are publicly available via the Bitcoin history stored on the blockchain. Most of the data used in this research were extracted from this publicly available blockchain data created by transactions. The size of the Bitcoin Blockchain at the time this research was conducted was around 160 GB [12]. Among this vast amount of data, we retrieved all blockchain data from the number 0 genesis block with the time stamp of 3 January 2009 18:15:05 to the number 52,6176 block with the time stamp of 5 June 2018 18:18:06. Then, we prepared a data series table containing the block number, difficulty, and time stamp of each block. Difficulty recalculation was done once every 2016th block and the reward for each block was halved for every 210,000th block. Since the difficulty changes at every 2016th block, we calculated the energy consumption and profitability of each hardware every 14 days (2016 block).

The second step was to compile the performance data of the hardware used in bitcoin mining. In this study, we used data from 43 ASIC, 4 FPGA, 111 CPU (32 AMD and 79 Intel), and 111 GPU (54 ATI and 57 Nvidia) processors. The list of all devices and their release dates are given in the Appendix (Tables A1–A4). The necessary data were collected from two sources. The first source was the data provided by the manufacturers that can be collected from data sheets and white papers of these manufacturers. As a second data source, we used websites such as "userbenchmark" and "passmark" to further collect necessary data and test the reliability of the manufacturers' data [13,14].

The third step was to review the price of Bitcoin. We used three data sources to find the daily value of the Bitcoin price. It was hard to estimate the price of Bitcoin before the Bitcoin exchange markets were founded. Therefore, we used the famous "Bitcoin pizza day" as our starting point. On 22 May 2010 Laszlo Hanyecz bought two pizzas by paying 10,000 Bitcoins. Each pizza was $25, and hence we assume the price of one Bitcoin to be $0.005 on that date [15]. Mt. Gox was active from 18 July 2010 to 25 February 2014 [16]. We used price data from Mt. Gox for that period. For the data from 25 February onwards, we used Bitstamp [17].

The last step of the data accumulation was the electricity price. To calculate an average electricity price in a given time span, we needed to know the mining locations. According to the estimated Hashrate by Pools (A pool is a place where miners share their sources (computational power) to solve the blocks and then share the reward in proportion to their hashing power) between 1 June and 4 June 2018, 70% of bitcoin mining was done in China. After China, Europe (10%), United States (10%), and rest of the world (10%) follow [18]. We calculated an aggregated Bitcoin electricity price in accordance with the mining locations and the prices in these places [19,20].

The main purpose of the methodology was to make two energy consumption estimations. The first estimation was the Minimum Energy Consumption. The minimum consumption was calculated by assuming that at each difficulty recalculation, the most efficient hardware on the market was used. We know that this is a theoretical minimum since miners will not always buy better performing machines whenever they are available, and they will not simply get rid of their existing hardware. To calculate the upper boundary of the energy consumption, we defined the term Maximum Energy Consumption. Estimation of the maximum consumption did not mean the use of the least efficient devices available in the market. It meant that the miners used the worst performing hardware, but mining was still profitable in terms of electricity prices. In other words, the operational costs due to electricity bills should not exceed the value of the bitcoin. Here, we neglected the capital expenditure and only took energy costs of the miners into account. The challenge was using daily electricity prices in mining locations. Instead, we picked up the mining locations during 1 June and 4 June 2018. After this we calculated an average electricity price for bitcoin mining by taking weighted averages of the mining locations. Table 2 shows the location of bitcoin mining by pools during this time.

Table 2. Bitcoin pools and locations.

Pool	Blocks	Percentage (%)	Country
BTC.com	179	26.76	China [1]
AntPool	98	14.65	China
SlushPool	79	11.81	USA [2]
BTC.TOP	65	9.72	China
ViaBTC	62	9.27	China
F2Pool	59	8.82	China
Unknown	32	4.78	NA
BitFury	16	2.39	Georgia
DPOOL	16	2.39	China
BTCC Pool	15	2.24	China
BW.COM	15	2.24	China
Bixin	10	1.49	China
BitClub Network	8	1.2	Iceland
58COIN	6	0.9	China

Bitcoin.com	4	0.6	USA
KanoPool	3	0.45	Iceland
Haominer	2	0.3	China

[1] 23% China, 2% North America, and 1% EU. [2] 6% North America, 5% EU.

To calculate the energy consumption of the process, we will proceed step-by-step. The power demand of the bitcoin mining is calculated as:

$$P = \frac{NH * EoH}{10^{12}} \tag{1}$$

with:

- Power (P) (MW)
- Network Hashrate (NH) (MH/s) (Total hash problems solved per second in Bitcoin network)
- Efficiency of Hardware (EoH) (J/TH) (Energy consumed by hardware per Tera hash problems solved)

The Network Hashrate is calculated as follows:

$$NH = D * \frac{2^{32}}{ASBB} \tag{2}$$

with:

- Difficulty (D)
- Network Hashrate (NH) (hash/s)
- Average Seconds Between Blocks ($ASBB$) (s) = 600

The Efficiency of Hardware (EoH) is defined as:

$$EoH = \frac{J}{TH} \tag{3}$$

with:

- Efficiency of Hardware (EoH) (J/TH) (Joules per Tera Hash Calculations)
- Energy (E) (J)

Hash Operations (H) and Tera Hash Operation (TH) where

$$TH = H * 10^{12} \tag{4}$$

Now, we should calculate the average time between two blocks:

$$AHBB = \frac{ASBB}{3600} = \frac{1}{6} \tag{5}$$

with:

- Average Hours Between Blocks ($AHBB$) (h)
- $ASBB$ is 600 s
- Block Count Between Difficulty Recalculation ($BCBDR$) = 2016

