SUSTAINABILITY ANALYSIS OF BITCOIN MINING

by

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ABSTRACT

SUSTAINABILITY ANALYSIS OF BITCOIN MINING

Blockchain technology is considered a disruptive technology that could revolutionize the financial system with its applications in fintech. While the use of blockchain technology has accelerated in various fields globally, the dilemma about energy utilization of this technology is unfolded. The most energy-consuming application of blockchain technology, Bitcoin mining, has been particularly questioned in the literature for its sustainability. In the present study, the hardware used for Bitcoin block production is evaluated from a thermodynamics perspective to solve the mystery of sustainability in block production lasting for the past decade. Changes in difficulty level in block algorithm and mining hardware's thermal power usage are considered to determine the second law efficiency of the mining process. Our findings suggest that graphics processing units (GPUs) initially used in mining and application-specific integrated circuits (ASICs) specifically designed and manufactured for Bitcoin block mining become inefficient over time, which needs to be switched with more efficient technology. This study implies that the second law efficiency of hardware used in block production declines with time before hitting a plateau, indicating a warning about the unsustainable time and switching more efficient mining hardware for miners and technology makers ahead of time.

ÖZET

BITCOIN MADENCİLİĞİNİN SÜRDÜRÜLEBİLİRLİK ANALİZİ

Blokzincir teknolojisi, fintech uygulamalarında kullanılabilirliği ile devrim yaratabilecek yıkıcı bir teknoloji olarak kabul edilebilir. Blokzincir teknolojisinin yaygınlaşması sırasında teknolojinin küresel olarak çeşitli alanlarda hız kazanması, enerji harcamaları konusunda ikilem ortaya çıkmasına sebep olmaktadır. Blokzincir teknolojisinin en çok elektrik tüketimine sebep olan kolu olan Bitcoin madenciliği; elektrik harcamaları ve sürdürülebilirlik anlamında literatürde araştırma konusu haline gelmiştir. Bu çalışmada Bitcoin madenciliği için kullanılan cihazlar termodinamik perspektifinden incelenerek Bitcoin madenciliğinin son 10 yılındaki verileri ışığında sürdürülebilirliği incelendi. Madencilik sürecinin ikinci yasa verimini belirlemek için; blok algoritması, madencilik donanımı, termal verimlilik ve zorluk seviyesindeki değişiklikler dikkate alınmıştır. Bulgularımız göz önünde bulundurulduğunda, başlangıçta madencilikte kullanılan ekran kartı (GPU) ve Bitcoin için özel olarak tasarlanmış ve üretilmiş özel entegre devreler (ASIC'ler) blok madenciliği için zamanla verimsiz hale gelmektedir, bu da daha iyi bir sistem ile değiştirilmeyi gerekli kılar. Bu çalışma; kullanılan madencilik cihazının zarar ettirmeye başlamadan önce ikinci yasa veriminin iyice düştüğünü ve madencileri öncesinde uyardığını söylemektedir.

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LIST OF SYMBOLS/ABBREVIATIONS

u	Internal energy
w	Work
q	Heat exchange
s	Entropy
X	Exergy
η	Efficiency
φ_{mHW}	Exergy destruction mining hardware
ASIC	Application-specific integrated circuit
BTC	Bitcoin
CPU	Central processing pnit
DED	Difficulty exergy destruction
D_{new}	New difficulty
D_{old}	Old difficulty
E_{real}	Exergy real device
E_{rev}	Exergy reversible device
EC_{block}	Electricity consumption for block
$EC_{block, \$}$	Electricity consumption for block in USD
MI_{block}	Mining Income from block
N_{mHW}^{D}	Required mining hardware due to difficulty
PT	Processing time
$hash_{avg}$	Average hashrate
NHR_{avg}	Average network hashrate
GPU	Graphics processing unit
HW	Hardware

1. INTRODUCTION

1.1 AIM OF THE STUDY

This study is aiming to present a valuable and applicable strategy about blockchain mining by considering the sustainability of both blockchain technology and global consumptions.

To achieve these goals; considering the inherent factors of blockchain technology, an attempt has been made to apply the laws of thermodynamics to blockchain mining. Mostly blockchain perspective of mining is ignored while the energy perspective is calculated for mining hardware. But blockchain mining can be affected by numerous parameters. Some of these parameters, like trading speculations, miners characteristics, unexpected regulations from authorities, are not concrete and predictable. The unchangeable effect of these parameters has been tried to be reduced by using equations based on the thermodynamic point of view and the SHA-256 algorithm.

1.2 BLOCKCHAIN TECHNOLOGY AND CRYPTOCURRENCIES

Blockchain technology has been regarded as a potentially disruptive technology that changes the way financial institutions function and many other possible business and societal impacts. In discussing blockchain technology's role as hype or real, Perera et al. (2020) reveal the blockchain's credible potential in the construction industry. Blockchain technology is used to run digital ballot boxes in voting, as a ridesharing platform in transportation, in food and agriculture supply chains. It can be utilized to solve many other real-life problems across different sectors. However, the greatest impact of blockchain technology has been in financial technology (fintech) so far since the technology was indeed developed for Bitcoin cryptocurrency (Yli-Huumo et al., 2016), as reflected in the studies on blockchain in the prior literature. The promoting role of blockchain technology and cryptocurrency in the fourth industrial revolution within the finance domain is inevitable (Su et al., 2020). Cryptocurrency can be a disruptive fintech to the existing economic and financial system upon its growing likelihood of becoming the global norm for transactions. Cryptocurrency has emerged as a new way of financing, creating alternative solutions to the financing system's issues based on the traditional fiat currency. The blockchain technology that the cryptocurrency is based on takes its power from a decentralized peer-to-peer system, allowing the data to be transferred without a central authority. While decentralization reduces the delays in the transformation, blockchain technology has other unique characteristics, such as anonymity, security, auditability, and transparency, which further increases its credibility and usage. Among several others, the first cryptocurrency, i.e., Bitcoin, secures its first place as the most used cryptocurrency. The rareness of Bitcoin due to the limit on the number of Bitcoin generated makes users attribute value to this currency, which also improved over the years as an accepted trustable payment. Despite the positive societal implications, blockchain technology has its own negative sides that are described in the words of Schinckus (2020) as the bad and ugly blockchain. The amount of electricity used has been a concern since almost 60% of blockchain technology applications are based on the proof-of-work algorithm (POW), which requires high computational power. There is a growing interest in the literature exploring energy consumption in producing cryptocurrencies (Küfeoğlu & Özkuran, 2019; Schinckus, 2020; Sedlmeir et al., 2020; Vranken, 2017). Considering various types of hardware and the duration of their usage, Küfeoğlu & Özkuran (2019) estimate the minimum and maximum power demand during the proof-of-work process in Bitcoin mining. This study estimates the peak biweekly electricity consumption in 2017 between 1.3 and 14.8 GW, nearly reaching Denmark and Finland's installed capacities. The estimates for Bitcoin mining's power requirements in 2017 are calculated to be 948 MW, nearly the same as Angola or Panama's total energy consumption. According to de Vries (2020), there are several drawbacks, like the assumption of constant electricity prices and market participants' choices in estimation methods for the energy consumption of Bitcoin mining. Despite the shortcomings, de Vries (2020) estimates Bitcoin's annual energy consumption to be close to the annual electricity consumption of a country like Belgium. de Vries (2018) refers to the design of the Bitcoin system as an *energy-hungry* one indicating a fast-growing problem for the business and technology world. The high costs associated with Bitcoin mining make scholars question the sustainability of the system. Ensuring the sustainability of Bitcoin mining is closely related to the goodness of the mining hardware technology. The exponential increase in energy demand for Bitcoin mining has caused rapid changes in the mining hardware technology that supports it. The

mining hardware has evolved from the first generation using CPUs to the fourth generation ASICs since the beginning of the mining process in 2009 to this time. Despite the developing technology and resources spent on it, Bitcoin mining's profitability still possesses a great deal of uncertainty even today. Looking at the issue from the miners' side, choosing the proper hardware and switching to new hardware at the right time is vital in mining profitability. On the other hand, viewing the issue from the technology makers' side, the development and launch of the right hardware at the right time are crucial to grab a significant share in the market. The uncertainty of producing and acquiring the proper hardware at the right time results in inefficiencies preventing to achieve the idealized higher profits from Bitcoin mining. There is a need for an objective analysis of the hardware to do the mining most efficiently, ensuring the system's sustainability for all parties benefitting from mining. Studies in the prior literature explore
the effects of basic parameters on mining's energy consumption, such as network hash rate, average electricity price, reward per block, and difficulty. However, such studies do not fully account for the effects of unchangeable parameters arising from the nature of the system itself. Given the uncontrollable nature of such parameters, our study offers a different perspective on how mining can be maintained by selecting the proper hardware on a sustainable basis. Developing hardware that will always be efficient is unlikely due to the inherent difficulty built into the design of the blockchain system. It is vital to develop hardware proper for the current difficulty level and adapt to the changing difficulty levels by switching them at the right times. Viewing the problem from a thermodynamics perspective, this study explores the mining hardware life cycle during which a decision to switch to new hardware needs to be made to maintain the system's sustainability to both miners and technology makers.

1.3. CONCEPTS OF EFFICIENCY

To understand and evaluate the exergy-based analysis for Bitcoin mining; laws of thermodynamics need to be understood clearly. Therefore, the first and second laws of thermodynamics should be thoroughly studied and adapted in accordance with the concept of cryptocurrency mining.

While investigating the efficiency of a system, two main approaches can be considered. One of them is only considering the current technology used on a specific system based on the first law of thermodynamics. The second approach is the second law perspective which also considers the system's reversible conditions.

1.3.1. The First Law Efficiency

The first law of thermodynamics states that energy cannot be created or destroyed; it can only be transferred or changed from one form to another. This is also known as the law of conservation of energy. The first law separates two different types of energy transfer; one of them is heat, and another is thermodynamic work. It claims only these two energy can result in internal energy change of a system. Both of these types of energies can be calculated and objectified so; any change of internal energy will result in a change in the system's outside environment. This correlation can be clearly seen from the equation below;

$$\Delta U = q + w \tag{1.1}$$

In this equation q is the exchanged heat between a system and its surroundings, w is the work done by the system and ΔU is total change in internal energy of a system.

Considering this basic information and inferences about the first law of thermodynamics, the application of first law efficiency to thermal systems can be explained as follows. When the efficiency of a system is examined from the perspective of the first law, only that system and the environment it interacts with are considered. In this approach, the efficiency is found by the ratio of the energy used to do work, which is not converted into thermal energy, to the total energy supplied to the system. By this relation formula for first law efficiency can be seen below.

$$\eta_{II} = \frac{Useful\ Energy\ Output}{Energy\ Input} \tag{1.2}$$

1.3.2. The Second Law Efficiency

Second law efficiency is the main approach of our investigation on the sustainability of Bitcoin mining. It is also known as exergetic efficiency. Unlike the first law efficiency, the second law efficiency involves calculating the efficiency of the system by referring to the conditions under which it is reversible. It can also be defined as the ratio of the system's useful work output to the reversible work output for work-consuming systems. On our terms, Bitcoin mining hardware like GPU, CPU, and ASICs works consuming hardware. So, the basic equation of second law efficiency applied to Bitcoin mining can be seen below.

$$\eta_{II} = \frac{Minimum\ Energy\ Available\ (Reversible\ Condition)}{Energy\ Consumed} \tag{1.3}$$

To gain a better understanding of second law efficiency, the terms exergy and entropy should be explained. When a system reaches reversible equilibrium with its environment, we can extract the most beneficial work from it. That most beneficial work is known as exergy. So, destruction of exergy in a closed system is simply the wasted work potential work, also known as dissipated energy. Exergy is highly related to entropy.

