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Bachelor thesis

2020 **Markéta Pěnkavová**

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Dynamics of Bitcoin mining profitability and its break-even electricity costs

Bachelor thesis

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Abstract

The aim of this thesis is to investigate the Bitcoin mining profitability throughout the years 2014 to 2020 with the focus on the year 2020. The analysis is based on the break-even electricity price estimates which are obtained by using a set of variables entering the Bitcoin mining process such as the block reward, transaction fees, network hash rate or power consumption. The calculations are performed under the assumption that miner owns the most efficient mining hardware available at the time while disregarding the original investments in the necessary hardware.

To further examine the relationship between the estimated break-even electricity price and the Bitcoin market price the cointegration analysis is performed employing a vector error correction model as the series seem to be nonstationary. The final results illustrate the substantial effect the Bitcoin market price has on the break-even electricity price estimates to the extent that there is rather long-term reaction in the break-even electricity price values to the shocks in the Bitcoin market price.

The findings from the research offer insights to the Bitcoin mining process suggesting that an access to extremely low electricity prices is needed to earn any profits from the Bitcoin mining activity in 2020.

Keywords

Analysis, Bitcoin, Bitcoin mining, Cryptocurrency, Profitability

Abstrakt

Cílem této práce je prověřit ziskovost těžby Bitcoinu v průběhu let 2014 až 2020, s důrazem na rok 2020. Tato analýza je postavena na hodnotách rovnovážné ceny elektřiny, získaných pomocí proměnných, které mají vliv na proces těžby Bitcoinu. Mezi hlavní použité proměné patří odměna za blok, poplatky spojené s transakcemi, hash rate sítě nebo spotřeba elektřiny. Veškeré výpočty jsou prováděny za předpokladu že těžaři vlastní nejefektivněší hardware dostupný na trhu v danou dobu. Zároveň jsou opomenuty původní investice do vybavení nutného k těžbě.

K následnému popsání vztahu mezi vypočítanou rovnovážnou cenou elektřiny a cenou Bitcoinu je, pro nestacionaritu dat, použita kointegrační analýza za využití vektorového modelu korekce chyb. Finální výsledky ukazují výrazný efekt, který má cena Bitcoinu na hodnoty rovnovážné ceny elektřiny. Dále je zde vidět dlouhodobá reakce rovnovážné ceny elektřiny na potenciální šoky v hodnotách ceny Bitcoinu.

Poznatky z výzkumu blíže vysvětlují proces těžby Bitcoinu a vedou k závěru, že pro ziskovost těžby v roce 2020 by bylo nutné mít přístup k extrémně nízkým cenám elektřiny.

Klíčová slova

Analýza, Bitcoin, Těžba Bitcoinu, Kryptoměny, Ziskovost

Declaration of Authorship

I hereby proclaim that I wrote my bachelor thesis on my own under the leadership of my supervisor and that the references include all resources and literature I have used.

I grant a permission to reproduce and to distribute copies of this thesis document in whole or in part.

Prague, 27 July 2020

Signature

Acknowledgment

I would like to express my appreciation and gratitude to prof. PhDr. Ladislav Krištoufek, Ph.D. His valuable guidance and support had helped me immensely during the writing of the thesis.

I would also like to thank him for the time spent on the reading of the thesis and for suggesting feasible improvements.

Bachelor's Thesis Proposal

Institute of Economic Studies
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Author's name and surname: Markéta Pěnkavová

Supervisor's name: doc. PhDr. Ladislav Krištoufek Ph.D.

Notes: Please enter the information from the proposal to the Student Information System (SIS) and submit the proposal signed by yourself and by the supervisor to the Academic Director ("garant") of the undergraduate program.

Proposed Topic:

Is bitcoin mining still profitable in 2019?

Preliminary scope of work:

Research question and motivation

The main research question I intend to focus on is whether bitcoin mining is still profitable in 2019.

Bitcoin mining has become rather popular during the last two years among cryptocurrency enthusiasts as the volatile price of bitcoin started declining and therefore it became less likely to gain return from investing in bitcoin by purchasing it. Hence many individuals became interested in making profit by bitcoin mining and the population of so-called "miners" began to expand. However, the more people would start mining bitcoin, the more difficult it would be to earn any significant profit as there would be higher competition.
This resulted in people in the filed of interest considering the advantages along with disadvantages of different types of bitcoin mining. Consequently, pool mining gained popularity as it appeared to be most beneficial. But it becomes challenging for a new miner to decide the pool he must join such that the profit is maximized. (M. Salimitari, M. Chatterjee, M. Yuksel and E. Pasiliao 2017) Furthermore, Meni Rosenfeld also focuses on this topic and describes the various scoring systems used to calculate rewards of participants in Bitcoin pooled mining. (Meni Rosenfeld 2011)

The topic of bitcoin mining profitability throughout the years 2012-2016 was discussed in a research paper published in *Electronic Markets* with results showing that bitcoin mining has become less profitable over time to the extent that profits seem to converge to zero. (Jona Derks, Jaap Gordijn and Arjen Siegmann. August 2018) This suggests that bitcoin mining might not generate any significant profit in the upcoming years. Therefore, in my thesis, I would like to follow up on their research by focusing on specific numbers concerning the year 2019 while discussing whether it could pay off to get into the bitcoin mining business at this time and if so, under what circumstances.

Contribution

The question of bitcoin mining profitability was a subject to research in the previous years – a general research was conducted, concerning bitcoin mining profitability in the years 2012-2016 (Jona Derks, Jaap Gordijn and Arjen Siegmann. August 2018), while others focused particularly on profit maximization for bitcoin pool mining (M. Salimitari, M. Chatterjee, M. Yuksel and E. Pasiliao 2017) and analysing bitcoin pooled mining reward systems. (Meni Rosenfeld 2011)
Overall, the existing literature focuses on the topic of bitcoin mining profitability during the past years. Thus, I will be analysing this question as for the year 2019 by which I will be extending the previous research and bringing up to date information to the debate.
In practice the research would contribute additional details to the discussion on the topic of bitcoin mining and its potential profitability.
Moreover, the research will provide specific data showing whether bitcoin mining is a sustainable way of generating profit in the year 2019 or whether it tends to be rather loss-making.

Methodology

I plan on constructing a multiple regression model in which the bitcoin mining profitability would be an explained variable while hash rate, bitcoin reward per block, mining difficulty, electricity cost, power consumption, pool fees, hardware prices, bitcoin's price and difficulty increase per year would be the explanatory variables.
Then I would examine how does each explanatory variable affect the bitcoin mining profitability and what could be possibly done to maximize the mining profits. Furthermore, I plan on inspecting the possibility of decreasing electricity costs in the long term by acquiring the electricity from renewable sources, a purchase of solar panels for instance.
As for the hypotheses, I intend to test whether the intercept in the multiple regression model could be equal to zero. Also, I would address the estimated coefficients in the model.
I will base my results on dataset constructed from data collected on sites: data.bitcoinity.org www.blockchain.com and www.quandl.com

Outline

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Conclusion
1. Conclusion on the results
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3. Suggested topics for further research

List of academic literature:

Arvind Narayanan, Joseph Bonneau, Edward W. Felten, Andrew Miller, Steven Goldfeder and Jeremy Clark. 2016. „Bitcoin and Cryptocurrency Technologies“ Book published by Princeton University Press

Jona Derks, Jaap Gordijn and Arjen Siegmann. „From chaining blocks to breaking even: A study on the profitability of bitcoin mining from 2012 to 2016“ *Electronic Markets* Research Paper. August 2018. Volume 28, Issue 3, pp 321–338

Joshua A. Kroll, Ian C. Davey and Edward W. Felten 2013 "The Economics of Bitcoin Mining, or Bitcoin in the Presence of Adversaries" Princeton University Senior Thesis

Mehrdad Salimitari, Mainak Chatterjee, Murat Yuksel and Eduardo Pasiliao 2017 "Profit Maximization for Bitcoin Pool Mining: A Prospect Theoretic Approach" published by 2017 IEEE 3rd International Conference on Collaboration and Internet Computing (CIC)

The Goldman Sachs Group, Inc. „All About Bitcoin“ *Global Macro Research, Top of Mind* March 11, 2014. Issue 21.

Meni Rosenfeld. 2011. „Analysis of Bitcoin Pooled Mining Reward Systems“ Academic Paper

Jonathan Berk and Peter DeMarzo, Stanford University. 2017. „Corporate Finance“ 4th Edition. Book published by Pearson

Contents

Introduction

Over the last few years many cryptocurrencies had emerged as the topic of digital currency became more relevant and desired. One of those being Bitcoin, the first decentralized cryptocurrency which was developed by an individual or possibly a group of people operating under the pseudonym Satoshi Nakamoto (Nakamoto 2008). The Bitcoin came into public knowledge in January 2009 when its source code was released as an open-source while the main ideas behind it were closely described in the original white paper. published in October 2008. It could also be said that Bitcoin is the most popular and well-known cryptocurrency as it was the first one to arise.

Bitcoin is a decentralized digital currency operating on peer-to-peer network. It uses a proof of work system when each transaction is verified by a group of nodes and it is then recorded and stored at distributed transparent ledger called blockchain. To ensure security, Bitcoin is encrypted by SHA-256 hash function which is one of six cryptographic hash functions belonging to the SHA-2 family. The legitimacy of transactions in the system along with the possession of a set amount of bitcoin is guaranteed by digital signatures (Nakamoto 2008). Each participant in the network has their own private key and public key while the digital signature of the partaker is generated by function whose output depends on both the particular transaction and the private key. Then the signature is verified by another function which uses the transaction details. the signature it aims to verify, and the public key in order to confirm the authenticity of the digital signature. Due to this mechanism everyone is protected from potential attempts of forging their digital signature as it should be impossible to find valid signature without the private key. As Bitcoin functions on a transparent distributed ledger where each transaction is recorded with its own ID containing a time stamp it protects the system from the double spending problem. Therefore, Bitcoin is able to operate as a trustworthy decentralized currency with no necessity to have a central authority.