Then, we calculate the average time between difficulty recalculation. Let us define the Average Time Between Difficulty Recalculation (ATBDR) (h)(days), then,

$$\text{ATBDR} = BCBDR * AHBB = 2016 * \frac{1}{6} = 336 \text{ h} = 14 \text{ days} \tag{6}$$

This means that we need to update the Difficulty data every 14 days. We calculate the minimum and maximum power demand and energy consumption of mining. Minimum energy consumption means that the mining is done via the most efficient hardware available in the market for the given time span (14 days in this case). Since hardware efficiencies are publicly available, it is straightforward to acquire this data. It is given in detail in the Appendix. Minimum power demand is calculated as follows:

$$Pmin = \frac{NH * Min(EoH)}{10^{12}} \quad (7)$$

Calculating the Maximum is the challenging step. Let us first define the Electricity Cost per Bitcoin (*ECPB*):

$$ECPB = \frac{TECPB * ABEP}{RPB} \quad (8)$$

with:

- *TECPB* is Total Energy Consumption Per Block (TWh)
- *ABEP* is Average Bitcoin Electricity Price ($/kWh)
- *RPB* is Reward Per Block (in bitcoin (BTC))

There are 2016 blocks in a difficulty recalculation period. Therefore,

$$TECPB = \frac{\text{Tot. En. Con. Betw. Dif. Recal.}}{2016}\ (\text{TWh}) \quad (9)$$

Total Energy Consumption Between Difficulty Recalculation (*TECBDR*) is calculated as

$$TECBDR = \frac{P * HBDR}{10^6} = \frac{NH * EoH * HBDR}{10^{18}} \quad (10)$$

where *HBDR* is Hours Between Difficulty Recalculation (h).

Let us define the Difficulty Recalculation Block (DRB_x) and Next Difficulty Recalculation Block (DRB_{x+2016}), Timestamp of Difficulty Recalculation Block ($TDRB_x$), and Timestamp of Next Difficulty Recalculation Block ($TDRB_{x+2016}$), then,

$$HBDR\ (h) = TDRB_{x+2016} - TDRB_x \quad (11)$$

Now we can calculate Yearly Energy Consumption Between Difficulty Recalculation (*YECBDR*) in TWh/year,

$$YECBDR\ (\text{TWh/year}) = TECBDR * \frac{365 * 24}{HBDR} \quad (12)$$

Now, an Average Bitcoin Electricity Price (*ABEP*) in $/kWh for the whole world is needed. Since it is rather difficult and tedious to find the mining locations every 14 days since 2009, at this step, we made use of the bitcoin mining pool data between 1 June and 4 June 2018, which is shown in Table 1. Firstly, we define Average Bitcoin Production Percent *ABPP* per locations as follows:

Average Bitcoin Production Percent China ($ABPP_{China}$) = 0.7
Average Bitcoin Production Percent Europe ($ABPP_{Europe}$) = 0.1
Average Bitcoin Production Percent America ($ABPP_{America}$) = 0.1
Average Bitcoin Production Percent Rest of the World ($ABPP_{Rest}$) = 0.1

Now, let us define the Average Bitcoin Electricity Price (*ABEP*). To do this, we need to use average electricity prices in China, Europe, US, and an average figure for the rest of the world [20]:

Average Electricity Price China ($/kWh) ($AEP_{China}$) = 0.08
Average Electricity Price Europe ($/kWh) ($AEP_{Europe}$) = 0.15
Average Electricity Price America ($/kWh) ($AEP_{America}$) = 0.1
Average Electricity Price Rest of the World ($/kWh) ($AEP_{World}$) = 0.1

Hence, ABEP will be:

$$\begin{aligned} ABEP\ (\$/\text{kWh}) = {} & (AEP_{China} * ABPP_{China}) + (AEP_{America} * ABPP_{America}) \\ & + (AEP_{Europe} * ABPP_{Europe}) + (AEP_{World} * ABPP_{World}) \end{aligned} \quad (13)$$

The final step to calculate Electricity Cost per Bitcoin (*ECPB*) is to calculate Reward Per Block (*RPB*). The reward is given in bitcoin (BTC). It starts with 50 BTC and halves every 210,000 blocks. It follows as in;

Between blocks of 0–209,999 = 50 BTC
Between blocks of 210,000–419,999 = 25 BTC
Between blocks of 420,000–629,999 = 12.5 BTC and so on.

After we calculate the Electricity Cost per Bitcoin (*ECPB*) and we get the Bitcoin Price (*BP*), we can define the boundaries of profitability for the miners. At this stage, we neglected capital investment and only focused on operational costs for mining itself and hence electricity prices. Therefore, we conclude that

$$\text{Profitability of A Mining Device } = \begin{cases} Profitable\ when\ ECPB < BP \\ Nonprofitable\ when\ ECPB \geq BP \end{cases} \quad (14)$$

Now, we can define the efficiency of the least efficient hardware that is still profitable. During each difficulty recalculation, we picked up the least efficient device under the condition *ECPB* < *BP*. We called the maximum power consumption Maximum (*PM*) meaning that the mining is burning its maximum energy while it is still profitable in terms of electricity process. Therefore, $P_M(TW)$ is given in (15) as:

$$P_M(TW) = \frac{NH * Efficiency\ of\ least\ efficient\ hardware\ still\ profitable\ while\ mining\ bitco}{10^{18}} \quad (15)$$

Table 3 shows the timeline and information of Bitcoin mining.

Table 3. Timeline of Bitcoin (BTC) mining.