Entropy is mainly affiliated with the disorder, uncertainty, and randomness of a system. In thermodynamics, it is also a measure of a system's unusable thermal energy that is potential work. Relationship between exergy and entropy results in exergy destruction. As stated in the second law of thermodynamics, the entropy of isolated systems can never decrease. Therefore, two ranges can be mentioned in exergy destruction while performing exergy analysis. These ranges are irreversible and reversible processes. Due to the relationship between entropy and exergy; exergy destruction in the reversible process is 0. If a system is not reversible and entropy generation occurs, exergy destruction is higher than 0.

$$X_{destroyed} = T_0 * S_{gen} \geq 0 \tag{1.4}$$

$$X_{destroyed} \begin{cases} > 0 \; Irreversible \; Process \\ = 0 \; Reversible \; Process \\ < 0 \; Impossible \; Process \end{cases} \tag{1.5}$$

2. MATERIALS AND METHODS

2.1. MINING HARDWARE TYPES

Since the first days of Bitcoin were released, many different hardware systems have been used to mine Bitcoin. The main three mining hardware can be listed as CPU, GPU, and ASIC.

2.1.1. Central Processing Unit

CPUs were used in the early days of mining. CPU (Central Processing Unit) is an electronic circuit that conducts input/output, basic arithmetic, and logic controls by specified instructions. These CPUs lost their popularity in time due to their inefficiencies in Bitcoin mining. Still, despite being inefficient, many people continued to use it, as these are hardware on every computer that draws less electricity than other hardware.

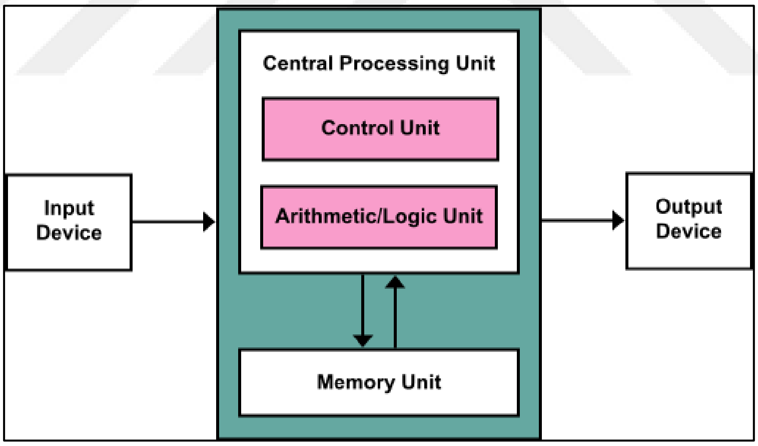

Figure 2.1 Central Processing Unit schematic

2.1.2. Graphics Processing Unit

The second and most common hardware is GPU (Graphics Processing Unit). Just like the CPU's GPU's are used in all computers too. GPUs are actively used in embedded systems, computer graphics, mobile hardware, etc. We can call the period when GPUs were dominant in the market the first era in mining. For a long time, GPUs remained profitable when changed at the correct intervals and when their combinations were made correctly. These combinations are called "mining rigs". Due to the low hash capabilities of GPU's miners choose to use this hardware in rigs. As the ASIC hardware, which we call the second era, became widespread in the market, GPUs started to fall into the second place.

Figure 2.2. Example of GPU mining rig

2.1.3. Application-Specific Integrated Circuit

ASIC (Application-specific integrated circuit) hardware was first released in 2013. This hardware is specially designed for Bitcoin mining. Unlike GPU and CPU, this type of hardware cannot be used for any other processes. ASICs have really high mining hardware efficiency when compared to GPU and CPU. Due to its high hash capabilities, it is actively used in mining farms in many parts of the world.

Figure 2.3. Example of an ASIC mining farm

In addition, ASIC hardware appeals not only to large institutions but also to individual users. There is also cheaper mining hardware with lower mining hardware efficiency on the market. Although the effect of hardware with low mining hardware efficiency is not seen individually, it greatly impacts sustainability in terms of digging mining and exergetics in a global sense.

2.1.4. Comparison of Mining Hardware Types

In the previous sections, different mining hardware and their general characteristics were mentioned. It was noted that ASIC hardware is more efficient and profitable. The graph below, which shows the hash rate capacities and electricity expenditures of 30 different hardware, can be examined to make them even more concrete.

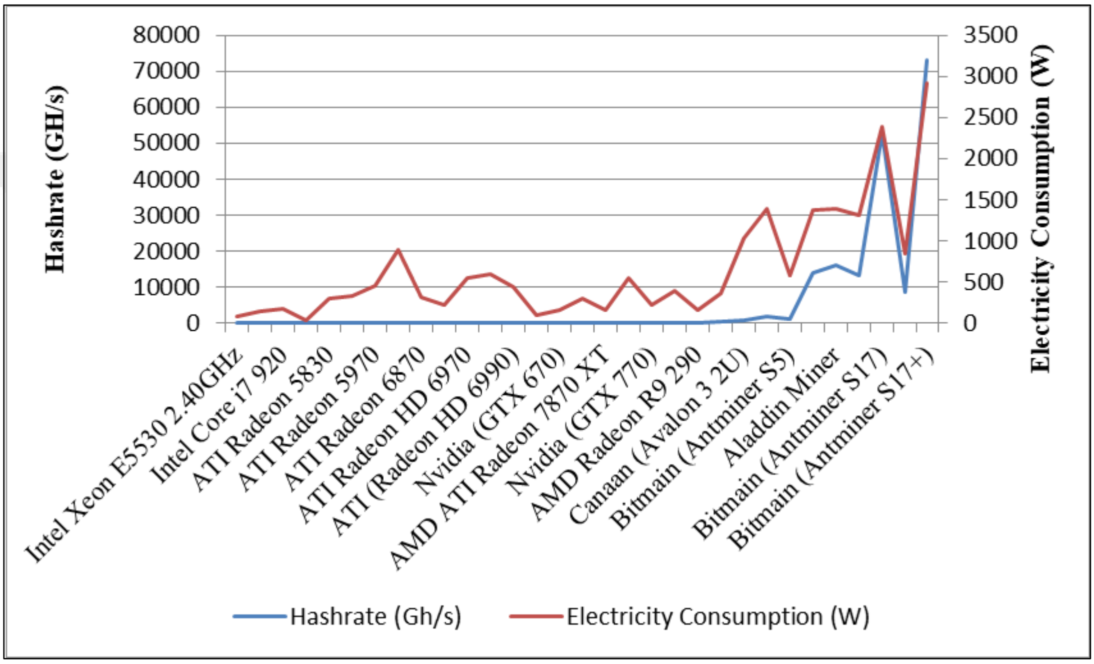

Figure 2.4. Comparison of different mining hardware

This figure contains four different CPUs, 16 different GPUs, and 11 ASIC hardware. If we get into numbers, we can see the dramatic change of hardware easily. A CPU in 2010 had a hash capability of 0.016 GH/s. A GPU in 2012 had a capability of 0.675 GH/s hash capability. This means that the hash capacity has increased 42 times in 2 years thanks to device changes and developments. An ASIC hardware had a 66 GH/s hash capability in 2013. In 3 years, hash capabilities are increased by 412400 percent. This highlights the importance of choosing hardware for mining and the following innovation without relying on traditional resources.

After ASIC hardware started to gain popularity among mining hardware, mining farms switched to this hardware and became profitable in the short term. After the SHA 256 algorithm started to correct using the difficulty level, ASIC hardware began to lose its profitability.

This situation forced technology companies producing ASIC hardware to improve and continuously triggered a mining format change. From the micro level to the macro level, the system's sustainability started to depend on when you switch your device.

2.2. CRYPTOCURRENCY MINING

The history of cryptocurrency goes back to Satoshi's paper released in 2008. This was the first time describing a peer-to-peer network system that allows the transfer of electronic cash without a third party to process the payments. Unlike real money, crypto coins are not related to gold or any centralized reserve system like the federal reserve system and banks. While it is nearly impossible to track or interrupt transactions in cryptocurrency exchange, the system offers low fees for the high amount of money transactions, making it reliable and practical. The first cryptocurrency created was Bitcoin, which is also the most commonly used one worldwide. Bitcoin is considered the most important coin for two reasons.

First, Bitcoin has the highest market capitalization with 502,508 billion dollars. The closest rival of Bitcoin's in the cryptocurrency exchange system is Ethereum with an 84,054 billion dollar market cap, only 17 percent of Bitcoin's market cap. The number of Bitcoins in circulation amounts to 18,584,325, while this number is limited to 21 million Bitcoins. Second, most of the altcoins can only be bought using Bitcoin, and their parity is related to Bitcoin. Considering the limit on the number of Bitcoins in the system, there are still more than two million Bitcoins left to mine as of December 2020. Bitcoin mining is a cognitive operation that includes sophisticated computers and algorithms. The main contribution of Bitcoin mining for people who do not mine but only use Bitcoin for trading is assuring transactions, keeping the system stable, and redounding new Bitcoins into the cryptocurrency exchange. This mining process uses the SHA-256 algorithm, which is one of the hash functions designed by the National Security Agency. This proof of work algorithm assures that transactions are safe and private where miners provide privacy (Narayanan et al., 2016). When transaction data is shared, miners race to assure transactions using the SHA-256 algorithm. By using the SHA-256 algorithm, miners find nonce values and share these with other nodes. If nodes validate the found values, a block gets generated, and miners involved in this mining operation get their rewards. A reward is given to miners in units of Bitcoin.

In 2009, when Bitcoin was first released, the reward per block was 50 Bitcoin, but the reward was halved every 210,000 blocks mined. The first halving occurred on November 26, 2012, where the reward dropped to 25 Bitcoin from the initial value of 50 Bitcoin. The most recent halving occurred on May 11, 2020, making the reward for being 6.25 Bitcoin. The next halving is expected to occur on May 7, 2024. The output of the processed data from a block produces a 64-digit hexadecimal number, which is termed as a hash. The rate of hashing is called hash rate, which functions as a proxy for network speed. The efficiency of the sophisticated computers used in block mining is evaluated with their hash rate capabilities. Both the number of miners and the efficiency of mining hardware used in mining are continually increasing. To keep the mining time per block constant, an operation is embedded to make block production harder in the algorithm, referred to as difficulty. The algorithm arranges the difficulty in every 2016th block to keep the mining time for one block to 10 minutes. When the average network hash rate increases and the time spent to mine one block reduces, difficulty arrangement is made, and difficulty increases.

The new difficulty is calculated as given in equation (2.1).

$$D_{new} = D_{old} x \frac{1.2096 \ x \ 10^6}{t_{last}} \tag{2.1}$$

2.3. MINING HARDWARE SELECTION

Electricity consumption concerns both traders and miners due to the high cost of electricity. There are four main mining hardware types: Graphics Processing Unit (GPU), Central Processing Unit (CPU), Field Programmable Gate Array (FPGA), Application Specific Integrated Circuit (ASIC). Although the SHA-256 algorithm is suitable for all these hardware types, it is not efficient with all of them. Mostly GPU and CPU were used for mining until ASIC hardware was released. We investigate different types and brands of mining hardware to get a better perspective on the evolution and efficiency of mining hardware development.

ASICs are specially designed for mining, unlike GPU and CPU that have other uses. We consider the development of ASIC as the start of a new era and examine the developments in two different timings that represent before the ASIC and after the ASIC. In the first era that covers the years between 2009 and 2014, GPUs were the mining industry's dominant technology. As of 2014, the first ASICs were released into the market, and the mining hardware choices of miners are started to change completely. The second era started with the wide acceptance of the ASICs, resulting in a strictly overpowering market. In understanding the life cycle of mining hardware, we selected 12 different mining hardware out of more than 30 hardware introduced in the market, representing the prominent characteristics of the overall usage. These characteristics include the release date, hash capability, electric consumption, and mining hardware efficiency, shown in Table 3.1. CPUs are not investigated within the first era since they are extremely inefficient for processing the SHA-256 algorithm. Even though GPUs lost their popularity as of 2014, their evolution and impact on Bitcoin mining in the first era provide a reasonable understanding of the parameters affecting Bitcoin mining.