The crucial role of verifying transactions in the Bitcoin network belongs to so-called "miners" who also then store the confirmed transactions on the distributed ledger. These miners devote attention to the latest broadcasted transactions in the system, then they inspect their authenticity and collect them into a new block which is then added into the blockchain. It could be said that the process of generating new bitcoin and contributing new units into the circulation is called mining as with each new block successfully added into the blockchain miner receives a reward in a form of new bitcoin units. To add the upcoming block to the blockchain the miner aims to find a solution to a complex mathematical puzzle while the likelihood of obtaining the correct answer closely depends on the computing power of the mining computer. When the accurate solution to the puzzle is guessed a reward in a form of certain amount of bitcoin is provided to the miner (Kroll, Davey, Felten 2013). This is referred to as a block reward. Also, with a mined block a miner receives a transaction fee for each transaction in this block (Nakamoto 2008) while the size of the transaction fee depends on the size of the transaction. This creates an incentive for the nodes to support the system by acting honestly instead of trying to cheat as the network is set in such way that it ought to be more profitable for the node to play by the rules (Nakamoto 2008). Furthermore, it results in a situation when new coins are added into the circulation without any central authority. However, there is a limited pre-set amount of bitcoin. The supply limit is 21 million bitcoin and according to Quandl[1], at the beginning of the year 2020 there were only approximately 2.9 million bitcoin left to be mined. Furthermore, Bitcoin is subject to a halving system when the block reward is cut in half after every 210 000 newly mined blocks (approximately every 4 years). The original block reward associated with the mined block was 50 BTC however, it has already been cut in half three times as of the spring 2020. The first halving was experienced on November 28 in 2012 when the block reward was reduced from 50 BTC to 25 BTC, then on July 9 in 2016 it was halved again, at that

[1] at `https://www.quandl.com/data/BCHAIN/TOTBC-Total-Bitcoins`

time from 25 BTC to 12.5 BTC. Most recently, the block reward was subject to halving on May 11 in 2020 as it dropped to 6.25 BTC. As Nakamoto (2008) states in the original white paper, at the time when all the coins have been mined the system becomes inflation free and the incentive will shift only to transaction fees. This is anticipated to occur in the year 2140, as stated by Meynkhard (2019) in his work on the fair market value of Bitcoin and the halving effect. Moreover, Meynkhard (2019) comments on the halving effect by proclaiming that *"Constant reduction of bitcoin issuance by 50 percent every four years leads to the reduction of bitcoin inflation"*, then clarifying that Bitcoin inflation is expected to gradually decrease up to insignificant numbers closely approaching zero in the upcoming years (by 2037 inflation is expected to be less than 0.1% and by 2053 the inflation rate would diminish to an negligible level), highlighting the Bitcoin advantage compared to fiat currencies.

As it will be further discussed later on in this thesis, Bitcoin tends to be very volatile in its price. Derks, Gordijn and Siegmann (2018) proclaim that *"the overall volatility of the bitcoin price makes it an unreliable unit of account"*. Moreover, its price volatility resulted in Bitcoin not being a very reliable store of value and it might be considered a higher risk investment. This makes it rather challenging to estimate potential profits it could bring to an individual interested in investing in Bitcoin or even participating in the network as potential miner.

This thesis will closely look at the situation behind Bitcoin mining throughout the years of 2014 to 2020 while it will focus on its profitability. First, it will review the research conducted on this topic. Then, using data from the course of the years 2014-2020 it will analyse whether it would still be beneficial for an individual to pursue Bitcoin mining in the year 2020 based on the estimates of the break-even electricity price. Then also analysing various models of mining hardware and the potential profitability resulting form a use of specific hardware. Followed by a cointegration analysis using time-series data examining the relationship between the estimated break-even electricity prices and the Bitcoin market price.

This bachelor thesis is organised as follows. To begin with, it will review the previous research along with related ideas from the existing literature concerning the examined issue. It will explore the evolution of Bitcoin mining in outline and after that it will shift its focus to the different viewpoints on the profitability of Bitcoin mining during the previous years and to the various factors affecting its extent. Then, in the methodology section, the data set utilised for the research would be described and this thesis would introduce the variables affecting the profitability of Bitcoin mining while the focus would be on estimating the break-even electricity prices. Consequently, there would be a discussion on the estimated numbers and possible mining profitability in 2020. Then, the focus would shift to the cointegration analysis using the estimated numbers on the break-even electricity price along with values on the Bitcoin market price. Subsequently, the next part of this bachelor thesis would be dedicated to comments on the output from the performed tests followed by interpretation of the results and their further clarification. To conclude the thesis, the results would be summarized and their meaning in practice would be commented on. Lastly, there will be feasible proposed issues that might be suitable for potential further research.

1 Theoretical background and literature review

Bitcoin mining happened to be the focus of numerous research papers since its beginnings. Some of which discussed the extent of its profitability and how it was changing over time. There are several factors that have notable impact on the profitability of Bitcoin mining, those will be closely described and analysed further on in this paper. To understand the situation of Bitcoin mining along with its cost-effectiveness in the year 2020, in this section this paper will briefly describe the evolution of Bitcoin mining since its beginnings as it was illustrated in the relevant literature. Then, its focus will shift to the previous research on the issue of lucrativeness connected to Bitcoin mining while concentrating on the specific variables affecting the profitability itself.

1.1 Brief overview of the evolution in Bitcoin mining

With the release of Bitcoin to public, on January 3, 2009 Satoshi Nakamoto mined the first block, also known as the Genesis Block, forming the foundation of the blockchain and marking an inception to the process of trading bitcoin. The following block was then mined 6 days later. Slowly new miners were joining the system and it was not until closely to a year later when Bitcoin mining gained crucial popularity.

With the rising interest in Bitcoin more miners joined the network and with time it became more demanding of them to succeed in the mining game. More computing power was required in order to reach their goal and their consumption of electricity that concurred with it began to increase substantially. The detailed evolution of the Bitcoin mining and the utilization of different means used by miners to achieve the desired result is closely discussed in the work of Narayanan et. al (2016) as follows.

At the beginning first Bitcoin miners only needed to own a standard computer with regular CPU (Central Processing Unit) power to be able to work on the mathematical puzzle, potentially solve it, add a new block into the blockchain and then receive the desired block reward in a form of new bitcoin units (Narayanan et. al 2016). However, with increasing number of bitcoin in the network together with its rising popularity it was becoming more difficult and time demanding to find the following block and add it into the blockchain. To accelerate the process of solving the computational problem more computing power was needed. Therefore, miners started using graphics cards or GPUs (Graphics Processing Units), instead of CPU, to be more effective as the new coding language OpenCL allowing them to do so was released in October 2010 (Narayanan et. al 2016). But soon, as Narayanan et. al (2016) mention in their work, it became rather unpractical for miners to use GPUs since they were not using them for their primary function which came with certain difficulties. Moreover, when GPUs were used in a bulk it could be challenging to come up with a cooling system for the setup altogether resulting in the growth in electricity consumption. As the time progressed, in 2011, it became frequent among miners to transition to FPGA (Field Programmable Gate Arrays) which were able to deliver overall better performance than GPUs as the power consumption was lower (Narayanan et. al 2016; Courtois, Grajek and Naik 2014). But regrettably miners encountered various errors while using FPGAs which is the reason why the use of this hardware did not prevail (Narayanan et. al 2016).

Then, in the year 2013, custom ASIC (Application-Specific Integrated Circuit) designed specifically for the purpose of Bitcoin mining was released to the market. As miners began to use ASICs it led them to a significant reduction in their cost of mining as it, among other things, resulted in decrease in the electricity consumption (Courtois, Grajek and Naik 2014). Due to the fact, that ASICs were produced explicitly for the demand of Bitcoin miners, it meant a significant change as for both speed and the energy efficiency in the Bitcoin mining community. Similarly as with different technology, ASICs were then gradually further developed and improved to their best possible performance. Moreover, Hanke (2016) discusses the method of speeding up the Bitcoin mining process by a factor of approximately 20% called AsicBoost. That is an algorithmic optimization used by miners to achieve more advantageous results in the operations.

The moderate development in the means used for Bitcoin mining was accompanied by the increase in the number of miners in the network as Bitcoin was gaining on its popularity over the years, since the origins of Bitcoin mining in 2009. This also led to the shift from individual mining to pool mining where miners share their computing power, as the rising mining difficulty connected to the increase in the number of miners resulted in Bitcoin miners weighting the benefits against the drawbacks of different types of Bitcoin mining. Consequently, pool mining gained popularity as it appeared to be beneficial at the time since miners could combine their mining power and then split the block reward among themselves according to each miner's contributed hashing power. Although, it becomes rather problematic for a new miner entering the contest to decide the pool they ought to join in order to maximise their profits (Salimitari et.al 2017). Furthermore, Rosenfeld (2011) mentions the various scoring systems used to calculate rewards of participants in Bitcoin pooled mining while analysing their pros and cons. In addition, large companies were building immense professional mining centers thus providing an incentive for individuals to transition their focus to pool mining rather than acting on their own. Regrettably for the original miners of Bitcoin, mining has become mostly controlled by large companies throughout the years. One of the reasons for such happening was the fact that Bitcoin mining appeared as a relatively straightforward way of making large profits. Therefore, it could be said that today the individual mining is not an option which would be that sought for anymore. Narayanan et. al (2016) raise an intriguing question in their work, and that is whether ASIC mining together with the creation of professional mining farms conflicts with the Satoshi Nakamoto's original idea of Bitcoin and that is for it to operate on a completely decentralized system where individual miners would be able to employ their own computer's CPU to mine Bitcoin and participate in the network.

1.2 The attitudes towards Bitcoin mining profitability in the previous years

The Bitcoin mining along with its rather volatile level of profitability happened to be a burning topic which was explored in numerous research papers since Bitcoin gained on its popularity. Some of which focused rather on a general research concerning Bitcoin mining and its overall profitability, as Derks, Gordijn and Siegmann (2018) who are behind the study on the declining profits connected to Bitcoin mining from 2012 to the year 2016. Whereas others, such as Salimitari et. al (2017) for instance, brought the attention specifically to the Bitcoin pool mining and they analysed different options for maximising miner's profits in this particular setting. Or Meni Rosenfeld (2011) who conducted research on the topic of Bitcoin pooled mining reward systems.

Houy (2016) examined the idea that the larger the mined block is the more time is required for it to be spread across the Bitcoin network and therefore it takes longer to reach consensus as well. Following up on this thought he stated that the miner's decision on the issue of what amount of transactions to include in the block is crucial as higher number of transactions contained in the block might result in decrease in the miner's probability of receiving the desired block reward. The reason for such happening would be that once a block is mined by a miner while being outraced by different block, it is considered to be *"orphaned"* resulting in the miner missing up on the chance of earning any reward for mining it (Houy 2016). As Houy (2016) concludes, this trade-off problem of either including large number of transactions in the block to achieve higher profits as there would be more transaction fees connected to the block, or focusing on less transactions to increase the chance of reaching the consensus quicker while successfully including the block in the blockchain and collecting the reward together with transaction fees is therefore, forcing miners to carefully consider the amount of transactions they ought to include in the mined blocks in order to maximise the probability of obtaining the block reward. Houy (2016) shows in the research article that *"the solution to this trade-off depends on how many transactions other miners include in the block they are trying to mine"* while closely describing the *"Bitcoin mining game"* whose outcome would be the number of transactions included in mined blocks. Therefore, it could be said that it is discussed in this research that the decision of a miner also depends on the actions and priorities of other contestants in the network. Rizun (2016) proposes a possible technique bringing improvements, when it comes to mining rather large blocks containing numerous transactions, in a form of cooperatively created subchains which could lead to reshaping the decision-making process as for the discussed trade-off. This method reduces the risk of a larger block becoming orphaned due to the block being build by layers instead of putting the whole block together and then releasing it (Rizun 2016).