Starting Block	Phase	Reward Per Block	BTC from Previous Round	Mined BTC	Cumulative BTC	Increase in Total	Percentage of Total	Estimated Time of Last Block
0	1	50.00	0.00	10,500,000.00	10,500,000.00	-	50.00%	3 January 2009
210,000	2	25.00	10,500,000.00	5,250,000.00	15,750,000.00	50.00%	75.00%	28 November 2012
420,000	3	12.50	15,750,000.00	2,625,000.00	18,375,000.00	16.67%	87.50%	9 July 2016
630,000	4	6.25	18,375,000.00	1,312,500.00	19,687,500.00	7.14%	93.75%	2020
840,000	5	3.13	19,687,500.00	656,250.00	20,343,750.00	3.33%	96.88%	2024
1,050,000	6	1.56	20,343,750.00	328,125.00	20,671,875.00	1.61%	98.44%	2028
1,260,000	7	0.78	20,671,875.00	164,062.50	20,835,937.50	0.79%	99.22%	2032
1,470,000	8	0.39	20,835,937.50	82,031.25	20,917,968.75	0.39%	99.61%	2036
1,680,000	9	0.20	20,917,968.75	41,015.63	20,958,984.38	0.20%	99.80%	2040
1,890,000	10	0.10	20,958,984.38	20,507.81	20,979,492.19	0.10%	99.90%	2044
2,100,000	11	0.05	20,979,492.19	10,253.91	20,989,746.09	0.05%	99.95%	2048
2,310,000	12	0.02	20,989,746.09	5126.95	20,994,873.05	0.02%	99.98%	2052
2,520,000	13	0.01	20,994,873.05	2563.48	20,997,436.52	0.01%	99.99%	2056
2,730,000	14	0.01	20,997,436.52	1281.74	20,998,718.26	0.01%	99.99%	2060
2,940,000	15	0.00	20,998,718.26	640.87	20,999,359.13	0.00%	100.00%	2064
3,150,000	16	0.00	20,999,359.13	320.43	20,999,679.56	0.00%	100.00%	2068
3,360,000	17	0.00	20,999,679.56	160.22	20,999,839.77	0.00%	100.00%	2072
3,570,000	18	0.00	20,999,839.77	80.11	20,999,919.88	0.00%	100.00%	2076
3,780,000	19	0.00	20,999,919.88	40.05	20,999,959.93	0.00%	100.00%	2080
3,990,000	20	0.00	20,999,959.93	20.03	20,999,979.96	0.00%	100.00%	2084
4,200,000	21	0.00	20,999,979.96	10.01	20,999,989.97	0.00%	100.00%	2088
4,410,000	22	0.00	20,999,989.97	5.01	20,999,994.98	0.00%	100.00%	2092
4,620,000	23	0.00	20,999,994.98	2.50	20,999,997.48	0.00%	100.00%	2096
4,830,000	24	0.00	20,999,997.48	1.25	20,999,998.73	0.00%	100.00%	2100
5,040,000	25	0.00	20,999,998.73	0.63	20,999,999.36	0.00%	100.00%	2104
5,250,000	26	0.00	20,999,999.36	0.31	20,999,999.67	0.00%	100.00%	2108
5,460,000	27	0.00	20,999,999.67	0.16	20,999,999.83	0.00%	100.00%	2112
5,670,000	28	0.00	20,999,999.83	0.08	20,999,999.91	0.00%	100.00%	2116
5,880,000	29	0.00	20,999,999.91	0.04	20,999,999.94	0.00%	100.00%	2120
6,090,000	30	0.00	20,999,999.94	0.02	20,999,999.96	0.00%	100.00%	2124
6,300,000	31	0.00	20,999,999.96	0.01	20,999,999.97	0.00%	100.00%	2128
6,510,000	32	0.00	20,999,999.97	0.00	20,999,999.97	0.00%	100.00%	2132
6,720,000	33	0.00	20,999,999.97	0.00	20,999,999.98	0.00%	100.00%	2136
6,930,000	34	0.00	20,999,999.98	0.00	20,999,999.98	0.00%	100.00%	2140

4. Results

There are questions about for how long BTC will be profitable for the miners. When we calculated the term Maximum, we stressed that the cost of BTC should not be higher than the price of BTC. Nonetheless, due to the complexity of the analysis, we limited ourselves with the BTC mining locations from 1 June to 4 June 2018. To see if this sample was representative of the whole historical data, we plotted Figure 2 to see the comparison between Maximum Cost of BTC (the cost of bitcoin mining under maximum power demand) and the price of BTC.