Table 2.1. Specifications of selected mining hardware

Type of Mining Hardware	Mining Hardware	Hash Capability (TH/sec)	Power Consumption (Watt)	Mining Hardware Efficiency (MH/Watt)
ASIC	Bitmain Antminer S3	0.478	368	2199
ASIC	Bitmain Antminer S5	1.155	590	1958
ASIC	Bitmain Antminer S9	11.5	1127	9894
ASIC	Ebang Ebit E11	44	1980	22222
ASIC	Bitmain Antminer S17 PRO	50	1975	25317
ASIC	Pantech SX6	8.5	1000	8500
GPU	AMD Radeon 5970	0.0003	294	1.02
GPU	AMD Radeon 7790	0.000325	205	1.59
GPU	AMD Radeon 7850	0.000485	251	1.93
GPU	AMD Radeon 7970	0.00065	141	4.6

We made our selection of the mining hardware based on the mining hardware efficiency. The values for the selected hardware are shown in the last column of Table 2.1. Mining hardware efficiency for mining hardware is calculated by dividing hash capability by electricity consumption, as illustrated in equation (2.2). Higher hash capability and lower electricity consumption result in more efficient hardware.

$$\eta_{mHW} = \frac{HC_{mHW}}{EC_{mHW}} \tag{2.2}$$

2.4. RAW DATA OF BITCOIN MINING

For the desired calculations, detailed data of bitcoin mining between 2009 and 2020 were brought together. In our analyses, five important data are used to calculate shown profit and exergy graphs. These data can be seen below;

- Mining Difficulty
- Average Network Hash rate
- Block Mining Time
- Bitcoin Unit Price
- Block Reward

The change of these data in the last ten years has been tried to be facilitated by graphing. These charts are given below. While Figure 2.5 shows the average network hash rate variation for the last ten years, mining difficulty change is presented in Figure 2.6.

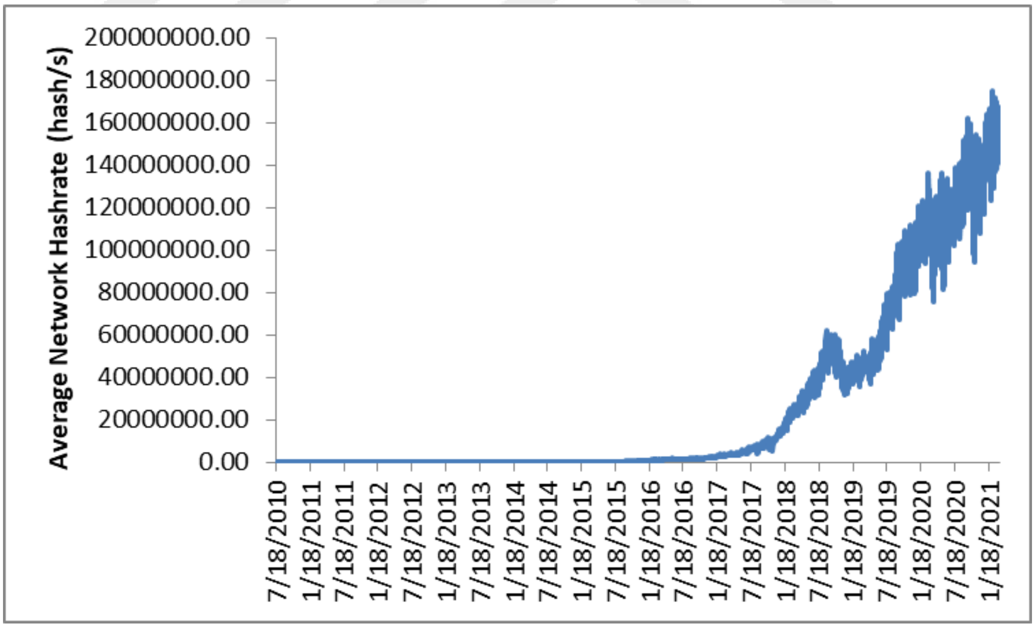

Figure 2.5. 10 Years data for average network hash rate

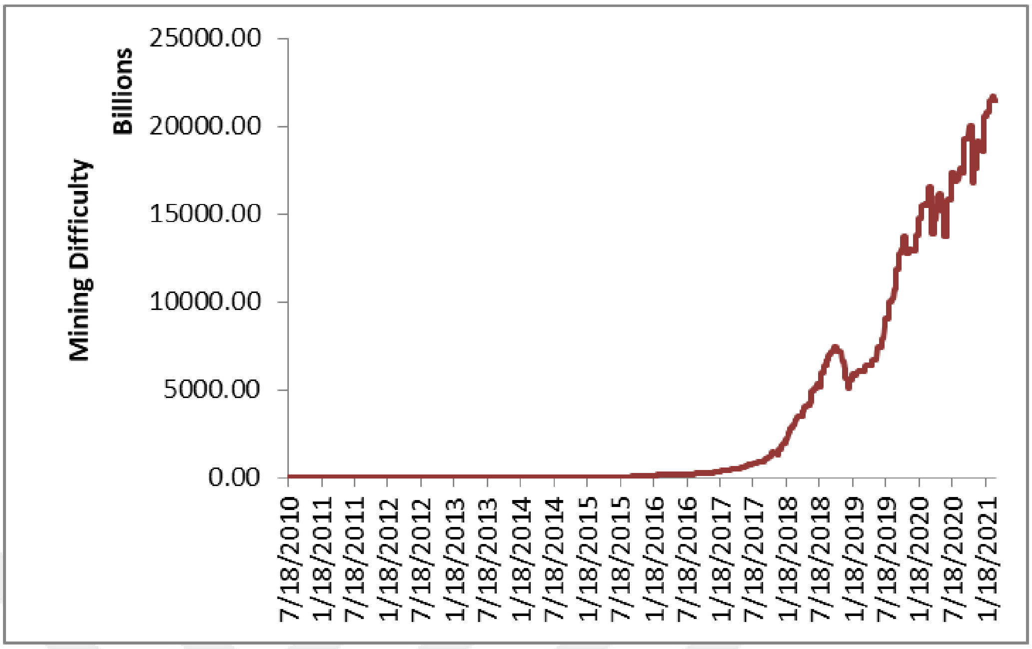

Figure 2.6. 10 Years data for mining difficulty

Mining difficulty and average network hashrate is explained in Section 2.2. Figure 2.5 and Figure 2.6 helps us to visualize these explanations. Increase in average network hashrate can easily be seen after 2017. Also increase in difficulty can be seen for mining difficulty with a similar path of average network hashrate. It is an expected result due to relationship between average network hashrate and difficulty and also connected with mining time per block in Figure 2.7.

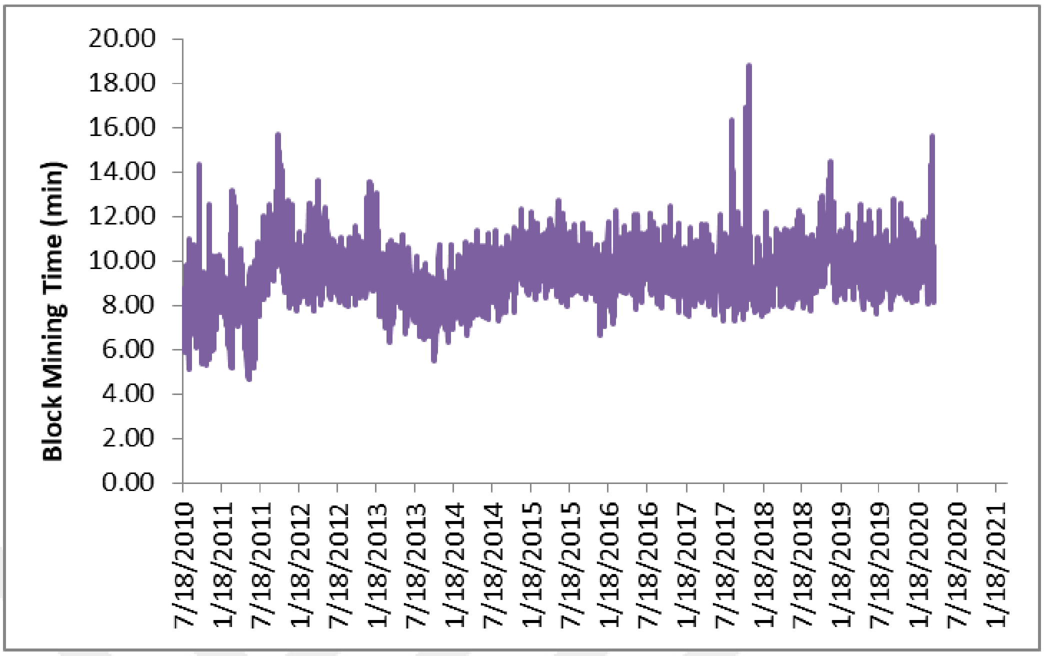

Figure 2.7. 10 Years data for block mining time

When miner's achieve better mining hardware; average network hashrate increase due to technological improvement. By the effect of increased average network hashrate; mining time per block decrease. Algorithm behind the Bitcoin mining tries to keep block mining time 10 minutes by adjusting difficulty, so mining difficulty increase and mining time per block can be kept 10 minutes approximately.