Related ideas to this topic are mentioned by Dimitri (2017) who aims to estimates the Nash equilibrium in the "mining game" using the ideas from game theory. In his work he presents the thought that at the Nash equilibrium of the Bitcoin mining game, assuming perfect information in the setting and the level of computational power used by an active miner depending also on the amount of bitcoins that might be received by the miner after figuring out the correct solution to the cryptographic puzzle, the decision to participate in the network as an active miner is subject only to their incurred marginal costs as set into contrast and compared against the other contestants' costs structure. Or as Dimitri (2017) expresses it in other words, *"the decision to be an active miner depends only upon how efficient his competitors are and not on how many bitcoins will be obtained as rewards."* This could be considered as an interesting idea as he proclaims that the amount of potentially gained reward does not seem to be the primary criteria for the miner as he enters the mining game whereas, the other participants' mining efficiency is.

As mentioned earlier, the issue of Bitcoin mining profitability throughout the years 2012-2016 was closely discussed in the research paper published in the 28th issue of the Electronic Markets with results pointing out the fact that Bitcoin mining had become less profitable over time to the extent that the profits connected to it appear to converge towards zero (Derks, Gordijn and Siegmann 2018). This research proposes the idea that Bitcoin mining would not become a significant source of one's income in the upcoming years after estimating the direct costs related to mining. Rather different approach could be found in the Huang, Levchenko and Snoeren (2018) research paper on estimating profitability of alternative cryptocurrencies in which when trying to estimate the mining costs Huang, Levchenko and Snoeren (2018) mention that *"the precise value is difficult to calculate, as the capital investment and energy costs differ across individual miners"* therefore, the authors decide to focus on the opportunity costs of the miner instead of the direct costs.

In the work on inefficiency and profitability of cryptocurrencies Agung et. al (2019) focus on the difference in the use of energy by different mining strategies while comparing the mining profitability of various cryptocurrencies. Agung et. al (2019) mention that mining profitability is also influenced by the exchange rate between Bitcoin and specific fiat currency and that *"cryptocurrencies price solely depends on supply, demand and the expectation of the holder"* as the price could not be influenced by the central bank nor the government with Bitcoin being a decentralized currency. Due to the volatility of Bitcoin price miners might have an incentive to switch to mining a different cryptocurrency which could appear to be more profitable at the time, and as of the *"permissionless nature of the blockchain"* miners are able to do so rather effortlessly (Agung et. al 2019). And as Agung et. al (2019) conclude, this results in the Bitcoin mining having rather hight level of uncertainty.

Furthermore, as Tredinnick (2019) discusses, potential profitability of

Bitcoin mining appears to have an uncertain future due to several fundamental arising issues miners are encountering within the Bitcoin network. The main problem Tredinnick (2019) mentions in the research would be the rising costs of Bitcoin mining as *"mining is designed to become more difficult over time, the profitability of mining is not guaranteed, threatening the entire infrastructure which underpins the validation of transactions."* Along with increasing demands on the power consumption as he points out its dramatic effects on the environment as well as its potential to undermine the viability of the whole Bitcoin system (Tredinnick 2019).

1.3 The general perspective towards variables affecting the Bitcoin mining profitability

There are several different factors that have significant impact on the level of Bitcoin mining profitability and its sustainability as of the financial resource in the long-term. The main incentive for the miner would be the received block reward along with presumed transaction fees associated with the transactions contained in the mined block (Nakamoto 2008). However, to reach this objective, miners incur various costs leading to it such as prices of hardware accompanied by efficient cooling arrangement and mainly the charges for required electricity for the systems to operate, it could be said that those are the main costs miners have to anticipate. Consequently, Bitcoin mining becomes profitable only if the gain of the block reward and transaction fees overweight the incurred costs that were accounted for during the process of mining the block.

The main element connected to the evolution in hardware used for mining over the years as it is affecting the speed of solving the cryptographic puzzle is hashing power, or hash rate then leading to the overall mining efficiency of the hardware. Miners were therefore aiming to achieve as high hashing power as possible to be able to mine Bitcoin efficiently. In the beginnings of Bitcoin mining miners were able to reach numbers in units of million hashes per second (around 1 MH/s to 5 MH/s) as for the computing power as they were mining on their computer's CPUs (Courtois, Grajek and Naik 2014). Then, as miners transitioned to using GPUs the hash rate would rise up to a few hundred million hashes per second (up to 200 MH/s to 300 MH/s) (Courtois, Grajek and Naik 2014; Narayanan et. al 2016). Again, with the use of FPGAs the hashing power increased significantly for the miners, as mentioned in the work of Narayanan et. al (2016), it climbed to numbers around one billion hashes per second (GH/s). Finally, with the year 2013 when ASICs were released and miners started shifting towards the use of such purposely customised units, as specified by ASIC Miner Value[2], the first units were able to reach hash rate approaching hundreds of GH/s as the first generation Avalon units operated at 68 GH/s. Over the past years ASICs had been further developed and their parameters had been perfected bringing the results in the form of rather quickly rising numbers as for the offered hashing power among other factors. According to data from the site ASIC Miner Value[3], during the year 2019 the new improved models of ASIC that appeared on the market were providing the average hashing power in the digits around 55 TH/s, and with the beginning of 2020 new models slowly advancing towards 100 TH/s were released to the market.

Hashing power is closely related to the electricity consumption as the amount of electricity power required depends on the efficiency of the used mining hardware. As Courtois, Grajek and Naik (2014) put the numbers in perspective in their published paper, the power consumption for different mining hardware was stated as follows: when miners operated on CPUs the required electricity was estimated to be roughly 4000 W per GH/s, then with the use of GPUs it dropped to approximately about 210 W per GH/s. Furthermore, the start of FPGAs usage was accompanied by another quite significant decline in the power consumption leading to up to 100 times lower electricity requirements in comparison to the original CPU mining, the power demands reduced only to about 50 W per GH/s (Courtois, Grajek

[2] at `https://www.asicminervalue.com/`

[3] See footnote 2

and Naik 2014). Then, when ASICs appeared on the market. the electricity consumption was further decreased and it was minimized to as low numbers as 0.35 W per GH/s which led to a significant drop in the overall cost of mining (Courtois, Grajek and Naik 2014).

The aspects discussed above are crucially affecting the decision making as for the purchase of hardware. Inevitably leading to also weighting the costs of hardware along with cooling systems which are needed for the miner's setup to be able to operate without complications. Moreover, this is closely connected to one of the main elements that have impact on the actual profitability of Bitcoin mining, and that is the level of electricity costs and the total accumulated expenses for electricity. Bitcoin mining is recognized to be rather demanding process as for the computing power which then results in the need of efficient cooling systems for the setup, together leading up to high electricity consumption. That appears to be the reason why it is vital for miners to possibly dedicate some effort to researching areas with low charges for electricity (Narayanan et. al 2016), or alternatively using power from renewable resources. According to Narayanan et. al (2016) it appears to be beneficial to situate the rather large mining centres in cold climate areas because it contributes to lowering the costs connected to the cooling systems. This statement could be understood in the way that for such mining centres the cooling cost are very likely to be high as their mining hardware structures tend to be enormous and therefore, taking the advantage of cold climate in order to reduce the costs for cooling systems would bring appealing results in terms of its effect on long-term profits.

Harvey-Buschel and Kisagun (2016) attempt to expand the research along with previously constructed models by accounting also for the pricing of off-peak power and investment strategies considering sunken costs connected to purchases of new technology, overall investing in its further development or even specific upgrades to increase the efficiency, while they acknowledge that electricity cost, hardware limitations and costs of cooling system are the main factors regarding the resulting profitability. Moreover, as mentioned earlier, the miner's incentive tends to be steadily shifting from block rewards towards the transaction fees where it would stagnate in the future once the bitcoin supply of 21 million units is exhausted (Nakamoto 2008). Harvey-Buschel and Kisagun (2016) comment on this notion by highlighting the reality of mining in the time to come being profitable and beneficial for the miner only in the case *"when the sum of transaction fees for unconfirmed transactions on the network exceeds the miner threshold of cost to mine"*. Therefore, it might become difficult for miners in the future to obtain large profits as the block reward would no longer be received by them meaning they would become entirely dependant on the transaction fees.

In the empirical study on cryptocurrency value formation, Hayes (2017) also points out the importance of computational power and the mining efficiency reasoning by Bitcoin mining being rather competitive. Hayes (2017) states in the study that *"the implications are that cost of production drives value and anything that serves to reduce the cost of bitcoin production will tend to have a negative influence on its price"*. To further unfold this problem, Hayes (2017) points out the variables reducing the marginal mining costs such as rising hardware energy efficiency, lower worldwide electricity prices, or decreased mining difficulty. As those variables pressure the mining costs downwards it results in decline in Bitcoin market price (Hayes 2017). Whereas the additional hashing power contributed to the whole mining network would tend to magnify the mining difficulty therefore, cause the Bitcoin market price to grow (Hayes 2017). Furthermore, Hayes (2017) raises a question whether the rising energy efficiency due to the technological progress could possibly outpace the increasing mining difficulty resulting from the growing Bitcoin network, or on the contrary. This could be considered an important problem as if the technological progress would manage to gradually improve the Bitcoin mining hardware energy efficiency in such way that it would overweight the growing network of miners and the overall mining difficulty, it would contribute to the Bitcoin mining process leaning towards profitability. Hayes (2017) also comments on the impacts of halving system by stating that *"a further implication is that when the Bitcoin block reward halves, it will effectively increase the cost of production overnight"*.

Rather different approach is described in the paper closely investigating Bitcoin mining profitability as Deutsch (2018) attempts to estimate the level of Bitcoin mining profitability using the historical data concerning the changing mining difficulty while also observing the influence of the different stages of the halving process and its possible impact on the overall profitability. As commented on by Deutsch (2018), the estimates proved to be reliable. Then using the obtained observations Deutsch (2018) discusses various scenarios concerning the break even point in mining Bitcoin while estimating the possible time to break-even.