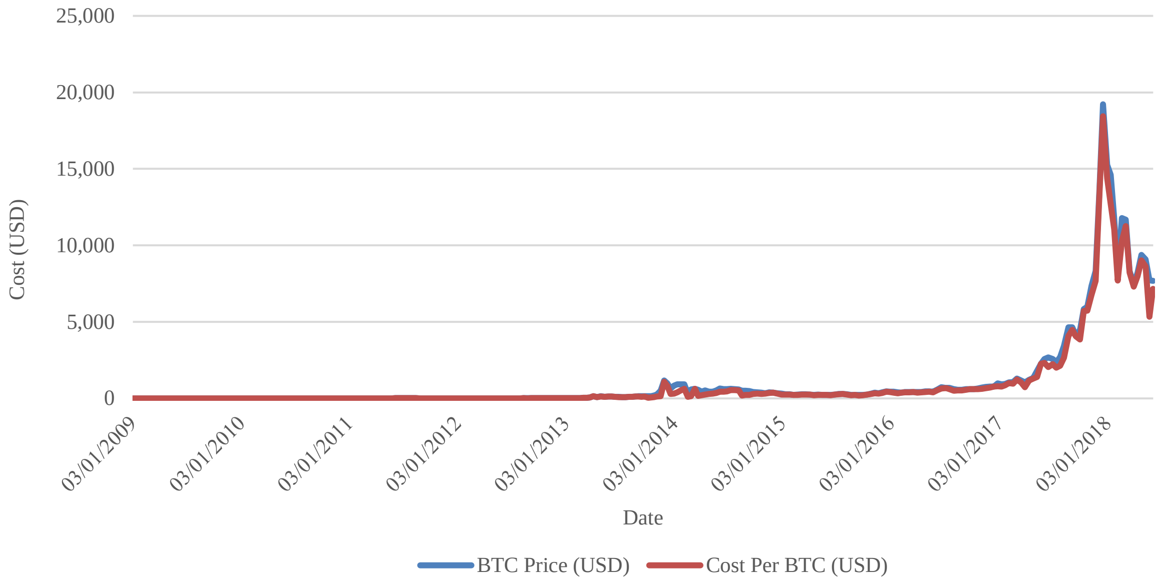

Figure 2. Maximum BTC cost vs. BTC price.

From Figure 2, we see that the cost per BTC is under the BTC price at all times. Therefore, we can claim that the Maximum should be the theoretical upper boundary of BTC mining.

After verifying our Maximum term, we calculated the yearly minimum and maximum energy consumption between difficulty recalculations of all devices available on the market. Figure 3 summarizes the energy consumption estimations from 2009 onwards.

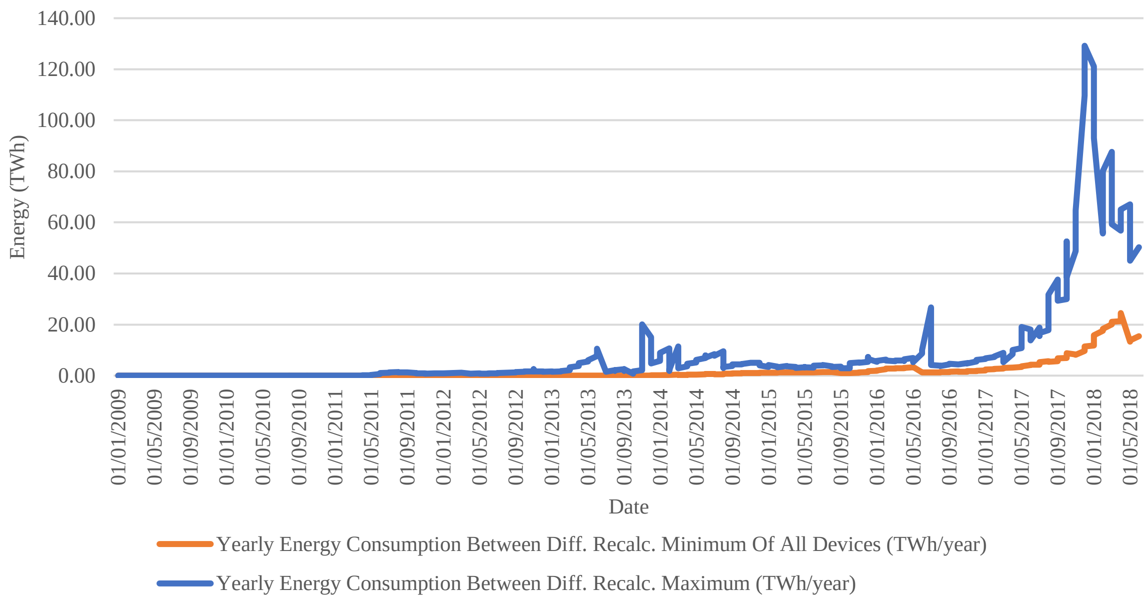

Figure 3. Minimum and profitable maximum energy consumption of bitcoin mining.

For example, between 18 December 2017 and 22 December 2017, mining with Antminer R4 (97 J/TH) yields the minimum energy consumption whilst, during the same period, use of ASIC Antminer S2 (1100 J/TH) corresponds to the maximum energy consumption. Power demand is another matter of concern and a debatable topic. Figure 4 shows the power demand change of minimum and maximum scenarios.

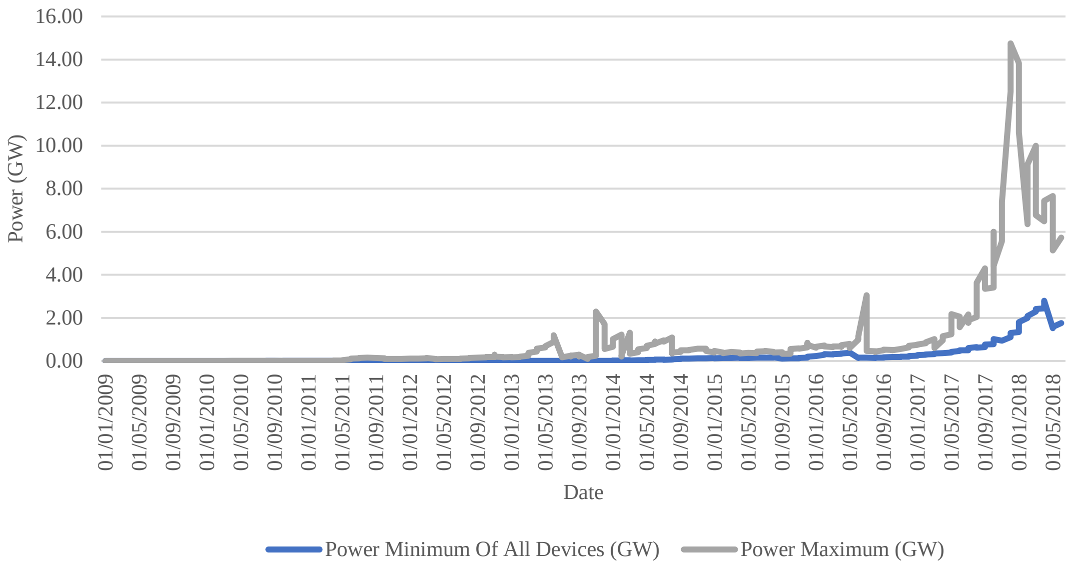

Figure 4. Minimum and maximum power demand of bitcoin mining.