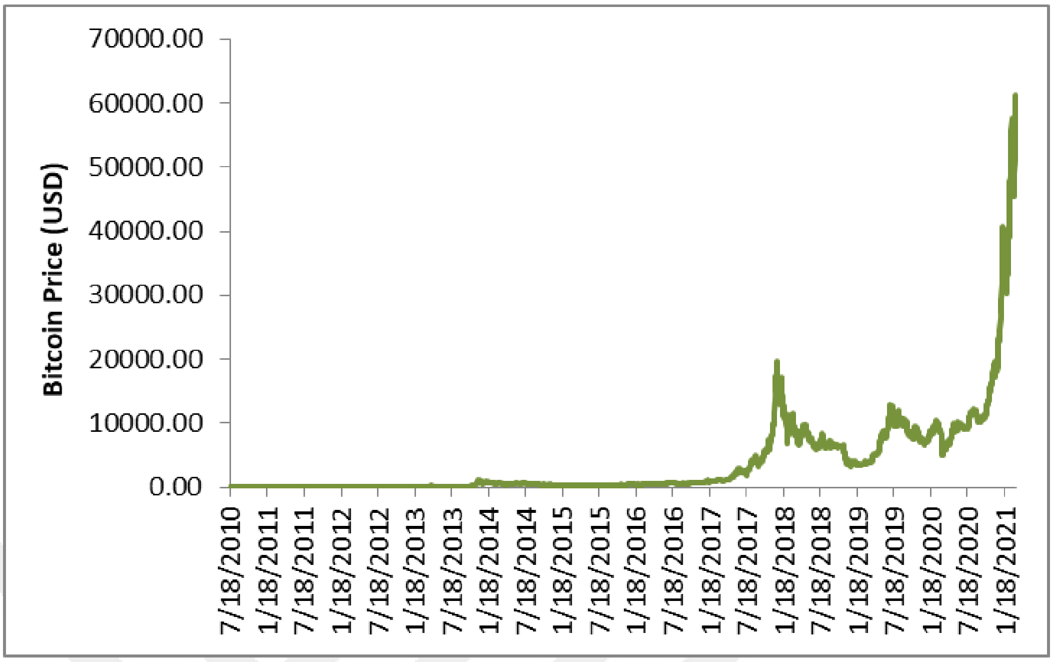

Figure 2.8. 10 Years data for Bitcoin price

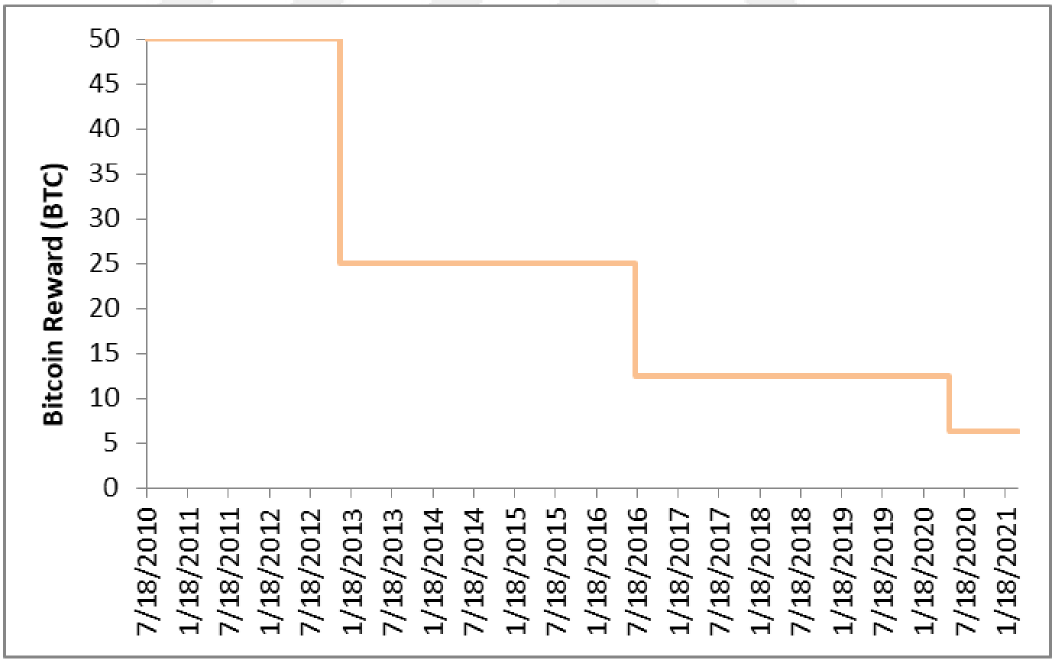

Figure 2.9. 10 Years data for Bitcoin reward

2.5. ELECTRICITY CONSUMPTION AND PROFIT OF MINING HARDWARE

In understanding how the technology changes to accommodate the ever-increasing demand for more efficient hardware in terms of higher hash capability and less electricity consumption, we calculate the profitability per mining hardware. The mining hardware is only useful during a specific time period following its release. We measure the usefulness of the mining hardware by profitability, which allows us to compare among different hardware.

To calculate the electricity consumption, we start with the required number of hashes to mine one block. The number of hashes needed to mine one block can be found by multiplying the average network hash rate by 600 seconds (i.e., 10 minutes is required to mine one block), as shown in equation (2.3). The value for the average network hash rate is obtained from reference websites.. Note that hash is expressed in TH in all our computations.

$$Hash_{avg} = NHR_{avg} \times 600 \tag{2.3}$$

We can calculate the processing time for the mining hardware to mine one block by dividing the number of hashes to mine one block (i.e., Equation 2.3) by the mining hardware's hash capability. The hash capability of the hardware is the hash rate given in the design specification of the hardware. Equation 2.4 shows the required time to mine one block.

$$PT = \frac{Hash_{avg}}{HC_{mHW}} \tag{2.4}$$

One mining hardware is not sufficient to mine one block in 10 minutes due to high difficulty levels. Since the processing time to mine one block will be much greater than 10 minutes, we divide the processing time obtained in equation (2.4) by 10 minutes to get the number of mining hardware needed to mine one block in 10 minutes, as shown in equation

(2.5). We use multiple mining hardware of the same kind to mine one block in the specified time period of 10 minutes.

$$N_{mHW} = \frac{PT}{600} \tag{2.5}$$

The selected mining hardware's electricity consumption to mine one block depends on the hardware's hourly electricity consumption and the number of mining hardware required to mine one block in 10 minutes. The electricity consumption is calculated as in equation (2.6).

$$EC_{block} = EC_{mHW} \times N_{mHW} \tag{2.6}$$

The electricity consumption calculated in kWh in equation (2.6) can be expressed in monetary value by multiplying it with the global average price for electricity per kWh. The electricity prices vary from \$0.01 to \$0.38 across the countries located in different parts of the world. To account for the variability in prices, we calculate the average electricity price to be \$0.14 per kWh using the electricity prices of 147 countries. The electricity consumption in U.S. dollars is expressed in equation (2.7).

$$EC_{block,\$} = EC_{block} \times EP_{avg} \tag{2.7}$$

We next calculate the profit made in mining one block by the selected hardware. Miners get a reward after processing a block. The profit for the mining process mainly comes from this reward. We can write the profit made in producing one block as follows.

$$P_{mHW} = MI_{block} - EC_{block,\$} \tag{2.8}$$

The mining income is expressed in equation (2.9) as the multiplication of the block reward measured in Bitcoins multiplied by the Bitcoin price in USD.

$$MI_{block} = BTC_{reward} \times BTC_{price} \quad (2.9)$$

2.6. THERMODYNAMICS PERSPECTIVE OF BLOCKCHAIN MINING

According to the first law of thermodynamics, energy can be converted to different forms; however, the total energy stays constant in isolated systems. While energy conversion is essential for the continuation of all systems, the conversion process degrades the quality of the energy introducing inefficiencies, which can be explained via the second law of thermodynamics. The loss due to energy degradation can be calculated using exergy analysis, where exergy is measured as the "energy content of a substance relative to a specified thermodynamic ground state". Exergy analysis has emerged as a valuable tool in thermodynamics, assessing the usefulness of the energy quantity and identifying the inefficiencies that occur in the degrading process of energy conversion.

The physical capital of the mining hardware built on the ever-growing technology has only been used with its efficiency in extracting the useful exergy of the system. We use exergy analysis to develop an exergetic model for block mining by viewing the process from a thermodynamics lens. However, symbolizing and explaining an exergetic model for block mining is complex due to the abundance of varying parameters. Understanding the difference between exergy destruction due to technical specifications (i.e., thermal inefficiency) and exergy destruction due to the nature of blockchain mining technology helps us simplify the model of exergetic explanation for block mining, as shown in Figure 2.10.

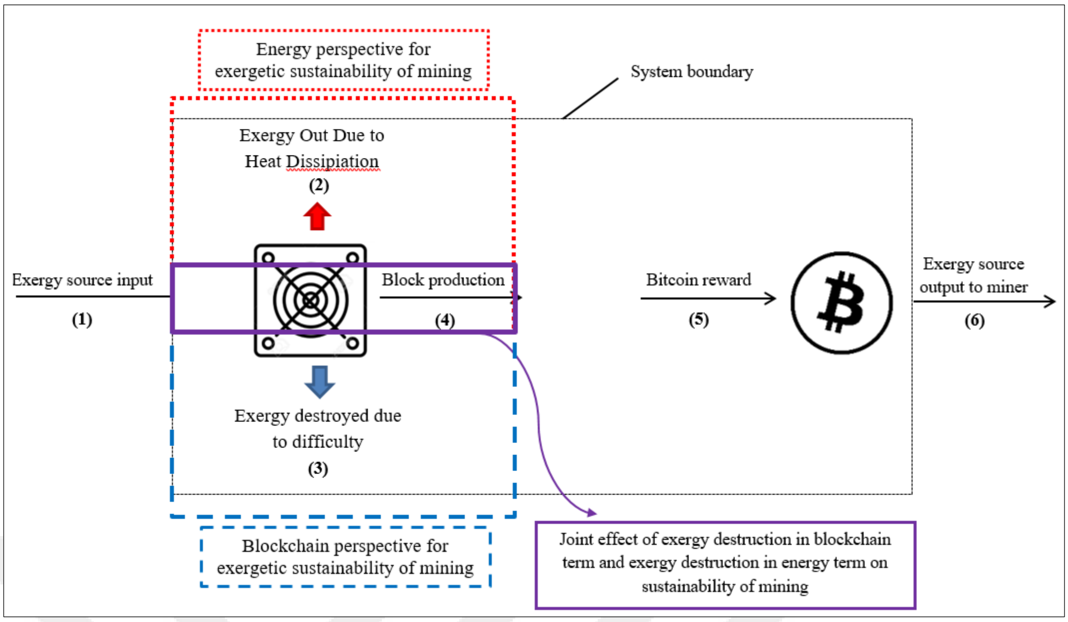

Figure 2.10. Exergetic schematic for blockchain mining

We visualize the block mining process as stages of acquiring exergy input, exergy out due to the thermal inefficiency and difficulty change in block mining, block production, rewarding in bitcoins, and exergy output released to the miner represented by numbers in parentheses in Figure 2.10. Exergy source input represented by refers to the electricity consumption of the mining hardware. The unit for electricity consumption can be either in USD or kWh depending on the calculation. Exergy destruction can occur in two different forms: due to thermal inefficiency (2) or the difficulty change in block mining (3). Stages 2 and 3 occur simultaneously.

Exergy destruction due to difficulty change in block mining (3) is one of the key aspects of understanding the exergetic sustainability of the mining process. Due to the algorithm behind the blockchain mining process, the difficulty is adjusted (via an increase or decrease in the amount of hash) to keep the mining time of one block 10 minutes. Difficulty adjustment is made in every 2016 block. As we achieve higher technologies with greater hardware efficiency, the difficulty increases as a response to this resulting in an increase in the required number of hashes to mine one block. Thus, to keep the mining process sustainable (i.e., limiting the mining time of one block to 10 minutes), the mining hardware with greater mining efficiency needs to be released in every 2016 block.

Block production represented by the number (4) refers to the achieved number of blocks resulting from the mining process. After a block is produced, bitcoin rewards are given to all miners involved in that block production at stage (5). This reward is halved in every 210.000 blocks, affecting the mining system's profitability and sustainability. The last stage in the process is the exergy source output (6), representing the most multi-disciplinary term in this assessment. It is both affected by technological improvements and bitcoin prices of its time. Using exergy analysis based on the proposed model given in Figure 3, we calculate the system's exergetic efficiency (i.e., second law efficiency). The second law efficiency of the system can be expressed as follows.

$$\mu_{II} = \frac{E_{rev}}{E_{real}} \tag{2.10}$$

Energy consumption by the actual device can be considered as the total electric consumption of the mining hardware given in equation 2.6. Energy consumption by reversible device given in the numerator of equation (10) can be written as,

$$E_{real} = E_{rev} - DED \tag{2.11}$$

The second term in equation (2.12) is the number of mining hardware required to produce one block, computed before via equation (5). *DED* in equation (2.11), the exergy destruction due to the difficulty change in block production is expressed in equation (2.14).

$$DED = EC_{mHW} \times N_{mHW}^{D} \tag{2.12}$$

The second term of the above equation represents the additional mining hardware required due to the difficulty change. Comparing the hashes needed to mine the current block relative to the hashes required for the first block, we calculate the additional mining hardware required. Here, the first block corresponds to the block mined when the hardware was first released.

$$N_{mHW}^{D} = \frac{Hash_{current} - Hash_{first}}{HC_{mHW} \times 600} \tag{2.13}$$

3. RESULTS ON EXERGETIC AND PROFIT ANALYSIS

3.1. EXPECTED PROFITABILITY OF MINING HARDWARE

We calculate the profit to produce one block for each of the mining hardware given in Table 2.1 using equation 2.2. We take into account the changing difficulty levels in selecting the days to calculate the profit. The difficulty level in Bitcoin's cryptographic algorithm is recalculated at every 2016th block, which corresponds to a period of approximately two weeks. While we consecutively sample a day for every two weeks, we increase the sampled data points as needed. When there is a significant change in the difficulty level, we take a minimum of three days from that week to clearly see the effects of change on profit. Besides, we include more data points when radical changes were observed in the price of Bitcoin during the mining period of the hardware.