Mora et. al (2018) are interested in the impact that cryptocurrencies have on the global warming, more specifically in the excessive electricity consumption along with the CO_2 emissions connected to the use of Bitcoin. Therefore, in their research, Mora et. al (2018) aim to estimate the future power demand based on the levels of utilized electricity at the time of their writing, concluding on the issues of increasing power demand in the Bitcoin mining trend that *"if its rate of adoption follows broadly used technologies, it could create an electricity demand capable of producing enough emissions to exceed 2°C of global warming in just a few decades"* while discussing that with the rising electricity demand there would seem to be and incentive for miners to relocate to places with lower electricity prices to maximize their profits. Additionally, Mora et. al (2018) discuss the ideas of the motivation to mine Bitcoin being highly influenced by the block reward, then mentioning the halving system and its possible effects on the attractivity of Bitcoin mining as the outcomes of the halving system could lead to a reduction in the general interest in Bitcoin.

Kufeoglua and Ozkuranbwho (2019) also concentrate their research specifically on the power and energy demand of the mining process as those variables are recognized to be the main operation costs in the mining activity. In their work they conclude that *"the choice of hardware is crucial in the energy consumption"* as hardware efficiency is one of the vital factors having a significant impact on the process of mining and hence on the resulting energy consumption (Kufeoglua and Ozkuranbwho 2019). Furthermore, Kufeoglua and Ozkuranbwho (2019) claim that the Bitcoin market prices appear to have close impact on the energy consumption as well, as *"with falling Bitcoin prices, the peak power demand drops as well"*.

Kristoufek (2020) investigates the relationship together with interactions between the prices of Bitcoin and the costs of Bitcoin mining in his paper, uncovering that the variables are closely affected by one another and they tend to a common long-term equilibrium. Then proposing that the marginal (electricity) costs along with the mining efficiency have become the crucial variables in determining the Bitcoin mining profitability in the recent years (Kristoufek 2020).

Yaish and Zohar (2020) study the pricing of ASICs used in cryptocurrency mining, in their paper they estimate the value of ASICs using the information on ASIC performance meaning taking into account the power consumption and hash rate, then combining those observations with variables such as the current exchange rate, price volatility, prices of electricity, the block reward and others. As miners are required to invest into mining hardware before they could possibly begin to earn any profits, nonetheless the needed hardware being a substantial investment, cryptocurrency mining is considered a rather high-risk venture (Yaish and Zohar 2020). Furthermore, in their work, Yaish and Zohar (2020) present an idea of higher volatility in price of the desired cryptocurrency would in fact have a positive impact on the value of mining hardware as it would result in its increase. This implication might seem unexpected as the general perception might be that high volatility would decrease the mining hardware value due to the fact that, it would lead to a higher risk for the miner (Yaish and Zohar 2020). As Yaish and Zohar (2020) further explain such happening, *"if the exchange rate plummets. the losses of miners are bounded (they can always shut off their machines and avoid paying for electricity), but if exchange rates increase steeply their gains can be significant"*. The reasoning brings up to the light the option a miner would have, and that is shutting off the mining setup in case of a sudden drop in Bitcoin price. That accompanied by the consequent choice of reconnecting the mining hardware back into the network once the Bitcoin price would increase to the point where it could possibly bring profits for the miner.

2 Dataset construction

In this section the focus will be on the analysis of the development in the Bitcoin mining profitability throughout the years 2014-2020 while estimating whether Bitcoin mining would still be profitable in the year 2020. Specific variables affecting the Bitcoin mining profitability would be discussed in detail along with various measures that could be applied to maximise the mining profits. The main variable of interest would be the power consumption, leading to the discussion on the topic of electricity costs. In addition, some options leading to a decrease in the electricity expenses in the long-run would be discussed in this section, for instance the possibility of acquiring electricity from renewable sources, or rather relocating the mining operations to countries with lower electricity costs.

To begin with, the overall profit is estimated by computing total revenues while also accounting for the incurred costs. Thus, Bitcoin mining is perceived as profitable only when the miner's revenues overweight the expenses. As for the revenues, the crucial determining factor of Bitcoin mining profitability would be the level of the block reward and transaction fees received per block. This issue is closely connected to the current degree of Bitcoin price on the market as it sets the value of gained reward at a certain point in time. Therefore, the question of whether it is desirable to mine Bitcoin could be established by also observing the Bitcoin's value determined by its current price on the market. That is, contemplating the level of profit miner would be able to yield once obtaining the block reward plus the transaction fees, and estimating the actual financial gain resulting from their effort by accounting also for the incurred costs. As it was mentioned earlier, hardware prices, costs of cooling systems and consequently power consumption (closely connected to the level of electricity costs) could be considered the main investment factors in the Bitcoin mining process. Another element classified among expenses could be possible pool fees. Then, in the stage when miner has an incentive to trade Bitcoin for fiat currency, the exchange fees arise. The variables affecting the decision making in the case of hardware, as they influence the speed by which a miner would be able to reach the goal in the form of a solved mathematical puzzle and a mined block, are hash rate, power consumption and also the gradual increase in the mining difficulty as another key variable having a crucial impact on the Bitcoin mining profitability is the mining efficiency of the specific hardware which would also be further discussed in this section.

For the purposes of this thesis, historical data from the years 2014 to 2020 are used, more specifically data from January 1, 2014 to May 31, 2020. The main utilized data sets are extracted from the site Quandl[4] while the data concerning Bitcoin market price are from the site Data Bitcoinity[5]. And also, the site ASIC Miner Value [6] is used to obtain specific data on the various mining hardware models.

Firstly, as stated above, profit yielding from Bitcoin mining would be computed by calculating miner's revenues while also accounting for the incurred expenses which would then be subtracted. This thesis will focus on the daily profitability of Bitcoin mining, that is estimating the mining profits achieved per day. This is illustrated by the following equation 1:

$$\Pi_d = R_d - C_d \quad (USD) \tag{1}$$

where Π_d stands for the estimated daily profit in USD while R_d signifies the Bitcoin miner's revenues per day and C_d represents the daily costs and expenses.

Then, to calculate the revenues side of the profit function, it would be fitting to begin with the cumulative gross revenues achieved per day and that by taking the earned block reward in the form of the value of total amount of Bitcoin mined per day, while also adding the transaction fees per day, and this number then multiplying by the related market price in USD per BTC unit. Consequently, yielding the numbers on mining gross revenues

[4] at `https://www.quandl.com/data/BCHAIN-Blockchain`
[5] at `https://data.bitcoinity.org/markets/price/all/USD?c=e\&t=l`
[6] at `https://www.asicminervalue.com/`

achieved per day. Expressed by an equation 2 as follows:

$$R_d^G = (B_d + F_d) \cdot p \quad (USD) \tag{2}$$

where R_d^G represents the Bitcoin miner's gross revenues per day in USD, B_d stands for the amount of mined Bitcoin per day in BTC, F_d for associated daily transaction fees in BTC and p for Bitcoin market price in USD.

As mentioned earlier, the original block reward associated with the mined block was 50 BTC however, the block reward is subject to a set halving system as it is cut in half after every 210 000 newly mined blocks. Thus, on November 28 in 2012 the block reward decreased to 25 BTC, then on July 9 in 2016 it reduced to 12.5 BTC. In addition, in the year of interest, 2020, the block reward was subject to halving on May 11 when it dropped to 6.25 BTC per block. Moreover, the transaction fees differ for each transaction depending on the size of the transaction along with the intentions of its sender as higher fee creates an incentive for the miner to include such transaction in a block sooner. The Bitcoin network is set in such way that a new valid block is found approximately each 10 minutes. Then, the amount of mined Bitcoin per day varies accordingly to all these factors.

As for the Bitcoin market price throughout the years 2014 to 2020, the price slightly differs across various Bitcoin trading platforms however, as it could be anticipated the differences are only minor. Therefore, for the purpose of this thesis, it would be fitting to calculate the average Bitcoin price across the numerous trading platforms to be able to focus only on one set of numbers. The Figure 1 below illustrates the changes in this average Bitcoin price over the course of the years 2014 to 2020. It can be observed that the Bitcoin market price (in USD) tends to be rather volatile. In the early years (2014 to 2016), as Bitcoin was not as well-known currency as it is today, its market price fluctuated around rather low values not exceeding 1 000 USD per BTC. With the beginning of 2017, accompanied by Bitcoin's gain in popularity, the price began to rise gradually leading up to the highest numbers in the graph, marked in the December of 2017. After the curve reached its peak the price started to decline slightly and it undulated around higher values until the later months of 2018 when it suddenly dropped to approximately 4 000 USD per BTC. Then again, with the beginning of April 2019 the market price started to grow steadily up until the end of June and the beginning of July when it peaked in numbers around 12 000 USD per BTC. Towards the end of 2019 the Bitcoin price stagnated around roughly 7 000 USD per BTC however, with the introduction of 2020 it began to climb up once more, only to plummet again in March and then going up in April, proving its high volatility.

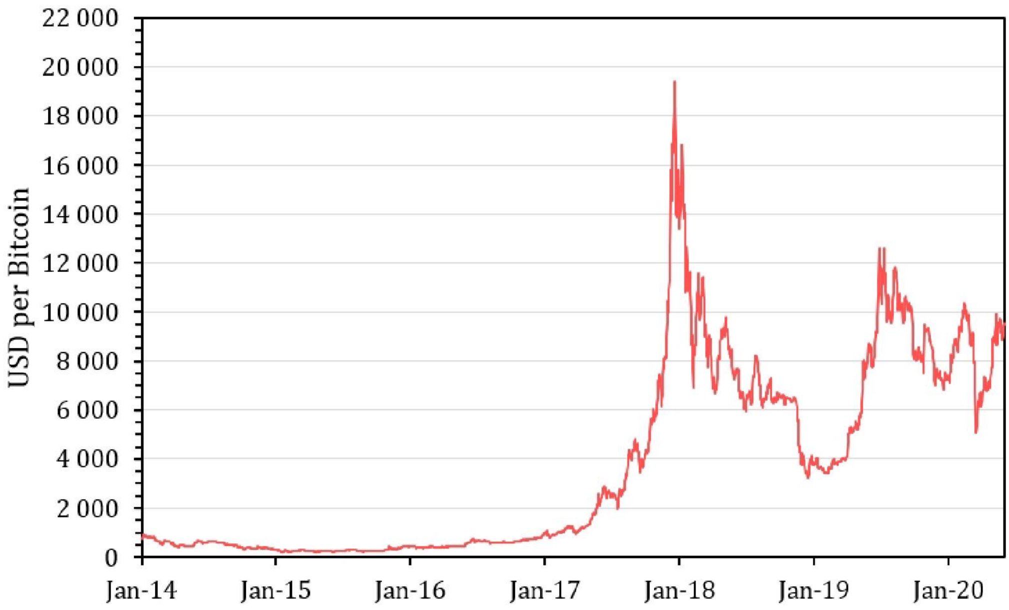

Figure 1: Averige Bitcoin market price (USD) through trading platforms in 2014-2020
Calculations by author; Original data from: Data Bitcoinity[7]

Hence, it could be stated that despite the lower digits in the Bitcoin market price reported in the beginnings of Bitcoin, it managed to gain on value and its price rose up to unexpectedly higher monetary values during the later years in such course that it came to numbers reaching 20 000 USD per BTC. What's more, Bitcoin managed to somewhat remain in higher values even until today, the year 2020, as compared to the sudden drop between 2018 and 2019 the price had more than doubled in 2020.