To illustrate how hardware choice and hence the efficiency of the hardware is important, we plotted the minimum energy consumption of bitcoin mining per each manufacturer. Figure 5 shows the minimum energy consumption of bitcoin mining per CPU, GPU, FPGA, and ASIC.

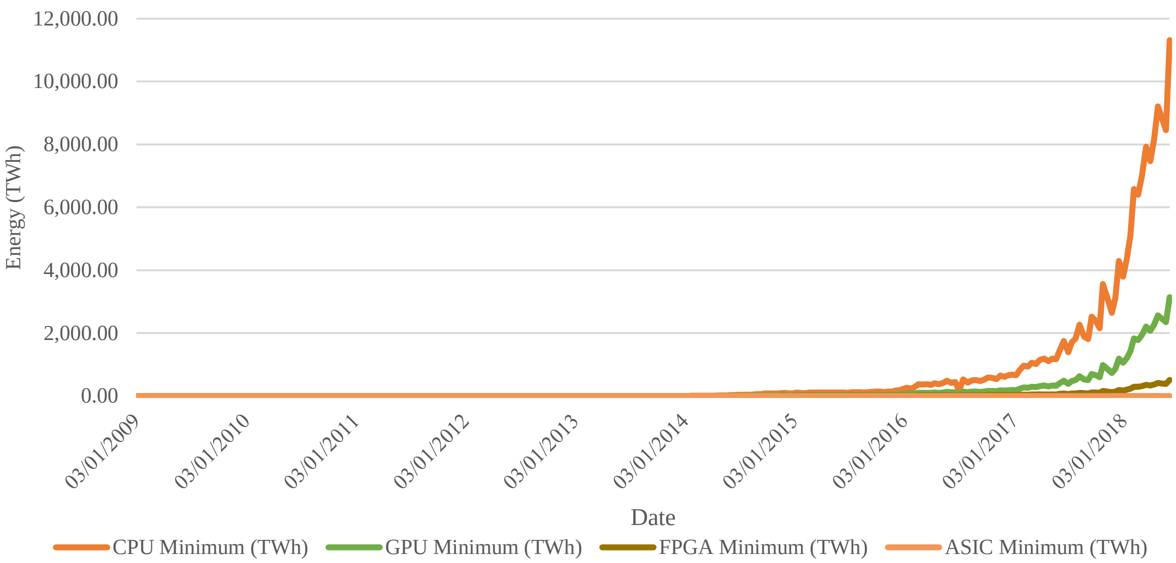

Figure 5. CPU, GPU, FPGA, and ASIC minimum energy consumption between difficulty recalculation.

The world's global electricity demand is around 23,000 TWh per year [21]. If all miners kept using CPU hardware, bitcoin mining would consume energy at around 11,000 TWh per year. As more efficient devices come to market, the mining process will become less energy consuming.

5. Discussion and Conclusions

Energy consumption of bitcoin mining is a very controversial topic. There are various estimations. However, these estimations vary considerably from study to study. This paper makes use of 160 GB of blockchain data and data from 269 different hardware models (CPU, GPU, FPGA, and ASIC) that are used for the mining process. We defined two metrics to measure the energy consumption. First is the minimum energy consumption. This metric simply picks the most efficient hardware in use during the recalculation process. However, as we pointed out earlier, this is the theoretical minimum boundary of the consumption. It is unlikely that the all miners will get rid of their existing hardware and buy and start using more efficient hardware the moment it is introduced in the market. The second metric is the profitable maximum. The idea is to measure the cost of electricity and then pick up the worst performing hardware in the market. However, the total cost should be under the price of bitcoin so that the miners will still be able to make a profit. This level will be the theoretical higher consumption boundary since it is not sustainable to continue mining if the operational costs of mining is higher than the price of the bitcoin.

The choice of hardware is crucial in the energy consumption. Figure 5 clearly shows that if miners kept using CPU only, by the year 2018 the minimum energy consumption would be higher than the total energy consumption of the United States and China combined [21]. One of the key findings of this paper is that the historical peak of power consumption of bitcoin mining took place during the bi-weekly period commencing on 18 December 2017 with a demand between 1.3 and 14.8 GW. This maximum demand estimation is between the installed capacities of Finland (~16 GW) and Denmark (~14 GW) [21]. During same period, the historical peak energy consumption between difficulty recalculation was about 129.20 TWh per year. Energy consumption is directly affected by the bitcoin prices as well. With falling bitcoin prices, the peak power demand drops as well. In the first half of 2018, the estimated minimum power demand was between 1.34 and 2.80 GW whilst the maximum demand was between 5.14 and 13.82 GW. During June 2018, yearly energy consumption was between 15.47 (minimum) and 50.24 TWh (maximum).