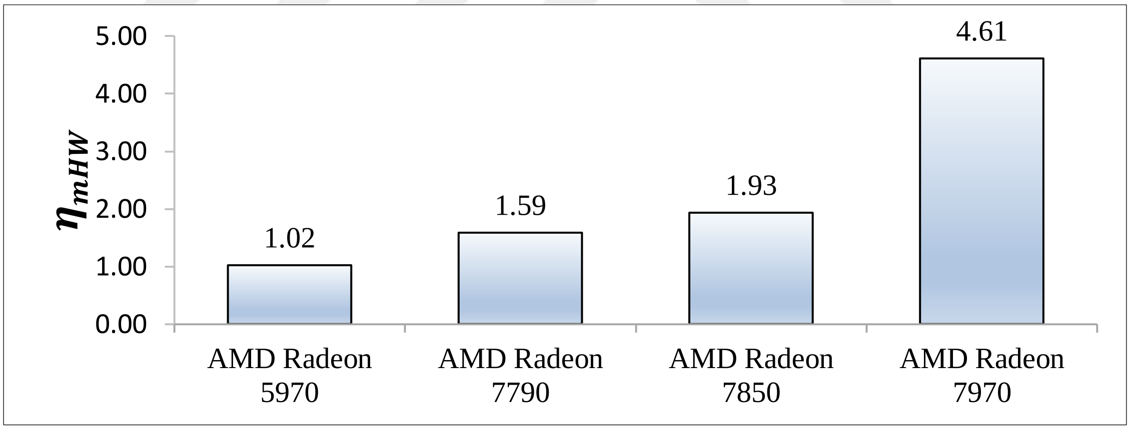

Figure 3.1. Mining hardware efficiency for investigated GPU hardware

We conduct the machine-based analysis of mining according to two eras for which the technology of the mining hardware changed significantly between these two. GPUs were the dominant technology during the first era, corresponding to the time between 2009 and 2014. The hardware efficiency for the four prominent GPUs investigated for our analyses is shown in Figure 3.1. The hardware efficiency ratios change between 1.02 and 4.61. The profitability of the machines is calculated and illustrated in Figure 3.2. The machine with the highest efficiency, AMD 7970, has the highest profitability during the specified period.

The higher the efficiency, the more efficient the mining hardware is, as reflected in the profit curves.

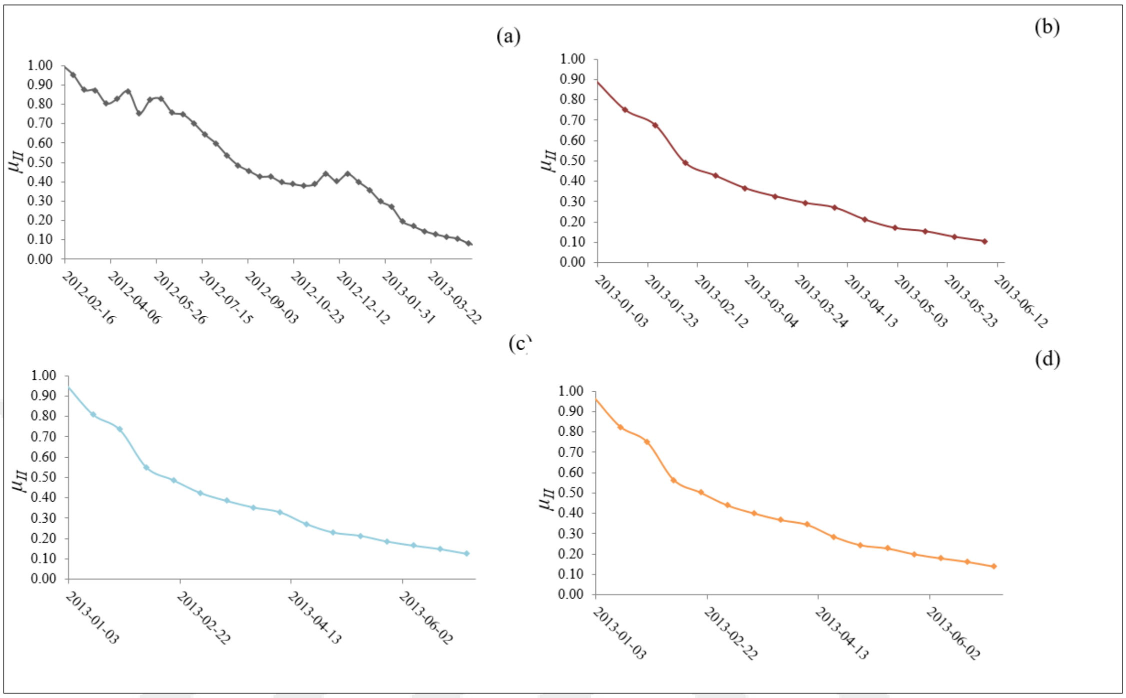

Figure 3.2. Profit over time for the investigated GPU hardware. (a) AMD 5970, (b) AMD 7790, (c) AMD 7850, (d) AMD 7970

The second era starts with the release of the first ASIC, changing miners' hardware choices completely. We analyze six different ASIC mining hardware for which the efficiencies change between 1,299 and 25,316, as shown in Figure 3.3. The associated profit plots for the valid time intervals are drawn in Figure3.4.

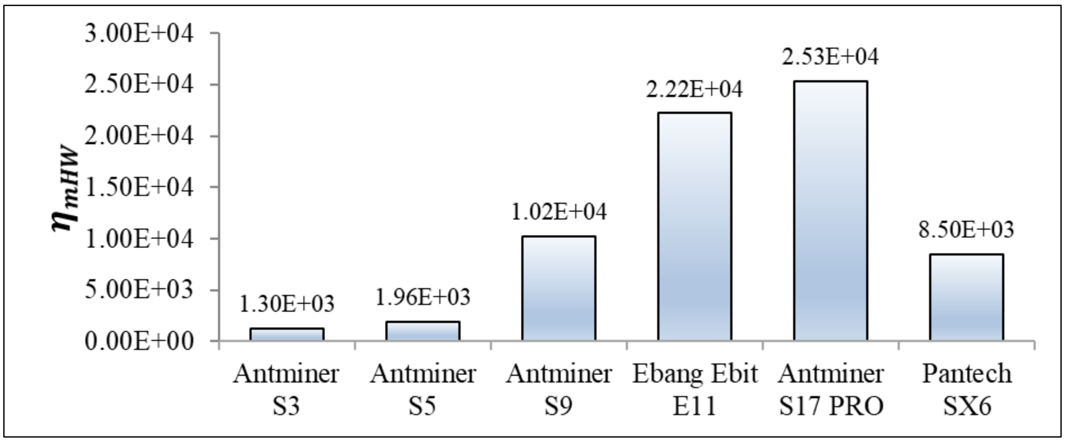

Figure 3.3. Mining hardware efficiency for the investigated ASIC hardware

The high profit made initially diminishes towards the end of the life cycle in ASIC mining hardware for Antminer S3, Antminer S5, and Ebang Ebit E11as shown in Figure 3.3. On the other hand, for Antminer S9, Pantech SX6, and Antminer S17 PRO, the profit slowly picks up, achieves the highest value, and then decays towards the end. The profit even takes negative values for some hardware. Nevertheless, the hardware that can no longer achieve positive profit leaves its place to hardware with newer technology, as can be observed from the plots of Figure 3.4.

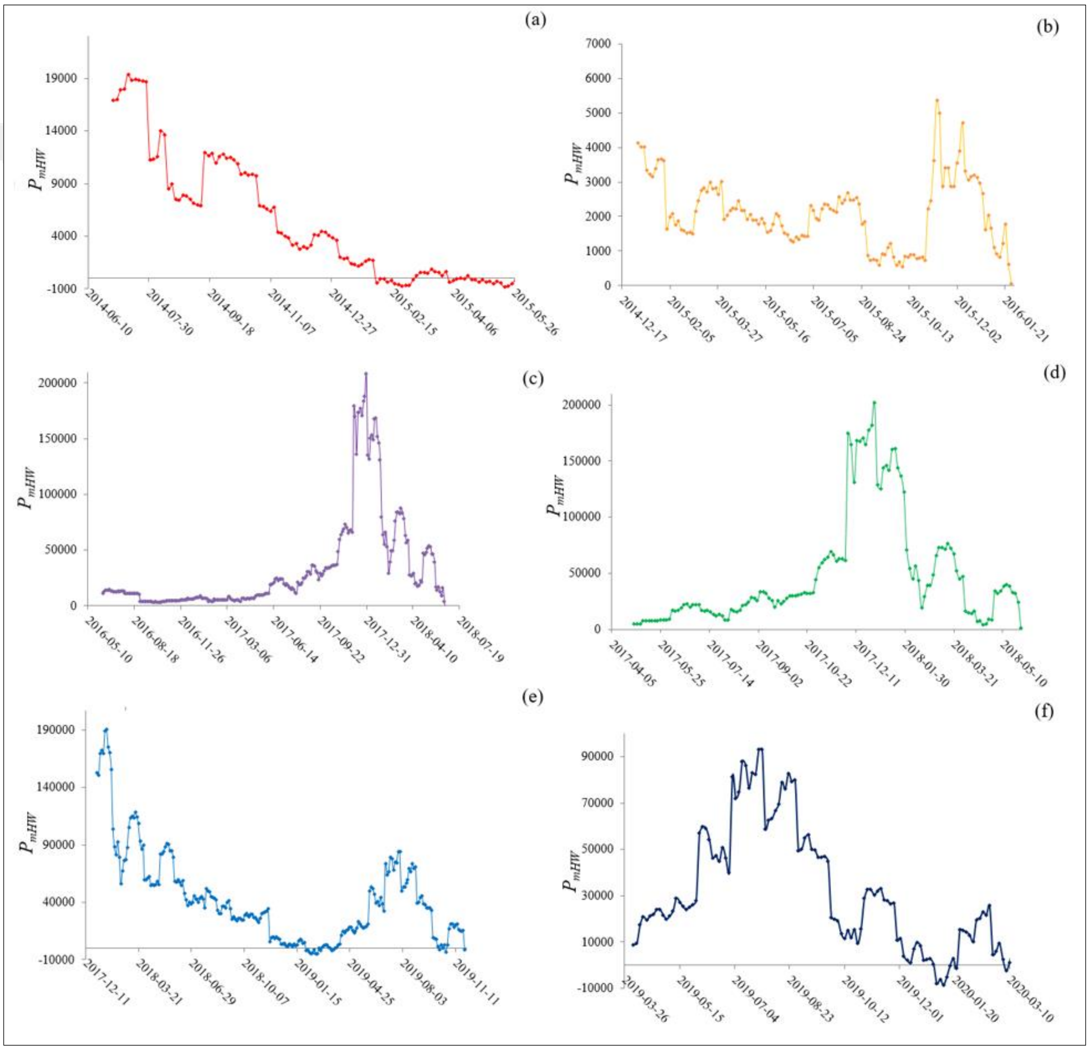

Figure 3.4. Profit over time for the investigated ASIC hardware. (a) Antminer S3, (b) Antminer S5, (c) Antminer S9, (d) Pantech SX6, (e) E Bang Ebit E11, (f) Antminer S17 PRO

3.2. THE EXERGETIC EFFICIENCY OF THE MINING HARDWARE

Exergetic efficiency, also known as second law efficiency, is used to assess energy systems in various sectors, including utility, transport, agriculture, and other industrial sectors (Flórez-Orrego et al., 2015; Hossain et al., 2020; Nielsen & Jørgensen, 2015). Exergetic efficiency, as expressed earlier, is the ratio of the energy consumption of the reversible device to the actual electric consumption of the real device. The energy consumption of the reversible device points to the case where we can deduct the exergy destruction due to the difficulty of the mining hardware reaching the theoretical maximum energy. We use exergetic efficiency computation to get an understanding of the theoretical maximum performance of an electric-consuming device. In applying the exergetic efficiency analysis to the mining hardware, we consider blockchain mining's distinctive parameters like difficulty level. In these computations, we use the difficulty level on the day the mining hardware was released as the theoretical maximum point due to the inevitable increase of difficulty level in the following days. The exergy destruction due to the difficulty increases as the difficulty level increases over time, which results in a decrease in the possible profitable lifetime of the mining hardware.

Figure 3.5 illustrates the exergetic efficiency of the GPU-based hardware. We observe the reduction in efficiency in all four cases, starting from a value in the range of approximately 0.80 to 0.90 and then hitting values close to zero efficiencies over the hardware's useful lifetime. The decaying pattern is generally similar for the ASIC-based mining hardware, as shown in Figure 3.6. However, there are some differences, such that for Antminer S3, Antimner S5, and Antimner S17 Pro, the steady-state for the exergetic efficiencies are established at around 0.20 to 0.30. Besides, the starting efficiencies are higher assuming values in the range of 0.85 to 0.95.