[7] at https://data.bitcoinity.org/markets/price/all/USD?c=e\&t=l

Then, as for the profit function part expressing the incurred expenses, numerous elements are needed to describe it. The essential outgoing currency flows from the Bitcoin miner are primarily investments in hardware, electricity expenses resulting from the overall power consumption, possible pool fees and exchange fees. However, a problem arises with the key expense, the hardware investment, as it is difficult to estimate the specific amount spent by a miner on such purchase due to numerous uncertain variables involved in the process. The purchasing cost of the mining hardware itself is challenging to obtain, the issue is that the price changes over time based on factors such as demand or the Bitcoin market price at the time. Moreover, there tend to arise transportation costs along with customs and taxes while this whole process tends to be accompanied by a purchase of additional hardware such as cooling systems, necessary cables or other complements. Also, there is no specific data available on the mining hardware lifespan which means another issue in estimating the exact amount spent on hardware investments over time. Therefore, investments in hardware would be omitted in the primary computations however, it would be a topic of discussion further on as the difference in mining profitability under different scenarios in such matter would be examined. Instead, to construct the equation explaining the costs, only the costs of potential pool fees and exchange fees would be considered while the electricity expenses would not be expressed in specific numbers in the equation as they would then rather be a topic of an extensive debate focusing on the highest electricity prices at which mining would still be profitable along with investigating various options of decreasing the electricity costs to minimum.

When exchanging Bitcoin for fiat currency, most often USD, exchange fees need to be accounted for. The exchange fees vary depending on a specific trading platform. After reviewing the available information on the largest trading platforms (such as BitFinex, Bitstamp, Bittrex, Coinbase, Huobi, Kraken or OKCoin[8]) it could be concluded that generally the exchange fees

[8]BitFinex at `https://www.bitfinex.com/fees`,

tend to be around 0% to 0.5% based on both the exchange platform and the amount of traded currency as the fees are usually volume based. Therefore, for the purpose of this thesis, the average of 0.25% would be assumed as the exchange fee. Based on the equations 1 and 2 the following arises:

$$R_d^N = R_d^G - (0.025 \cdot R_d^G) \quad (USD) \tag{3}$$

$$R_d^N = 0.975 \cdot (B_d + F_d) \cdot p \quad (USD) \tag{4}$$

where R_d^N stands for the daily net revenue in USD, R_d^G represents the Bitcoin miner's gross revenues per day in USD, B_d stands for the amount of mined Bitcoin per day in BTC, F_d for associated daily transaction fees in BTC and p for Bitcoin market price in USD.

Another cost, in a form of possible pool fees, might arise if a miner is not yielding satisfying profits as is, as then there is an option to join a mining pool and share the mining power, then reaching different results. That comes at a price of having to share the reward according to the contributed hashing power, along with paying a pool fee. The pool fees that might arise as another cost for the miner in such case tend to reach numbers between 1% to 2.5% as for the large pools. according to the Bitcoin Wiki[9], in addition to the payed pool fees some of the mining pools, such as AntPool or BTCC Pool, keep the transaction fees as well. When demonstrating the option of joining a mining pool in the analysis of mining profitability, the average value of 1.75% would be substituted for the pool fees. However, the results showing a miner's profit when a member of a pool would be only illustrative as in such case the revenues might differ depending on the reward distribution system of the particular mining pool. Continuing on the equations 3 and 4

Bitstamp at `https://www.bitstamp.net/fee-schedule/`,

Bittrex at `https://bittrexglobal.zendesk.com/hc/en-us/articles/360009625260-What-fees-does-Bittrex-Global-charge`,

Coinbase at `https://help.coinbase.com/en/coinbase/trading-and-funding/pricing-and-fees/fees.html`,

Huobi at `https://www.huobi.com/en-us/about/fee/`,

Kraken at `https://www.kraken.com/features/fee-schedule`,

OKCoin at `https://support.okcoin.com/hc/en-us/articles/360015261532-OKCoin-Fee-Rates`

[9] at `https://en.bitcoin.it/wiki/Comparison\_of\_mining\_pools`

the daily net revenues for a member of a pool would be computed using the following equation 5, and consequently 6:

$$R_d^{Npool} = R_d^G - (0.0175 \cdot R_d^G) - 0.025 \cdot [(1 - 0.0175) \cdot R_d^G] \quad (USD) \tag{5}$$

$$R_d^{Npool} = 0.9579 \cdot (B_d + F_d) \cdot p \quad (USD) \tag{6}$$

where R_d^{Npool} stands for the daily net revenue in USD when a member of a pool, R_d^G represents the Bitcoin miner's gross revenues per day in USD, B_d stands for the amount of mined Bitcoin per day in BTC, F_d for associated daily transaction fees in BTC and p for Bitcoin market price in USD.

Finally, the leading factor in estimating the overall Bitcoin mining profitability is the mining efficiency which can be measured either in Gh/J or J/Gh therefore, it can be determined by dividing the hash rate by the power usage of a miner as displayed in the following equations 7 and 8:

$$\epsilon = \frac{Hashrate}{PowerConsumption} \quad \frac{(Gh/s)}{(W)} \tag{7}$$

$$\frac{\frac{Gh}{s}}{W} = \frac{Gh}{W \cdot s} = \frac{Gh}{J} \tag{8}$$

where ϵ stands for the said mining efficiency and it is measured in Gh/J therefore the larger the value, the better the performance of a miner. Whereas if it would be displayed in J/Gh it would mean a better performance with lower value.

Then, employing the data available at ASIC Miner Value[10] the mining efficiency of various mining hardware models would be computed. Consequently, when calculating with the mining efficiency of various mining hardware models it would be assumed that miners are rational when making choices on the market and they would therefore decide to utilize the most efficient mining hardware available at the time. Moreover, combining the obtained values on the mining efficiency (using the values in J/Gh for easier calculations) together with the network hash rate on the specific day results in the information on the daily energy consumption of

[10] at `https://www.asicminervalue.com/`

the mining process, as shown in the following equations 9 and 10.

$$C = NetworkHashrate \cdot \epsilon \quad \left(\frac{Th}{s}\right) \cdot \left(\frac{J}{Gh}\right) \tag{9}$$

$$C_d^J = NetworkHashrate \cdot \epsilon \cdot 24 \cdot 3600 \cdot 1000 \quad (J) \tag{10}$$

where C stands for the energy consumption, then C_d^J for the daily energy consumption in J, ϵ signifies the mining efficiency in J/Gh and Network hash rate is measured in Th/s.

Now, to obtain the daily consumption measured in kWh the equation 11 below would be used.

$$C_d^{kWh} = \frac{C_d^J}{3600 \cdot 1000} \quad (kWh) \tag{11}$$

where C_d^{kWh} stands for the daily energy consumption in kWh and C_d^J for the daily consumption in J.

As mentioned earlier, the main variable of interest and one of the key variables in estimating the Bitcoin mining profitability is the electricity price. That is due to Bitcoin mining being a very demanding process as for the consumed electric power meaning the electricity price affects the resulting profits to a great extent. To receive the numbers on the electricity price a miner would pay at the break-even point, the equation 12 would be employed.

$$P_{kWh} = \frac{R_d^N}{C_d^{kWh}} \quad (USD) \tag{12}$$

Where P_{kWh} stands for the electricity price in USD per kWh, R_d^N for the daily net revenue and C_d^{kWh} for the daily energy consumption in kWh.

First, the break-even electricity price over time would be estimated for the period from 2014 to 2020, while assuming miners operate with the most efficient mining hardware available at the time. Then, to be able to compare various types of mining hardware and their potential profitability in 2020, the break-even electricity price (at the time of release, and then in May 2020) for each type of such hardware would be calculated. To receive these numbers, the same equations as in the previous calculations would be employed, only on a monthly level.

3 Break-even electricity price of Bitcoin mining

The results of the performed analysis would be presented in this section. Firstly, the values of the estimated electricity price at the break-even point over the years 2014-2020 with focus on the year 2020 would be the topic of discussion. Then, moving on to specific numbers on the break-even electricity price for different types of mining hardware and that at the time of the release of the hardware and then in May 2020. Continuing with a debate on the possible mining profitability based on the estimated values, as greater value on the break-even electricity price the greater the potential for the actual Bitcoin mining profitability.

3.1 The estimated break-even electricity price per kWh for the years 2014 to 2020

The resulting numbers on the break-even electricity price for the years 2014 to 2020 are displayed in the Figure 2 below. And consequently, to narrow the time frame, the estimated values for the years 2015 to 2020 are shown in the Figure 3. The results lead to an option for speculations on the numbers concerning the maximum electricity price a miner can afford to pay while still making profit as such price would have to be lower than the estimated break-even electricity price.

The Figure 2 shows a peak in numbers at the beginning of the observed time frame, in the early months of 2014, reaching values up to 18 USD per kWh and pointing out the time of greater profitability. However, the numbers then dropped to values around 0.50 USD per kWh, during the remaining time in 2014, where they began to undulate for the rest of the observed period, until May 2020. Thus, to observe the numbers of the later years better, the time frame would be narrowed in the Figure 3 then illustrating the changes in the estimated break-even electricity price per kWh over the years 2015 to 2020.