It is almost impossible to make a precise estimation of the future energy consumption of bitcoin mining simply due to two reasons. Firstly, the bitcoin prices directly affect mining and hence energy consumption. Especially since 2017, the prices have fluctuated massively in the market, and it is hard to estimate the future value of bitcoin. Secondly, hardware efficiency is another major factor. As many as 269 different hardware models could have been used in mining. Since we scanned all available hardware in the market, as of June 2018, we claim the maximum and minimum estimations of this paper are the theoretical boundaries of the energy consumption of Bitcoin mining. However, on a regular basis, we see a more efficient device introduced in the market almost each month. It is hard to predict the future efficiencies of the devices that manufacturers will introduce. Finally, one more crucial highlight is that by the year 2028, 98.44% of all bitcoins will be produced. The discussion about the energy consumption of bitcoin mining is likely to persist until then.

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Appendix A

Table A1. CPU hardware.

Producer	Model	Efficiency (J/TH)	Release Date
Intel	Pentium III mobile	113,333,333	19/03/2001
Intel	Pentium 4 2.0A	63,882,353	01/01/2002
Intel	Pentium 4 630	65,116,279	01/01/2002
Intel	Xeon Prestonia 2.4	60,185,185	01.10.2002
AMD	Athlon XP 2000+	112,903,226	01.07.2002
Intel	Xeon 2.8	92,500,000	01.10.2003
Intel	Pentium M 1.6	10,563,380	01/04/2004
AMD	Athlon 64 3500+	75,423,729	01.07.2004
AMD	Athlon 64 X2 3800+	37,572,254	01.07.2004
AMD	Athlon 64 X2 4000+	34,210,526	01.07.2004
AMD	Sempron 3000+	77,500,000	17/09/2004
AMD	Athlon 64 X2 4400+	31,100,478	23.05.2006
Intel	Core 2 Duo T5500	8,139,535	28.08.2006
Intel	Xeon X5355	5,272,408	01/10/2006
AMD	Opteron 8220 x16	3,800,000	01/02/2007
Intel	Core 2 Quad Q6600	9,545,455	01.01.2007
Intel	Xeon 5335	8,556,150	01.01.2007
AMD	Athlon 64 X2 6000+	44,483,986	20.02.2007
Intel	Core 2 Duo T5450	14,000,000	01.04.2007
Intel	Core 2 Duo U7600	9,090,909	01.04.2007
Intel	Core 2 Duo E6550	26,530,612	01/07/2007
Intel	Core 2 Duo E6850	9,629,630	01/07/2007
Intel	Pentium Dual-Core E2180	14,444,444	01/07/2007
Intel	Xeon E7220	12,698,413	01.07.2007
Intel	Xeon E7320	106,666,667	01.07.2007
AMD	Athlon 64 X2 6400+ Black Edition	43,103,448	20/08/2007
Intel	Core 2 Duo T7250	7,777,778	01.09.2007
Intel	Xeon E5410	8,163,265	01.10.2007
Intel	Core 2 Extreme X9000	6,111,111	01/01/2008
Intel	Core 2 Duo E8200	28,260,870	01/01/2008
Intel	Core 2 Duo E8400	9,420,290	01/01/2008
Intel	Core 2 Duo E8500	9,027,778	01/01/2008
Intel	Xeon E5440	10,958,904	01.01.2008
AMD	Phenom X4 9650	19,387,755	27/03/2008
Intel	Atom Z520	1,666,667	01.04.2008
Intel	Atom 230	4,123,711	01.04.2008
Intel	Atom N270	2,100,840	01.04.2008
Intel	Core 2 Quad Q9400	8,636,364	01.07.2008
Intel	Core 2 Quad Q9650	5,088,377	01.07.2008
Intel	Core 2 Duo T9400	8,333,333	01.07.2008
Intel	Xeon E7450	6,000,000	01.07.2008
Intel	Core 2 Duo E5200	11,612,903	01/07/2008
Intel	Core 2 Duo E7300	8,376,289	01/07/2008
AMD	Turion X2 RM-70	34,210,526	04/07/2008
AMD	Phenom X4 9650 Black Edition	25,714,286	01/10/2008
Intel	Core 2 Duo P8700	11,016,949	01/10/2008
Intel	Core i7 920	6,770,833	01/10/2008
Intel	Pentium Dual-Core E5400	28,634,361	01/01/2009