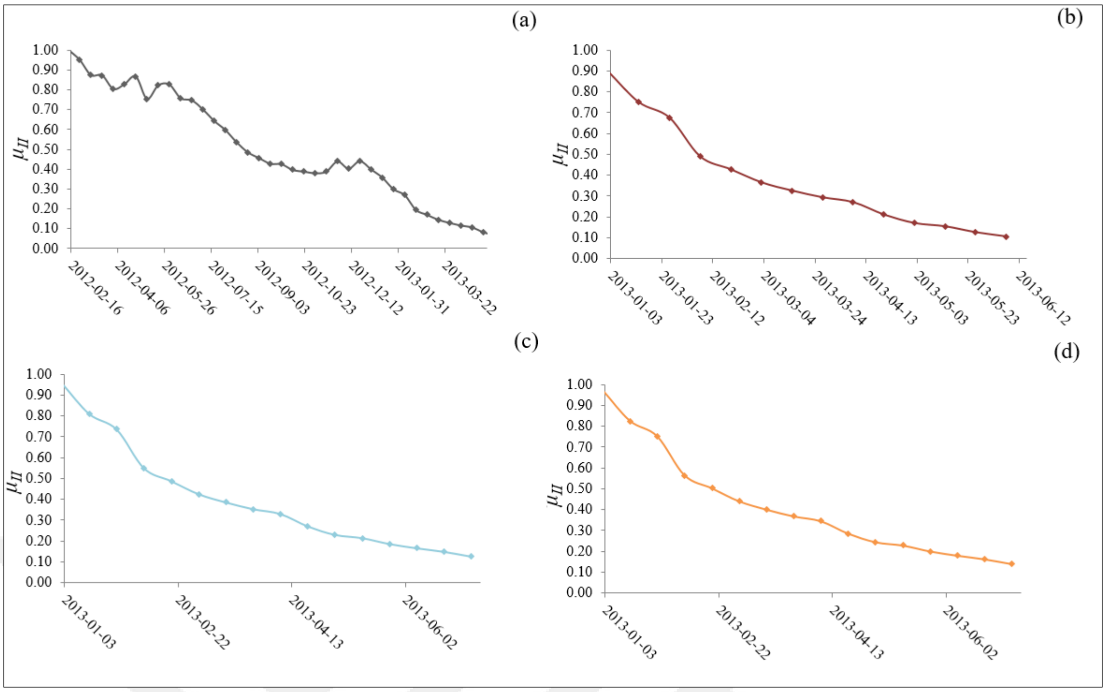

Figure 3.5. Second law efficiencies for the investigated GPU mining hardware (a) AMD 5970, (b) AMD 7790, (c) AMD 7850, (d) AMD 7970

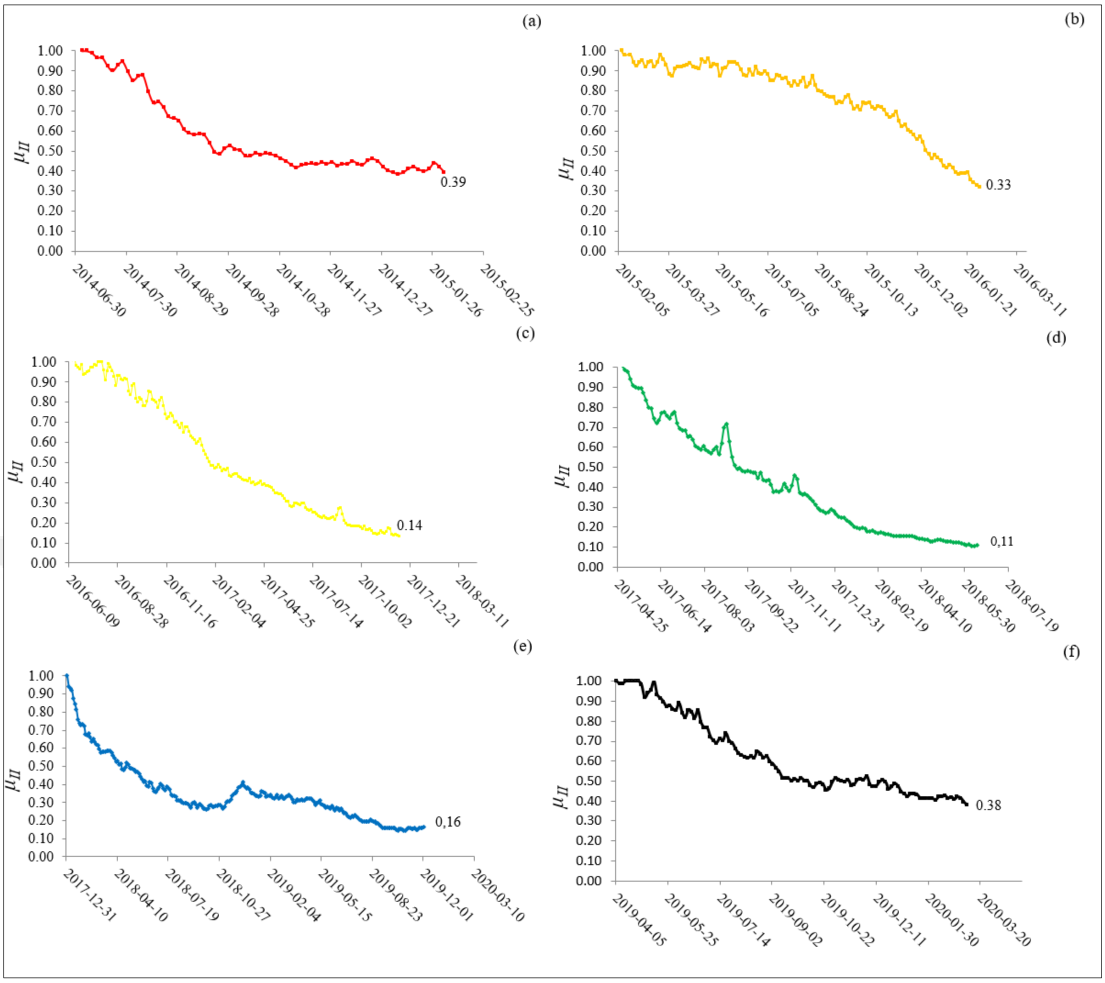

Figure 3.6. Second Law Efficiencies for the investigated ASIC mining hardware. (a) Antminer S3, (b) Antminer S5, (c) Antminer S9, (d) Pantech SX6, (e) E Bang Ebit E11, (f) Antminer S17 PRO hardware

3.3. THE SWITCHING BEHAVIOUR OF THE MINING HARDWARE FOR SUSTAINABILITY

We combine the individual profit plots of each mining hardware investigated in this study on a single plot to compare different hardware. The corresponding profit plots for GPU and ASIC mining hardware are shown in figure 3.7 To have a more holistic view of what affects the profitability plots, we also rearrange the profit equation of 2.8 by inserting the terms given via equations 2.3 to 2.7. Thus, we obtain a single equation showing all the parameters with a stake in the selected hardware's profit. In contrast, an increase in parameters that are shown in bold results in an increase in profit, the rest of the other parameters have the opposite effect.

$$P_{mHW} = BTC_{reward} \times BTC_{price} - \frac{NHR_{avg}}{HC_{mHW}} \times EC_{mHW} \times EP_{avg} \tag{3.1}$$

We consider the Bitcoin price and the average electricity price constant. The only parameters that affect the profit are the average network hash rate and the hardware's hash capability, as shown in equation (3.1). After reaching the point where profit in mining can no longer be maintained, the increase in the mining hardware's hash capability needs to be more than the increase in the network average hash rate. We call this point the "switching point," which indicates the change for better mining technology to accommodate the increase in the network hash rate and the increasing difficulty associated with mining.

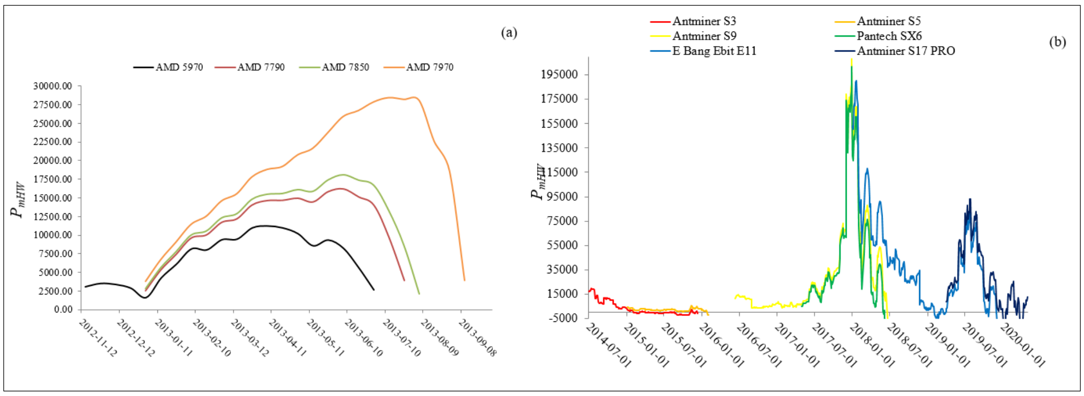

Figure 3.7. The profit overtime for all the investigated (a) GPU and (b) ASIC hardware

The figure above demonstrates the profit change for all the four GPU hardware explored in this study. The four profit plots highlight a similar concave pattern where the profits are initially low, make a peak, and eventually diminish. The highest peak profits are realized for the hardware with the highest mining efficiency. The lower the machine's mining efficiency, the sooner the profit will diminish, as shown in figure 8a, where the earliest decline in profits is achieved in AMD 5970. Hitting the lowest profit levels indicates a change in the mining hardware towards a better-performing one that could remain profitable for longer periods. As can be observed in Figure 8b, the early released mining hardware, including Antminer S3 and S5, have comparatively very low profits, which diminish to levels close to zero at the end of their life cycles. The following miners,

Antminer S9 and Pantech SX6 have similar profit patterns, where Pantech SX6, with the higher mining hardware efficiency, follows Antminer S9. Both hardware makes the highest peak of all due to the very high Bitcoin prices at the beginning of 2018. As of 2018, the newly released E Bang Ebit E11 comes into play with initially very high profits. The last version of ASIC miner, i.e., Antminer S17 PRO, becomes effective as of the second quarter of 2019 and makes the same profit as the Ebang Ebit E11during 2019. At the beginning of 2020, E Bang Ebit E1 is no longer a choice for mining, leaving space to Antminer S17 PRO. Overall, we observe similar paths of profit for all ASIC-based mining hardware. The initial high-profit levels diminish over time, which replaces the hardware with a new one that is more profitable.

While both plots in Figure 3.7 signal a switchover behavior, this behavior is more distinct in the ASIC hardware than in the GPU hardware. This could be explained by the selection of the time intervals for the two types of hardware. In our analysis of ASIC hardware, the time periods in which the hardware promise profitability was examined strictly following the dates on which the hardware was released. For GPU hardware, the exact dates when GPU hardware was released were not used. The main reason for this is that in the first years when GPU hardware was used for mining, although Bitcoin reward was high, the price of Bitcoin was low. This can mislead the observations of GPUs' long-term profitability and when to switch them. Because the primary use of GPUs is not mining and the drastic decrease in its use for Bitcoin mining over the years, the analysis of ASIC hardware is more revealing, as can be observed from the plots of figure 3.7. Besides, the ASIC hardware is specifically designed for mining and is actively used with new generations manufactured continuously. The second law efficiency perspective provides a more objective interpretation for the diminishing profits and switchovers for both hardware types. The profit paths of mining hardware can be associated with their exergetic efficiencies. Combining the second law efficiency plots for all hardware on a single plot, we obtain figures 3.8nand 3.9 for GPU and ASIC hardware, respectively.

Each hardware is effective during a certain period of time, which settles the hardware's life cycle. The consistent pattern of the decaying efficiency during the life cycle of the hardware signals for the switching timing of the hardware technology as shown for both GPU and ASIC hardware. Despite the narrow time interval that can be examined for GPU hardware, the point to switch from AMD 5970 graphics card to other graphics cards can also be observed, as shown in the second law efficiency plots.