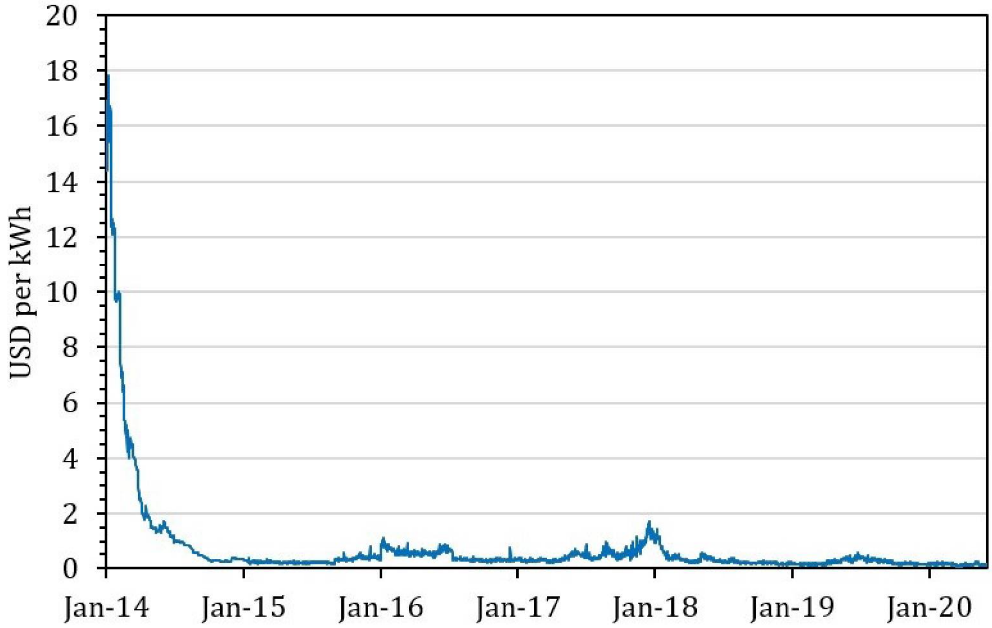

Figure 2: Estimated electricity price at the break-even point over the years 2014-2020

Calculations by author; Original data: Asic Miner Value. Data Bitcoinity and Quandl[11]

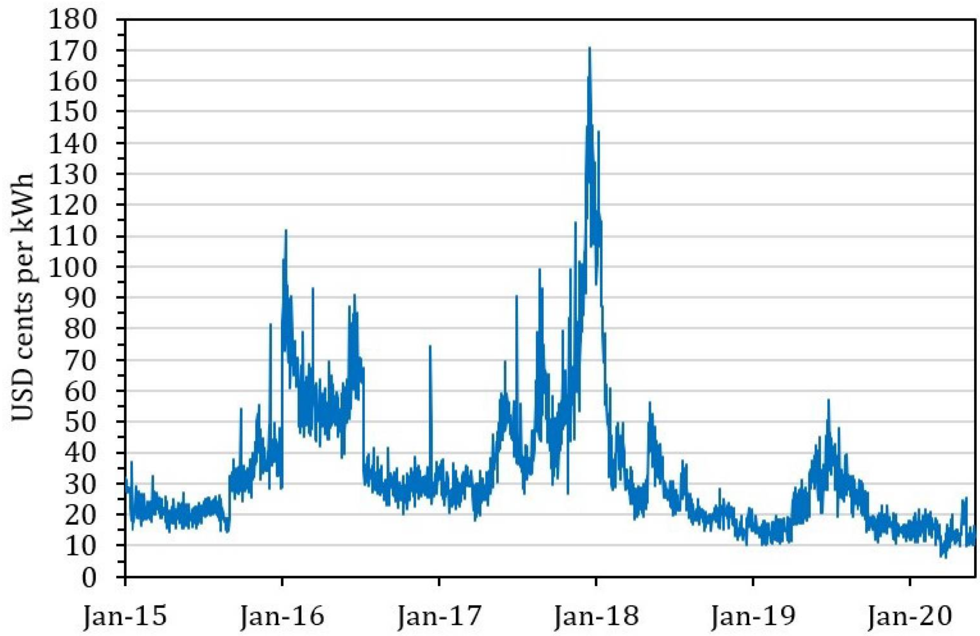

Figure 3: Estimated electricity price at the break-even point over the years 2015-2020

Calculations by author; Original data: Asic Miner Value, Data Bitcoinity and Quandl[12]

[11] Asic Miner Value at https://www.asicminervalue.com/,
Data Bitcoinity at https://data.bitcoinity.org/markets/price/all/USD?c=e&t=l,
Quandl at https://www.quandl.com/data/BCHAIN-Blockchain

[12] See footnote 11

It could be seen in the Figure 3 that the resulting digits are rather low not giving a great space for the potential profitability for the miner as the highest electricity price for mining to still be profitable would have to be lower than the estimated electricity price at the break-even point. Overall, the data are not presenting any specific trend. The values fall between approximately 0.05 and a little over 1.70 USD per kWh. As could be seen in the Figure 3 the curve representing the break-even electricity price is very volatile, due to many factors affecting the values. Therefore, the progression of the break-even electricity price in time is rather unpredictable. The Figure 3 shows that during most of the year 2015 the break-even electricity price fluctuated around 0.20 USD per kWh then, towards the end of the year it went up to numbers around 0.40 USD per kWh. With the beginning of 2016 the estimated numbers dramatically increased reaching values up to 1.10 USD per kWh signifying greater space for profitability, shortly followed by a decline to values around 0.50 USD per kWh however, the numbers increased again reaching 0.90 USD per kWh in the middle of the year, few days later falling to 0.30 USD per kWh where they undulated for the rest of the year and part of 2017. Nevertheless, this decline in the break-even electricity price was followed by gradual growth of the price which would bring greater profits for Bitcoin miners. The growth in price lasted until the time around January 2018 when it rose up to numbers reaching 1.70 USD per kWh marking the highest point of the curve over the observed time period. Unfortunately, the mentioned peak in values was soon succeeded by a sudden drop to digits around 0.30 USD per kWh where the price fluctuated for the rest of the period of interest coincided with slight drops and rises within the size of 0.20 USD per kWh. As for the year 2020. the values of the break-even electricity price levelled off around 0.10 to 0.20 USD per kWh making it challenging for Bitcoin miners to earn any profits.

In general, Bitcoin mining is a process that requires excessive amounts of energy - as estimated, in 2020 the average daily consumption of Bitcoin mining industry fluctuated around 65 to 110 million kWh with a daily average of 50 kwh per mining device then shifting to numbers approaching 80 kWh per device in May. Therefore, electricity price would have a significant impact on the resulting profitability of Bitcoin mining. Consequently, it appears to be beneficial for miners to locate in countries with low electricity prices. In addition, another way to reduce electricity expenses would be to mine Bitcoin in places with cold climate as it would reduce the costs along with power consumption of additional cooling systems needed for the mining setup. Ideally, combination of both low electricity prices and rather cold climate would bring greater profits to miners. Furthermore, the use of renewable electricity could also contribute to lowering the electricity expenses. Besides, it would be favourable for the environment if a renewable energy would be employed in the mining process, at least to a certain degree.

According to data from the site Blockchain Charts[13], the country representing the largest part of the Bitcoin mining industry as it accounts for a substantial share of the network hash rate is China due to relatively low electricity prices and its considerable technological progress. Other popular countries for mining are Canada, USA, Island, Sweden, Kazakhstan, Georgia, Iran or some parts of Russia.

The whole overview of Bitcoin mining areas presented in the extensive CoinShares research by Bendiksen and Gibbons (2019) is displayed in the Figure 4 below where it could be seen that the major mining regions are mostly located in the tempered climate zone and partly also in the polar and subpolar climate zone aiming for areas with rather low temperatures.

Furthermore, the latest available data on the household and then the industry electricity prices in the countries popular for Bitcoin mining are displayed in the Table 1 below. Due to difficulties with obtaining representative data, Iran and Russia were excluded from the observations despite the fact they belong to the major mining regions. The data are from the second half of 2019 thus, it could be assumed that the digits would remain rather similar in the first half of 2020.

[13] at `https://www.blockchain.com/pools`

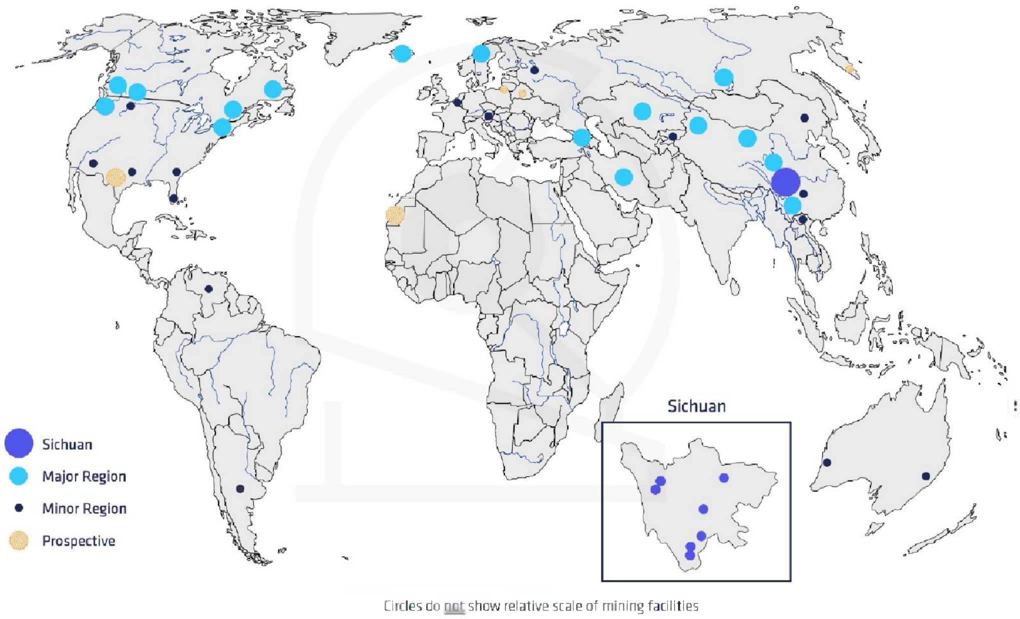

Figure 4: Global Overview of Bitcoin Mining Regions

Source: Bendiksen and Gibbons (2019)

Country	**Household electricity price (USD per kWh)**	**Industry electricity price (USD per kWh)**
Canada	$ 0.100	$ 0.090
Georgia	$ 0.070	$ 0.064
China	$ 0.074	$ 0.084
Island	$ 0.160	$ 0.045
Kazakhstan	$ 0.040	$ 0.050
Sweden	$ 0.230	$ 0.078
USA	$ 0.150	$ 0.110
Average	$ 0.118	$ 0.074

Table 1: Lates available (2019) data on electricity prices in main Bitcoin mining regions

Calculations by author; Data from: CEIC, Eurostat and Global Petrol Prices[14]

It could be seen, in the Table 1, that the household electricity prices range from 0.04 USD per kWh (in Kazakhstan) to 0.23 USD per kWh (in Sweden)

[14]CEIC at `https://www.ceicdata.com/en/china/electricity-price`,
Eurostat at `https://ec.europa.eu/eurostat/statistics-explained/index.php/Electricity\_price\_statistics`,
Global Petrol Prices at `https://www.globalpetrolprices.com/electricity\_prices/`

in the popular Bitcoin mining regions. Whereas, the industry electricity prices fall between 0.045 USD per kWh (in Island) and 0.11 USD per kWh (in the USA) in the observed countries. The average electricity price per kWh in the countries where Bitcoin mining seems to be popular is 0.118 USD for households and 0.074 USD for businesses. As a result, it could be concluded that it would bring greater profits to the miner when having an access to the industry prices for the electricity because they are, in general, lower that the household prices for the electric power.