Intel	Celeron E3400	11,016,949	01/01/2009
Intel	Core 2 Duo T6400	8,333,333	01.01.2009
Intel	Core 2 Duo T7450	9,459,459	01.01.2009
Intel	Xeon E5506	8,333,333	01.01.2009
Intel	Xeon E5520	12,307,692	01.01.2009
Intel	Xeon E5530	11,204,482	01.01.2009
Intel	Atom N280	4,798,464	01.01.2009
AMD	Phenom II X3 720	13,194,444	09/02/2009
AMD	Phenom II X4 810	8,260,870	09/02/2009
AMD	Phenom II X4 955	11,363,636	01/04/2009
Intel	Core i7 950	6,878,307	01/04/2009
Intel	Celeron E3300	29,545,455	01.07.2009
Intel	Core 2 Quad Q8200	8,715,596	01/07/2009
Intel	Core i7 820QM	3,260,870	01/07/2009
AMD	Athlon II X2 250	11,607,143	02/07/2009
AMD	Phenom II X4 965	12,727,273	01/08/2009
AMD	Athlon II X4 630	6,074,766	16/09/2009
AMD	Athlon II X2 240e	16,605,166	20/10/2009
Intel	Xeon X5650	3,321,678	01.01.2010
Intel	Xeon X5680	5,416,667	01.01.2010
Intel	Core i7 980x	6,770,833	01/01/2010
Intel	Core i3 530	9,626,955	01/01/2010
Intel	Core i3 350M	23,648,649	01/01/2010
Intel	Core i5 650	14,313,725	01.01.2010
Intel	Core i5 750	6,785,714	01.01.2010
Intel	Core i7 620M	5,555,556	01/01/2010
Intel	Core i7 720QM	5,696,203	01/01/2010
Intel	Xeon E5620	6,477,733	01.01.2010
Intel	Xeon E5630	10,000,000	01.01.2010
Intel	Xeon E7520	10,555,556	01.01.2010
Intel	Xeon W3680	7,222,222	01.01.2010
Intel	Atom N450	3,437,500	01.01.2010
Intel	Atom D510	5,652,174	01.01.2010
AMD	Opteron 6174	2,782,609	29.03.2010
AMD	Opteron 6172	4,181,818	29.03.2010
AMD	Opteron 6128	7,098,765	29.03.2010
Intel	Core i5 450M	19,444,444	01/04/2010
AMD	Phenom II X6 1090 T	7,833,333	27/04/2010
AMD	Phenom II X6 1055 T	4,025,424	01/05/2010
Intel	Atom N550	4,314,721	01.07.2010
Intel	Atom 330	4,314,721	01.07.2010
AMD	Phenom II X6 1055 T	5,868,545	21/10/2010
AMD	Phenom II X6 1100T	5,681,818	07/12/2010
Intel	Core i5 2400	6,785,714	01.01.2011
Intel	Core i5 2400S	3,915,663	01.01.2011
Intel	Core i5 2500K	4,611,650	01.01.2011
Intel	Core i7 2600K	5,107,527	01.01.2011
Intel	Core i7 2600	3,974,895	01.01.2011
Intel	Core i7 990x	3,903,904	01/01/2011
Intel	Core i7 2635QM	15,358,362	01/01/2011
Intel	Core i7 3770k	18,780,488	01/01/2011
Intel	Xeon X5690	5,000,000	01.01.2011
AMD	Zacate E-350	9,473,684	04/01/2011

AMD	Ontario C-50	1,451,613	04/01/2011
AMD	A8-3850	1,666,667	30/06/2011
AMD	A8-3870K	1,052,632	30/06/2011
AMD	A4-3400	2,801,724	07/09/2011
Intel	Core i7 3930k	1,951,952	01/10/2011
Intel	Xeon E5-2690	4,090,909	01.01.2012
Intel	Xeon E3-1230 V2	3,502,538	01/04/2012
Intel	Xeon X5365	11,538,462	01/04/2012
AMD	A8-3850	952,381	01/10/2012
Intel	Core i3 2100	7,850,242	01/07/2013

Table A2. FPGA hardware.

Model	Efficiency (J/TH)	Release Date
X6500 FPGA Miner	43,000	29 August 2011
Icarus	50,526	1 November 2011
Lancelot	65,000	1 May 2012
ModMiner Quad	47,619	4 May 2012

Table A3. GPU hardware.

Producer	Model	Efficiency (J/TH)	Release Date
Nvidia	8800 GTX	5,272,727	08/11/2006
Nvidia	8800 GTS	9,166,667	12/02/2007
Nvidia	8500 GT	18,750,000	17/04/2007
Nvidia	8600GT	9,893,993	17/04/2007
Nvidia	8600M GT	4,056,795	01/05/2007
Nvidia	8400M GS	5,500,000	01/05/2007
Nvidia	8400 GS	17,391,304	15/06/2007
ATI	6790	681,818	01/07/2007
Nvidia	8800M GTX	3,987,730	01/11/2007
Nvidia	8800 GT	4,200,000	11/12/2007
Nvidia	9500M GS	6,250,000	01/01/2008
Nvidia	9600 GT	6,066,411	21/02/2008
Nvidia	9800 GX2	3,406,536	18/03/2008
Nvidia	9800 GTX	4,302,397	01/04/2008
Nvidia	9300 GS	14,792,899	01/06/2008
Nvidia	9300GE	15,923,567	01/06/2008
Nvidia	GTX 280	5,038,429	17/06/2008
ATI	4850	1,466,667	25/06/2008
Nvidia	9800 GT	3,458,498	01/07/2008
ATI	4870	1,666,667	01/07/2008
Nvidia	9800 GTX+	4,325,153	16/07/2008
Nvidia	9500 GT	7,407,407	29/07/2008
Nvidia	9400 GT	14,836,795	27/08/2008
ATI	4650	1,548,387	10/09/2008
ATI	4670	1,638,889	10/09/2008
ATI	FirePro V8700	1,776,471	11/09/2008
Nvidia	GTX 260	5,625,174	16/09/2008
ATI	4830	1,727,273	21/10/2008
ATI	4350	1,818,182	30/10/2008
Nvidia	GTX 295	2,394,366	08/01/2009
ATI	4570M	3,375,000	09/01/2009
Nvidia	GTX 285	3,823,805	15/01/2009