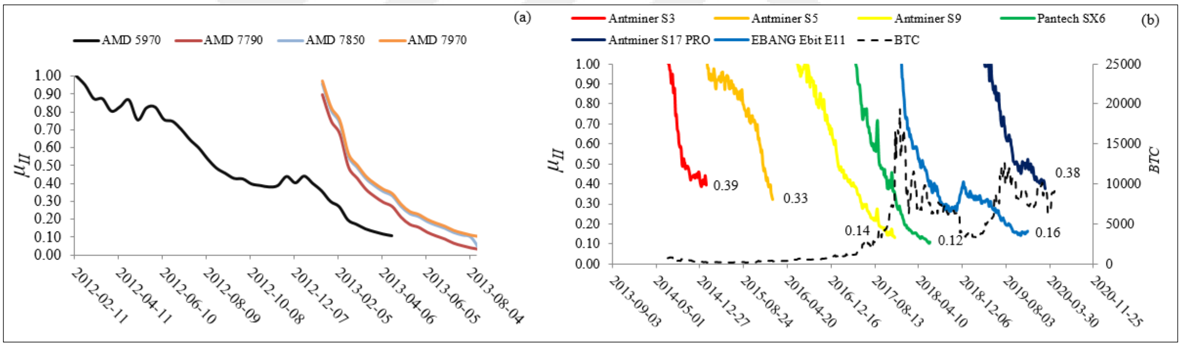

Figure 3.8. The second law efficiency over time for all the investigated (a) GPU and (b) ASIC

In section 3, detailed exergy and profit analysis are shown for ten mining hardware. A case study is done to understand these analyses better and comprehend the idea behind the analysis. This case study includes actual data taken from the historical mining data. This case study can be helpful for both a Bitcoin miner and a technology maker studying improvements of mining hardware.

3.4. CASE STUDY: ANTMINER S9 BITCOIN MINER

The key point of this case study is determining the switching point and answering the questions like; when to switch the hardware? How long will this hardware be profitable? These questions are tried to be answered in this section. Antminer S9, which is Application-Specific Integrated Circuit hardware, is chosen for this case study.

Antminer S9 is released in 2017 with a promise of 13.5 TH/s hash rate capability and power consumption of 1323 W. The second law efficiency, given in equation (2.10), graph is shown below for the Antminer S9 emerges.

As stated on the schematic in section 2, our exergy approach covers thermal losses and mining difficulty levels. For this reason, we can see in the graph that the second law efficiency increases at times. Despite this, there is a steady decline in yield, as expected. After the 7th month of 2017, efficiency decreased under 0.3 and stopped increasing. Just by looking at to second law efficiency graph, it can be said that this point is a switching point.

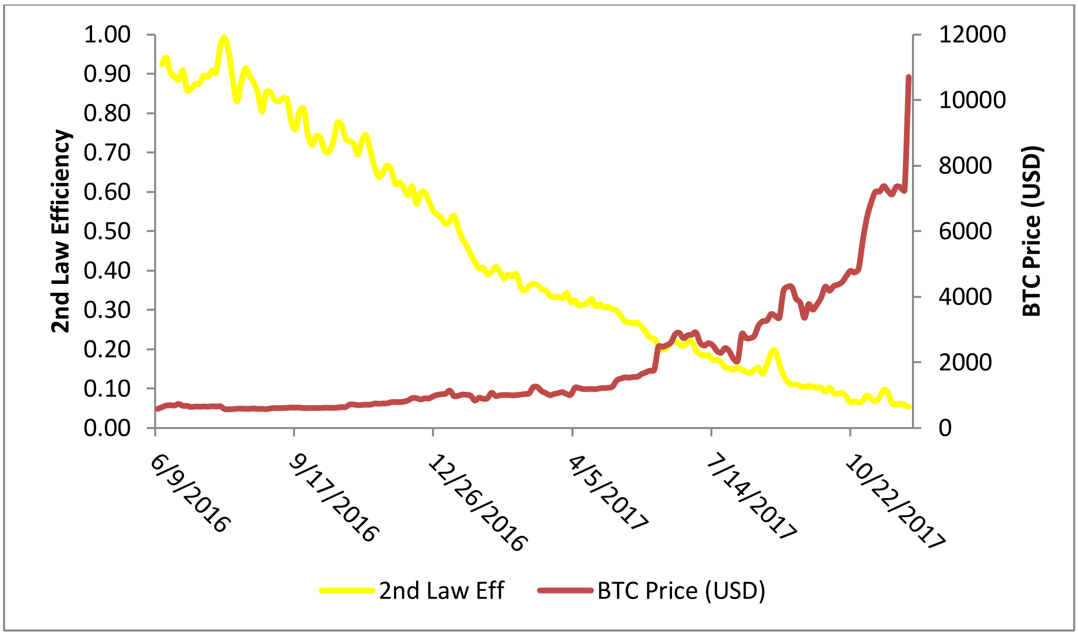

Figure 3.9. Second law efficiency and BTC price at the time of Antminer S9

At this point, mistakes can be made if the basis of exergy analysis and the concept of irreversibility is not well studied. This is why the above figure shows the change in Bitcoin price simultaneously and the second law efficiency change for Antminer S9. Because; when performing exergy analysis, predictable or calculable data such as mining difficulty are included in the equation. In the light of these data, it can be calculated how much the mining hardware can maintain its profitability if the bitcoin price drops to the minimum. However, there is no such upper limit for profitability. For this reason, it is necessary to consider the second law efficiency and the Bitcoin price according to the calculation date referenced for the second law efficiency. Antminer S9 is a perfect example of this situation.

If we get back to our graph, we can see that Bitcoin prices are increased 500 percent since the release date of mining hardware. Due to this dramatic change, even though the second law efficiency is 0.1, mining hardware can maintain its profitability.

3.5. GLOBAL ELECTRICITY EXPENDITURES AND BITCOIN MINING RELATIONSHIP

The use of electrical energy worldwide is increasing every year. Most of this electrical energy used consists of non-renewable sources. For this reason, it is not only the economic and technological side of cryptocurrency mining; The relationship between the environment and sustainability should also be examined. In this sense, the electrical energy spent for bitcoin mining around the world between 2013 and 2019 was investigated. Since blockchain technology is not decentralized in itself, some assumptions were used to approximate the consumed electrical energy. The first assumption made in this regard was on the mining hardware used.

Investigated mining hardware can be seen in Table 3.1. Since it is difficult to collect reliable data on historical mining hardware, at least three different types of mining hardware were selected for each year. While making these choices, sales figures, accessibility, and hash rate capacity criteria were considered. Among the hardware examined, there are 8 CPUs, 16 GPUs, and 11 ASIC-type hardware.

Then, research was conducted on which types and brands of hardware are used and how often they are used around the world, and the electricity consumption for the quarter of the year is calculated by making assumptions about what percentage of the hashes are currently made. Then what device could it be from?

Table 3.1. Investigated mining hardware

Hardware Model	Hardware Type
Intel Xeon E5530 2.40GHz	CPU
Intel Core i7 950	CPU
Intel Core i7 920	CPU
Intel Atom D510	CPU
ATI Radeon 5830	GPU
ATI Radeon 5870	GPU
ATI Radeon 5970	GPU
Nvidia Tesla S2070	GPU
Intel Atom N450	CPU
ATI Radeon 6870	GPU
ATI Radeon 6950	GPU
ATI Radeon HD 6970	GPU
Intel (Core i7-2760QM)	CPU
Intel (Core i7 3930K)	CPU
ATI (Radeon 6990)	GPU
ATI (Radeon HD 6990)	GPU
ATI (Radeon 5770)	GPU
Nvidia (GTX 670)	GPU
ATI (Radeon 7970)	GPU
AMD ATI Radeon 7870 XT	GPU
Intel (Xeon Phi 5100)	CPU
ATI (Radeon HD 7990)	GPU
Nvidia (GTX 770)	GPU
Canaan (Avalon 1)	ASIC
AMD Radeon R9 290	GPU
Bitmain (Antminer S3)	ASIC
Canaan (Avalon 3 2U)	ASIC
Bitmain (Antminer S4)	ASIC
Bitmain (Antminer S5)	ASIC
Bitmain (Antminer S9)	ASIC
Aladdin Miner	ASIC
Bitmain (Antminer S9K)	ASIC
Bitmain (Antminer S17)	ASIC
Bitmain (Antminer R4)	ASIC
Bitmain (Antminer S17+)	ASIC

After calculating the electricity consumption for Bitcoin mining every quarter of years, these data compared with global electricity consumption. The total electrical energy consumed worldwide and at the same time how much of this energy is renewable were taken from the sources and included in the comparison.

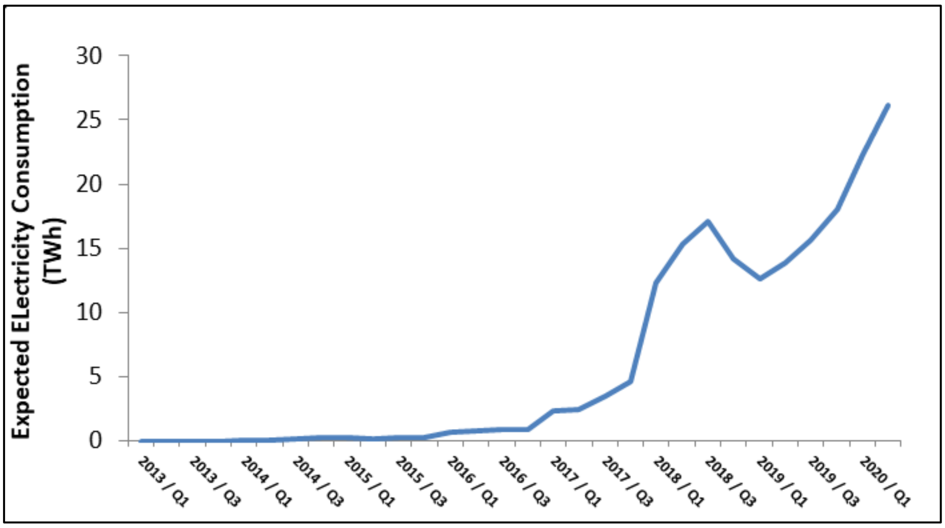

Figure 3.10. Expected electricity consumption for Bitcoin mining in 7 years

From Figure 3.10, it is clear that electricity consumed for Bitcoin mining increases dramatically. Thanks to technological improvements, we can observe a decrease in consumption only for the first quarter of 2019. However, it did not take long for Bitcoin's difficulty to increase and result in higher electricity consumption.

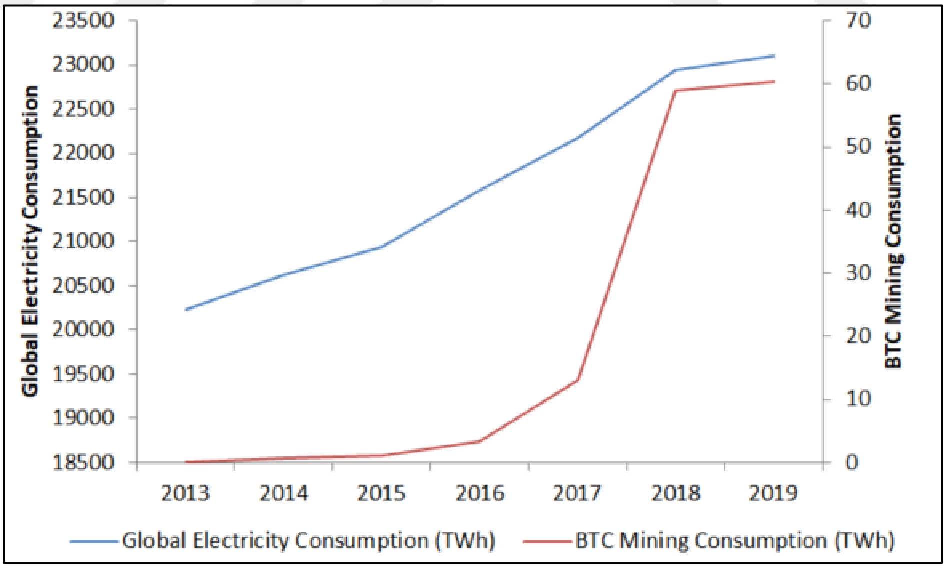

Figure 3.11. Electricity consumption comparisons; global vs. BTC Mining

From Figure 3.11 dramatic increase in electricity consumed by Bitcoin mining can be seen clearly. Just looking at this graph, it can be said that in Bitcoin mining, miners and technology makers should consider profit and sustainability.