Therefore, if compared with the results of the performed analysis on the break-even electricity price with focus on the year 2020, it could be stated that under the current circumstances, while assuming miners are using the most efficient mining hardware available it would still only pay off for miners to locate in countries with extremely low electricity prices or to pay the industry electricity price as the estimated break-even price for the electricity in this time frame ranges from 0.10 to 0.20 USD per kWh barely leaving any space for potential profitability. With the regular household electricity prices it would be challenging to earn any profits as on some days the break-even electricity price might actually exceed the household electricity price leading to significant losses for the miner which would have to be covered from any potential profits the miner would earn on other days, eventually resulting in minimal profits, if any, in the long-run. While with the industry prices for electricity there appears to be a better change for the miner to earn profit in the long-run due to the fact that these prices still remain, to some extent, lower that the estimated break-even price for the year 2020. However, if miners would operate in countries which offer low electricity rates, such as Kazakhstan or possibly Georgia, it might still be profitable to mine Bitcoin even at a household electricity rate, in 2020.

3.2 The break-even electricity price for different types of mining hardware at the time of release and then in May 2020

An analysis of different types of mining hardware concerning the break-even electricity price at the time of the release and then in May 2020, leading to the debate on the possible mining profitability would be done, using the same equations as before, only on the monthly level. The results are displayed in the Table 2 below, where the models of mining hardware are rated by the highest efficiency (in Gh/J).

Model	Release	Efficiency (Gh/J)	Break-even el. price at time of release	Break-even el. price May 2020
Bitmain Antminer S19 Pro (110Th)	May-20	33.85	$ 0.14	$ 0.14
Bitmain Antminer S19 (95Th)	May-20	29.23	$ 0.12	$ 0.12
MicroBT Whatsminer M30S	April-20	26.32	$ 0.14	$ 0.11
Bitmain Antminer S17 Pro (50Th)	April-19	25.32	$ 0.19	$ 0.11
Bitmain Antminer S17 Pro (53Th)	April-19	25.31	$ 0.19	$ 0.11
Bitmain Antminer S17+ (73Th)	December-19	25.00	$ 0.13	$ 0.11
ASICminer 8 Nano S 58Th	December-19	23.20	$ 0.12	$ 0.10
Ebang Ebit E11++	October-18	22.22	$ 0.18	$ 0.09
Bitmain Antminer S17 (53Th)	April-19	22.22	$ 0.17	$ 0.09
Bitmain Antminer S17 (56Th)	April-19	22.22	$ 0.17	$ 0.09
Bitmain Antminer S17e (64Th)	November-19	22.22	$ 0.14	$ 0.09
StrongU STU-U8	July-19	21.90	$ 0.19	$ 0.07
MicroBT Whatsminer M31S	April-20	21.74	$ 0.11	$ 0.09
StrongU STU-U8 Pro	September-19	21.43	$ 0.15	$ 0.08
ASICminer 8 Nano 44Th	October-18	20.95	$ 0.15	$ 0.08
Innosilicon T3 43T	January-19	20.48	$ 0.13	$ 0.09
MicroBT Whatsminer M20S	August-19	20.24	$ 0.15	$ 0.07
Ebang Ebit E12+	September-19	20.00	$ 0.13	$ 0.07
Bitmain Antminer T17+ (64Th)	December-19	20.00	$ 0.10	$ 0.08
ASICminer 8 Nano Pro	May-18	19.00	$ 0.17	$ 0.05
Innosilicon T3+ 52T	May-19	18.57	$ 0.23	$ 0.08
Ebang Ebit E11+	October-18	18.18	$ 0.13	$ 0.07
Bitmain Antminer T17 (40Th)	May-19	18.18	$ 0.23	$ 0.08
Bitmain Antminer T17e (53Th)	November-19	18.18	$ 0.11	$ 0.08
Innosilicon T3 39T	March-19	18.14	$ 0.13	$ 0.08
Ebang Ebit E12	September-19	17.60	$ 0.12	$ 0.07
Innosilicon T3+ 57T	September-19	17.27	$ 0.13	$ 0.07
MicroBT Whatsminer M21S	June-19	16.67	$ 0.23	$ 0.07
MicroBT Whatsminer M21	August-19	16.67	$ 0.18	$ 0.09
Innosilicon T3 50T	July-19	16.13	$ 0.26	$ 0.09
MicroBT Whatsminer M10S	September-18	15.71	$ 0.11	$ 0.05

Canaan AvalonMiner 1047	September-19	15.55	$ 0.12	$ 0.07
MicroBT Whatsminer M10	September-18	15.38	$ 0.14	$ 0.07
Ebang Ebit E11	October-18	15.38	$ 0.17	$ 0.09
Canaan AvalonMiner 1066	September-19	15.38	$ 0.16	$ 0.09
Innosilicon T2 Turbo+ 32T	September-18	14.55	$ 0.14	$ 0.07
Bitmain Antminer S11 (20.5Th)	November-18	13.40	$ 0.10	$ 0.05
Holic H28	December-18	13.33	$ 0.08	$ 0.05
Holic H22	December-18	12.94	$ 0.08	$ 0.06
Bitfury Tardis	November-18	12.70	$ 0.11	$ 0.06
Bitmain Antminer S9 SE (16Th)	July-19	12.50	$ 0.15	$ 0.05
Innosilicon T2 Turbo	August-18	12.12	$ 0.11	$ 0.04
Canaan AvalonMiner 921	September-18	11.76	$ 0.13	$ 0.06
Bitfily Snow Panther B1+	August-18	11.67	$ 0.12	$ 0.05
Bitfily Snow Panther B1	July-18	11.59	$ 0.15	$ 0.04
Aladdin Miner 16Th/s Bitcoin	July-18	11.43	$ 0.18	$ 0.05
Innosilicon T2 Terminator	May-18	10.96	$ 0.14	$ 0.04
Ebang Ebit E10	February-18	10.91	$ 0.34	$ 0.04
Halong Mining DragonMint T1	April-18	10.81	$ 0.24	$ 0.04
Bitmain Antminer S9j (14.5Th)	August-18	10.74	$ 0.11	$ 0.05
Bitmain Antminer S9i (14Th)	May-18	10.61	$ 0.16	$ 0.04
Canaan AvalonMiner 841	April-18	10.54	$ 0.25	$ 0.05
Bitmain Antminer S9 Hydro (18Th)	August-18	10.42	$ 0.13	$ 0.05
Bitmain Antminer S9k (13.5Th)	August-19	10.31	$ 0.09	$ 0.04
Bitmain Antminer R4	February-17	10.30	$ 0.30	$ 0.04
Bitmain Antminer S9 (11.5Th)	January-16	10.20	$ 0.22	$ 0.02
Bitmain Antminer S9 (12.5Th)	February-17	10.20	$ 0.30	$ 0.04
Bitmain Antminer S9 (13.5Th)	September-17	10.20	$ 0.32	$ 0.04
Bitmain Antminer S9 (14Th)	November-17	10.20	$ 0.64	$ 0.04
Bitmain Antminer S9i (13Th)	May-18	10.16	$ 0.29	$ 0.08
Bitmain Antminer S9 (13Th)	July-17	10.00	$ 0.35	$ 0.04
GMO miner B3	November-18	9.66	$ 0.08	$ 0.04
Canaan AvalonMiner 821	February-18	9.58	$ 0.39	$ 0.05
Ebang Ebit E9i	July-18	9.51	$ 0.18	$ 0.05
Ebang Ebit E9.3	May-18	9.09	$ 0.14	$ 0.04
Ebang Ebit E9.2	May-18	9.09	$ 0.16	$ 0.04
Bitfily Snow Panther A1	January-18	9.07	$ 0.27	$ 0.03
Pantech SX6	September-17	8.50	$ 0.38	$ 0.04
Bitmain Antminer T9 (12.5Th)	August-17	7.93	$ 0.36	$ 0.03
Bitmain Antminer T9 (11.5Th)	April-17	7.93	$ 0.18	$ 0.03
Bitfury B8	December-17	7.66	$ 0.62	$ 0.03
Bitmain Antminer T9+ (10.5Th)	January-18	7.33	$ 0.29	$ 0.03
Ebang Ebit E9+	January-18	6.92	$ 0.27	$ 0.03
Pantech WX6	January-18	6.80	$ 0.36	$ 0.04
Canaan AvalonMiner 741	April-17	6.35	$ 0.14	$ 0.03
MicroBT Whatsminer M3X	March-18	6.10	$ 0.12	$ 0.03

MicroBT Whatsminer M3	January-18	6.00	$ 0.24	$ 0.03
Bitmain Antminer V9 (4Th)	March-18	3.89	$ 0.07	$ 0.02
Bitmain Antminer S7-LN	January-16	3.87	$ 0.58	$ 0.04
Bitmain Antminer S7	September-15	3.66	$ 0.30	$ 0.02
Bitmain Antminer S5	December-14	1.96	$ 0.29	$ 0.01
Bitmain Antminer S3	January-14	1.31	$ 9.36	$ 0.01

Table 2: Estimated break-even electricity price for different types of mining hardware (released over the years 2014-2020) at the time of the release and then in May 2020 Calculations by author; Original data from: Asic Miner Value, Data Bitcoinity and Quandl[15]

The Table 2 shows, as could be anticipated, that the most efficient mining hardware available is the Bitmain Antminer S19 Pro and then subsequently the Bitmain Antminer S19, both released in May 2020. The estimated break-even electricity price is 0.14 USD per kWh for the former and 0.12 USD per kWh for the latter. As they are rated the first two most efficient, the associated break-even electricity price is the highest from all the observations resulting in potential profitability. When comparing the resulting numbers on the break-even electricity price in May 2020 for the various types of mining hardware with the data on the current electricity rates in Table 1, it could be concluded that it would not seem to pay off for the miner to still mine Bitcoin in 2020 while having hardware from earlier time than approximately December 2019. Despite the fact that such hardware was yielding profits at the time of release as the associated break-even electricity price was higher that the regular rate for electricity. To keep earning decent profits in 2020 it might be risky to use hardware with lower estimated break-even price for electricity than 0.10 USD per kWh, as the industry electricity price in most of the major mining regions, along with household price in Kazakhstan and Georgia, is below that value and with mining hardware having even lower break-even electricity price there would not be that much space to compensate for potential jumps in the charged prices for electricity.