Nvidia	GTS250	4,097,203	03/03/2009
ATI	FirePro V7750	2,111,111	27/03/2009
ATI	4890	1,557,377	02/04/2009
ATI	4770	1,111,111	28/04/2009
ATI	4730	1,527,778	08/06/2009
ATI	3410	12,000,000	05/07/2009
Nvidia	GTX 275	4,315,271	04/09/2009
ATI	4860	1,940,299	09/09/2009
ATI	5870	628,763	23/09/2009
ATI	5850	626,556	30/09/2009
Nvidia	G210	9,023,669	12/10/2009
Nvidia	G220	11,851,852	12/10/2009
Nvidia	G230	6,193,548	12/10/2009
ATI	5750	741,379	13/10/2009
ATI	5770	687,898	13/10/2009
Nvidia	G240	3,562,210	17/11/2009
Nvidia	G240M	2,346,939	17/11/2009
ATI	5970	554,717	18/11/2009
Nvidia	GT 330	3,464,203	02/01/2010
ATI	5470M	882,353	07/01/2010
ATI	5650	729,167	07/01/2010
ATI	5870M	264,550	07/01/2010
ATI	5670	888,889	17/01/2010
ATI	5450	1,583,333	04/02/2010
ATI	5570	650,000	09/02/2010
ATI	5550	951,220	09/02/2010
ATI	5830	717,213	25/02/2010
Nvidia	GTX 470	2,622,591	26/03/2010
Nvidia	GTX 480	2,468,404	26/03/2010
Nvidia	GTX 465	3,105,108	31/03/2010
ATI	FirePro V3800	623,188	26/04/2010
ATI	FirePro V4800	862,500	26/04/2010
ATI	FirePro V7800	541,176	26/04/2010
ATI	FirePro V5800	621,849	26/04/2010
Nvidia	GTS 360M	1,520,000	01/07/2010
Nvidia	GTS 350M	1,346,154	01/07/2010
Nvidia	GTX 570	2,069,357	12/07/2010
Nvidia	GTX 580	1,558,110	11/09/2010
Nvidia	GTX 590	1,558,110	11/09/2010
Nvidia	GTX 670	1,517,857	11/09/2010
Nvidia	GTX 325M	2,190,476	01/10/2010
Nvidia	GT 330M	1,018,519	01/10/2010
ATI	6850	738,372	22/10/2010
ATI	6870	650,862	22/10/2010
Nvidia	GT 440	2,745,098	10/11/2010
Nvidia	GT 430	2,420,949	10/11/2010
Nvidia	GTS 450	2,340,989	10/11/2010
Nvidia	GTX 460	2,412,545	10/11/2010
Nvidia	GTX 460SE	2,660,046	15/11/2010
ATI	6950	735,294	15/12/2010
ATI	6970	773,994	15/12/2010
ATI	6490M	1,437,500	01/01/2011
ATI	6570	882,353	01/01/2011

Nvidia	GT 610M	1,280,683	12/01/2011
ATI	6750	1,056,338	21/01/2011
ATI	6450	666,667	07/02/2011
ATI	6990	559,701	08/03/2011
Nvidia	GTX 550Ti	2,577,778	15/03/2011
Nvidia	GTX 560M	1,908,397	30/03/2011
ATI	6770	600,000	19/04/2011
ATI	6670	647,059	19/04/2011
Nvidia	GT 520M	1,348,315	01/05/2011
Nvidia	GT 525M	1,575,342	01/05/2011
Nvidia	GT 540M	2,187,500	01/05/2011
Nvidia	GT 550M	2,049,180	01/05/2011
Nvidia	GT 530	2,793,296	14/05/2011
ATI	6480G	1,875,000	14/06/2011
ATI	6520G	1,323,529	14/06/2011
ATI	6530D	2,439,024	20/06/2011
ATI	6550D	1,515,152	20/06/2011
Nvidia	GTX 560Ti	3,101,920	29/11/2011
ATI	6930	581,250	01/12/2011
ATI	7970	450,450	01/01/2012
ATI	7950	392,157	01/01/2012
ATI	7770	439,560	01/02/2012
ATI	7750	528,846	01/02/2012
ATI	7850	452,962	01/03/2012
ATI	7870	432,099	01/03/2012
Nvidia	GT 650M	2,528,090	22/03/2012

Table A4. ASIC hardware.

Producer	Model	Efficiency (J/TH)	Release Date
Canaan	AvalonMiner Batch 1	9351	01/01/2013
Canaan	AvalonMiner 2	1600	01/10/2013
KnCMiner	Jupiter	1484	05/10/2013
ASICminer	BE Cube	6667	01/11/2013
Antminer	S1	2000	01/12/2013
Antminer	U1	1250	01/12/2013
Spondoolies	Hammer	651	19/03/2014
Antminer	S2	1100	01/04/2014
Antminer	U2+	1000	01/05/2014
Canaan	AvalonMiner 3	941	01/05/2014
Antminer	S3	766	01/06/2014
KnCMiner	Neptune	570	07/06/2014
ASICminer	BE Blade	7719	10/07/2014
Spondoolies	RockerBox	425	22/07/2014
Antminer	S4	700	01/10/2014
Antminer	S5	511	01/12/2014
Antminer	U3	1000	15/01/2015
Antminer	S7	273	01/09/2015
Canaan	AvalonMiner 6	309	01/10/2015
Antminer	S9-11.5	98	01/06/2016
Antminer	S7-LN	258	01/06/2016
Canaan	AvalonMiner 721	167	01/10/2016
Canaan	AvalonMiner 741	158	01/12/2016

Antminer	R4	97	01/02/2017
Antminer	S9-12.5	98	01/02/2017
Antminer	T9-11.5	126	01/04/2017
Antminer	S9-13.0	100	01/06/2017
Antminer	T9-12.5	126	01/08/2017
Antminer	S9-13.5	98	01/10/2017
Antminer	S9-14	98	01/11/2017
Canaan	AvalonMiner 821	109	01/12/2017
Antminer	T9+	136	01/01/2018
Antminer	V9	257	01/03/2018
Canaan	AvalonMiner 841	99	01/03/2018
Bitfury	BF8162B	96	01/05/2018
Antminer	S9i-14.0	94	05/01/2018
Antminer	S9i-13.5	97	01/05/2018
Antminer	S9i-13.0	99	01/05/2018
ASICminer	8 Nano Compact	51	01/05/2018
ASICminer	8 Nano Pro	53	01/05/2018
ASICminer	48 Th Air	158	01/05/2018
ASICminer	24 Th Compact	167	01/05/2018
ASICminer	48 Th	167	01/05/2018

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