Table 3.2. Electricity consumptions

Year	Global Electricity Consumption (TWh)	Renewable Energy Consumption (TWh)	BTC Mining Consumption (TWh)
2013	20236	4857	0.008
2014	20616	4948	0.6
2015	20942	5236	1.0
2016	21585	5396	3.3
2017	22171	5321	13.0
2018	22949	5967	58.9
2019	23105	6238	60.3

By using the values from table 3.2. it can be said that if miners or technology makers do not take action about the sustainability of mining, these consumption values will increase rapidly. While the energy spent for Bitcoin mining was 0.06% of the global energy expenditure in 2017, this rate has increased to 0.26%, or 4.4 times, in just two years.

A more worrying picture emerges when the renewable energy resources consumed globally are compared with the electrical energy spent on bitcoin mining. The 60 TWh of electrical energy spent only for Bitcoin mining in 2019 corresponds to 1% of the renewable energy consumed globally. To explain the numbers more concretely, some of the countries in the world that consume less electricity than the electricity used for Bitcoin mining are as follows: Switzerland, Kuwait, Greece, Algeria, Israel, Bangladesh, Romania, Uzbekistan, Singapore, Portugal, Peru, Hong Kong, New Zealand. Only 43 of the 218 well-known countries in the world consume more electricity than bitcoin mining. With this level, Bitcoin ranked 44th in the world ranking.

During the electricity consumption calculations, the unit price for electricity is accepted as 0.14 USD per kWh. To achieve this number, different electricity unit prices are gathered from 147 countries. Averages of these electricity prices from 147 countries are used. Prices can be seen in Figure 3.12.

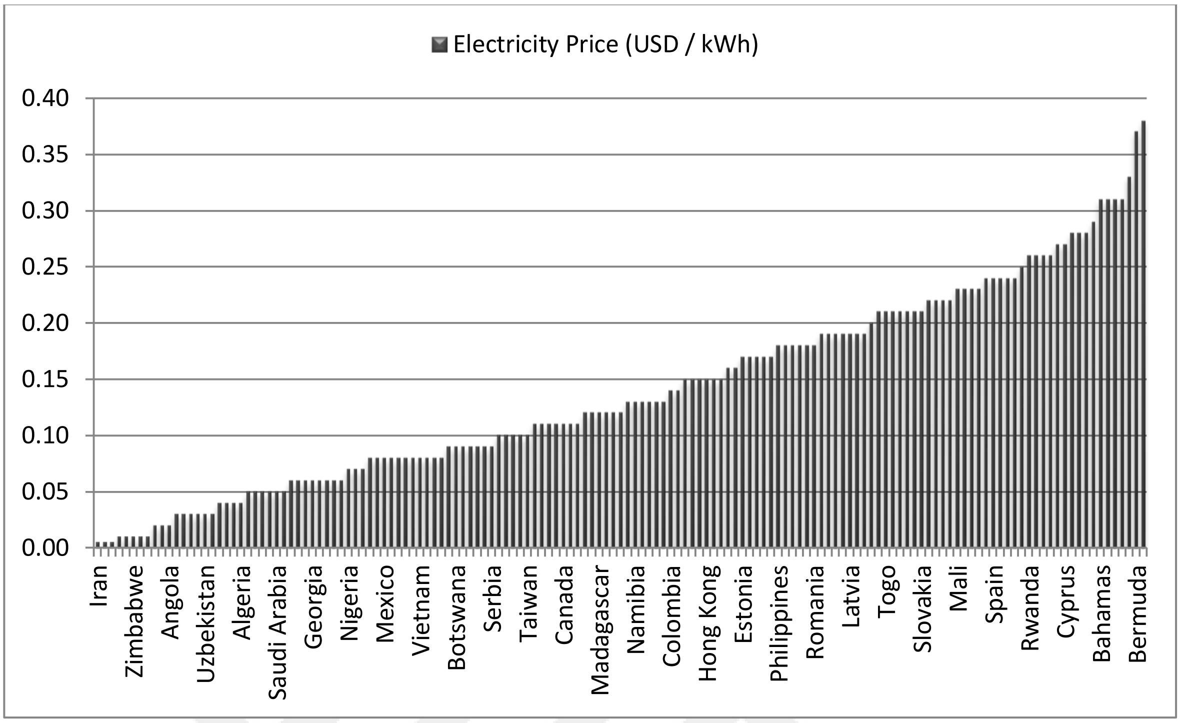

Figure 3.12. Electricity unit prices for different countries

4. DISCUSSION

After the emergence of Bitcoin in 2009 and other cryptocurrencies that followed, the crypto market began to take its place in the world in every sense. Especially after the market value of Bitcoin started to increase continuously after 2012, researchers from many different fields started to focus on the subject. One of the issues that received the most attention was the impact of the crypto money market on global energy expenditure and its impact on technology. With the annual electricity spent for Bitcoin mining exceeding the annual electricity expenditure of many countries worldwide, this issue has entered the radar of researchers and country leaders. Studies conducted until today have always focused on the annual electricity and the profitability of mining. This perspective prevented it from making a significant contribution to the analysis of the sustainability of Bitcoin mining.

In order to better understand the sustainability of mining and create an engineering-based infrastructure, we decided to approach the issue from a thermodynamic perspective. In this context, it became necessary to choose different types of mining hardware. For the selection of this hardware, the so-called mining hardware efficiency; The definition was used, which provides the opportunity to compare the efficiency of the hardware among themselves. Although the future of mining is basically in ASIC hardware, GPU hardware is also included due to individual GPUs in mining today. The second law-based exergy approach used for thermodynamic thermal efficiency was used for the first time in this research to define efficiency in cryptocurrency mining. Thanks to this approach, the loss of potential energies of the hardware, which are due to thermal inefficiencies, and the SHA-256 algorithm, which forms the basis of Bitcoin mining, can be calculated numerically. When this second law efficiency approach was applied from the time the hardware was first introduced to the day they started to become unprofitable, we saw that there is a correlation between. This correlation contains important clues about when the device used in the mining process should be replaced. Although some assumptions were made about the purchase price of the hardware and the time of sale of the mined Bitcoin in the research, it can be said that it is an essential resource for both miners and companies producing mining hardware

5. CONCLUSION

Within the scope of this research, we checked the accuracy of our hypothesis by making some assumptions about cryptocurrency mining. In this research explicitly made for Bitcoin, the concept of "sustainability," which has been unfortunately ignored, was tried to be highlighted, considering not only the profitability of cryptocurrency mining but also the second law efficiency. In addition, it was tried to find answers to the questions that all crypto money miners seek answers in the light of scientific methods. The most important of these is when to change the mining hardware he uses. The second question is what should be the reference of the parameters to be considered when changing the device.

As a result of the research, it can be said that when mining hardware should be changed, it should be connected to parameters independent of Bitcoin price as much as possible. Because if the Bitcoin price rises, a device that seems profitable and efficient actually causes the miner to lose potential gains in the long run and harms the sustainability of mining at the macro level. Exergetic analyzes based on the second law perspective of thermodynamics should be used to determine the point where this device, which we call the switching point, is changed. As a result of these analyzes; Not only the profitability in dollar terms but also the determination of the interval in which the second law efficiency of the device is constantly decreasing is of great importance. When this range is reached, it is necessary to switch to more efficient hardware on the market. But at this point, it is important to examine the word "efficient". Just because a device draws less electricity does not mean it is more efficient. For this, we call mining hardware efficiency; it is important how much hash can be made with 1 watt of energy. Higher mining hardware efficiency means more efficient hardware.

In addition, the second law efficiency of the new hardware should be calculated by making certain assumptions. These assumptions should cover the following three important parameters; last three months' difficulty level change, network average hash rate, and thermal efficiency of the hardware. If these methods are appropriately adapted to cryptocurrency mining, electricity consumption due to inefficient devices and faulty policies will be reduced. Considering that the global electricity consumption of Bitcoin mining is higher than in many countries, this approach should lead not only miners but also everyone working in the field of energy and exergy.

6. FUTURE WORK

In this study, the last annual records of Bitcoin's economic and mining data were used. Many other cryptocurrencies work similarly to Bitcoin's mining algorithm. This approach can be applied to many other cryptocurrencies such as Ethereum, litecoin, with some minor modifications. The other cryptocurrencies mentioned generally have more stable mining device development as they emerged after the CPU, GPU, and ASIC evolution that bitcoin has undergone. For this reason, the methods used in the research are likely to yield more meaningful results in the cryptocurrencies mentioned.

In addition, since our research includes Bitcoin before 2016, which is challenging to analyze and obtain accurate data, the initial purchase prices of the hardware are not taken into account. If a narrower range is scrutinized in further research, the initial purchase prices, cooling costs, and potential hardware failure rates to be used in the calculations can also be added to the equation.

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APPENDIX: SAMPLE CALCULATIONS

To explain our calculation methods and approach better, sample calculations are done for a randomly chosen day. By using our equations; electricity consumption of mining hardware and profit data are calculated for block in that chosen day.

Ebang Ebit E11 mining hardware is chosen for the date March 24, 2018. Historical data and mining hardware specifications for that day can be seen below;

- Network Hashrate (TH/sec) = 24537112
- Difficulty = 3.00738E+12
- Bitcoin Price (USD) = 3812
- Bitcoin Reward = 12.5
- Hardware Hashrate (TH/sec) = 44
- Electricity Consumption (kW) = 1.98
- Electricity Price (USD/kWH) = 0.14

By using equation 2.3 required hashes to mine one block at that time can be found;

$$24537112 \times 600 = 14722267200 \text{ TH}$$

Processing time can be found by equation 2.4;

$$\frac{14722267200}{44} = 334{,}596{,}982 \sec = 92944\ hrs$$

Electricity consumption to mine that block can be found by equation 2.6;

$$1.98 \times 92944 = 184029\ kW$$

Electricity consumption in USD can be found by equation 2.7;

$$184029 \times 0.14 = 25764 \text{ USD}$$

Mining income can be calculated by using equation 2.9;

$$12.5 \times 3812 = 119409 \text{ USD}$$

Profit can be calculated by using equation 2.8;

$$119409 - 25764 = 93645 \text{ USD}$$

For our chosen sample calculation block, Bitcoin miner in profit of 93645 USD.

Sample calculations for exergetic analysis are not shown in detail due to high number of data. For exergetic analysis a reference date was needed to be chosen which is accepted as reversible device. In our assumptions reversible device is chosen as the first day of the mining hardware.

For chosen mining hardware Ebang Ebit E11, difficulty in first day is 1.92258E+12. And for the date which we make our sample calculations, difficulty is 3.00738E+12. Increase in difficulty is 56 percent. So this difficulty change directly affects the average network hashrate.

The average network hashrate at the reversible device is 15314207 TH/s. And at the sample calculation date, average network hashrate is 24537112 TH/s. Increase in average network hashrate is 38 percent and difference is 9222905 TH/s. This difference is the source of our Difficulty Exergy Destruction (DED). By using difference in average network hashrate, spent electricity due to difficulty change can be found.

Processing time can be calculated by using equation 2.15;

$$\frac{9222905 \text{ x } 600}{44\ x\ 3600} = 34936\ hrs$$

Electricity consumed in;

$$34936\ x\ 1.98\ = 69174\ kWh$$

69174 kWh electricity consumed per block due to difficulty increase.

So, second law efficiency can be found by equation 2.10;

$$\frac{184029 - 69174}{184029} = 0.62$$