[15] Asic Miner Value at `https://www.asicminervalue.com/`,
Data Bitcoinity at `https://data.bitcoinity.org/markets/price/all/USD?c=e\&t=l`,
Quandl at `https://www.quandl.com/data/BCHAIN-Blockchain`

As could be seen in the Table 2, miners located in these countries might therefore use the following models while still earning profit: ASICminer 8 Nano S (58Th), Bitmain Antminer S17+ (73Th), Bitmain Antminer S17 Pro (53Th), Bitmain Antminer S17 Pro (50Th), MicroBT Whatsminer M30S, Bitmain Antminer S19 (95Th) and Bitmain Antminer S19 Pro (110Th).

The industry electricity price in the major mining regions is higher than 0.10 USD per kWh only in the USA, as there the price is 0.11 USD per kWh. Therefore, if a miner would be located in the USA then even more efficient mining hardware with break-even electricity price exceeding 0.11 USD per kWh would have to be used to yield profit. This means, only Bitmain Antminer S19 and Bitmain Antminer S19 Pro (both released in May 2020) could be utilized for Bitcoin mining in USA to still bring profit to a miner in 2020. Surely the choice of hardware usage depends on the charged electricity prices at the place where the miner is located however, the electricity prices vary so in general, it could be said that having a hardware with lower break-even electricity price than the mentioned 0.10 USD per kWh might generate losses rather than profit in the long-run.

The choice of hardware for Bitcoin mining mainly depends on each individual and the amount of profits they aim to generate. The maximum electricity price a miner could afford to pay while still earning profits would be right under the break-even electricity price for the employed hardware. The question is, whether an extremely low profit would still be better for the miner than no profit arising with shutting down the systems. Or if the miner would rather relocate the resources to another goal and earn larger profits in other field of interest than Bitcoin mining. This issue leads to unused mining capacities which arise when mining is no longer profitable for the miner as in such case the miners shut down the systems and refocus to another source of income. Consequently, when the Bitcoin market price suddenly increases this formerly put aside mining hardware might participate in the network again as it appears likely to be profitable for the miner to resume the Bitcoin mining, by which contributing more hash power to the network once more.

As mentioned earlier, the displayed numbers (Figures 2 and 3, Table 2) on the break-even electricity price, leading to information on the overall Bitcoin mining profitability, are computed under the assumption that a miner already has the full mining setup and without accounting for the original investment in the mining hardware. The prices of such hardware appear to be estimated in such way that the return on the investment might be approximately 10 months. Nonetheless, there are no specific data available on its lifespan which results in difficulties with the estimation of expenses connected to the mining hardware. Therefore, making it difficult to evaluate whether it would still pay off to purchase the necessary hardware and start mining Bitcoin in 2020. It could be argued that with the current level of the estimated break-even electricity price it would not seem to be a lucrative idea to invest means into the mining hardware in 2020 and begin mining Bitcoin, as it would take a long time to generate such funds that it would cover the initial investment, before even starting to earn regular profit.

4 Interactions between the estimated break-even electricity price and the Bitcoin market price

The relationship between the Bitcoin market price (in USD) and the estimated break-even electricity price (in USD and then in BTC) which suggests the level of the mining profitability, would be examined in this section using a cointegration analysis. The used data would be from the years 2015 to 2020. Following up on the previous calculations, the results on the break-even electricity price would be used. Along with data on the Bitcoin market price, those from the site Data Bitcoinity[16] as before. The calculations and model estimates would be done in Gretl.

4.1 Constructing the model and performing tests

The possible cointegration relationship between two time-series variables would be investigated in this section based on the fact that both of the variables are very likely nonstationary as they are rather inconsistent in values over time. Therefore, the cointegration analaysis would be performed, similarly as in the work of Kristoufek (2020), attempting to correct for the nonstationarity of the data and revealing there is a cointegration relationship between the two stochastic processes. In the model the explained variable would be the estimated break-even electricity price while the explanatory variable would be the Bitcoin market price. To observe the expected percentage change in the break-even electricity price when the Bitcoin market price alters by a certain percentage, the log-log model would be utilized (working with natural logarithm). The basic static model could then be written as:

$$\log(y_t) = \beta_0 + \beta_1 \log(x_t) + \epsilon_t \tag{13}$$

where $t = 1, ..., T$ is a time index, β_0 is the intercept, β_1 a coefficient determining the effects of $\{x_t\}$ on $\{y_t\}$, and $\{\epsilon_t\}$ is an error term.

The values of the estimated break-even electricity price and the Bitcoin

[16] at `https://data.bitcoinity.org/markets/price/all/USD?c=e\&t=l`

market price are plotted in the Figure 5 below using logarithmic scale, showing the data series are very likely nonstationary due to high volatility in time (the sequence is not identically distributed), as discussed earlier.

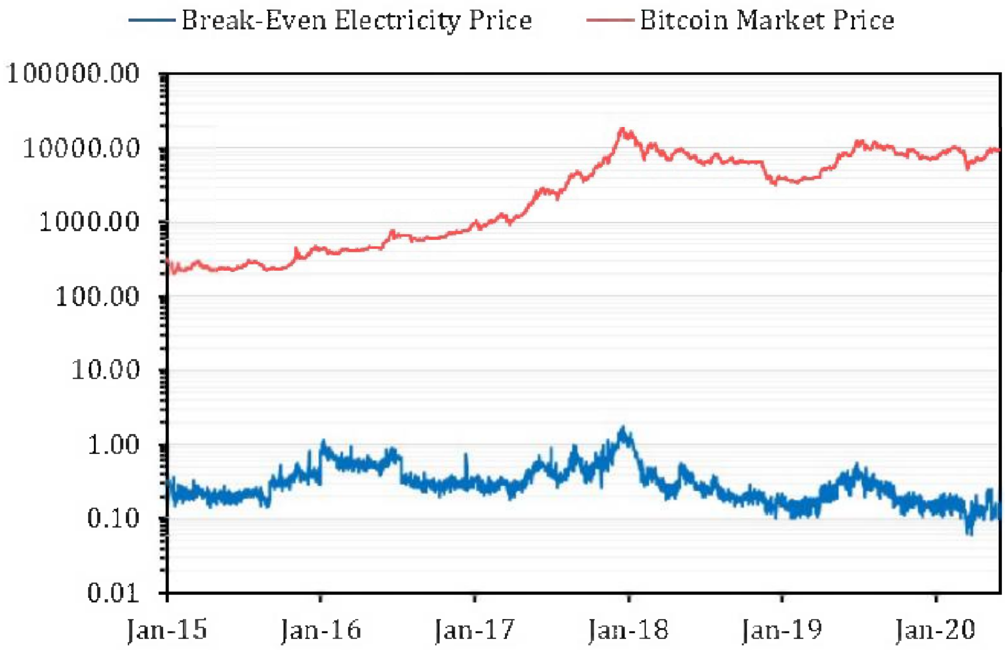

Figure 5: The values of the break-even electricity price (in USD) and the Bitcoin market price in the logarithmic scale

To verify this notion the augmented Dickey-Fuller test for the unit roots would be performed - the null hypothesis that a unit root is present in the series would be tested. And as the unit roots null hypothesis was not rejected ($p = 0.23$ for the break-even electricity price and $p = 0.89$ for the Bitcoin market price) both stochastic processes are nonstationary, as assumed. Also, the results show that both variables of interest possess a unit root therefore, they are of the same level of integration. Such unit root processes are said to be integrated of order one, or $I(1)$. Meaning that the first difference of the process would be weakly dependent and also likely stationary.

Following up on this notion, the vector error correction model would be constructed:

$$\Delta \log(y_t) = \alpha_0 + \alpha_1 \Delta \log(x_t) + \delta[\log(y_{t-1}) - \widehat{\log(y_{t-1})}] + u_t \qquad (14)$$

where $\delta[\log(y_{t-1}) - \widehat{\log(y_{t-1})}]$ is the error correction term. When $\delta < 0$ the error correction term works in such way that it navigates y back to the equilibrium. However, when $\delta > 0$ it leads to y diverging from the equilibrium. Consequently, rewriting the error correction model using the vector autoregression (VAR) form while using the Bayesian information criterion to recognize that the optimal number of lags is $k = 4$ (for both the model with and without a time trend), yields:

$$\Delta \log(x_t) = \alpha_{10} + \sum_{i=1}^{k-1} \alpha_{1i} \Delta \log(x_{t-i}) + \sum_{j=1}^{k-1} \beta_{1j} \Delta \log(y_{t-j}) + \delta_1 [\log(y_{t-1}) - \widehat{\log(y_{t-1})}] + u_{1t} \quad (15)$$

$$\Delta \log(y_t) = \alpha_{20} + \sum_{i=1}^{k-1} \alpha_{2i} \Delta \log(x_{t-i}) + \sum_{j=1}^{k-1} \beta_{2j} \Delta \log(y_{t-j}) + \delta_2 [\log(y_{t-1}) - \widehat{\log(y_{t-1})}] + u_{2t} \quad (16)$$

To better observe the cointegration relationship between the variables and to determine the significance of a time trend in the model the vector autoregression would be done - using the following equation 17 which is based on the work of Hendry and Juselius (2001). The equation could be written as:

$$\Delta \log(X_t) = \sum_{i=1}^{k} \phi_i \Delta \log(X_{t-i}) + \Pi \log(X_{t-1}) + \pi + \gamma t + \epsilon_t \quad (17)$$

where ΔX_t is a vector of (2×1) differenced series at time t, ΔX_{t-i} represents a (2×1) vector of differenced lagged values of the series at various time periods, ϵ_t is a vector of error disturbances at time t, the constant term for each variable is represented by $\pi(2 \times 1)$ vector while the time trend by $\gamma(2 \times 1)$ vector. The short-term cointegration relationship between the lagged values of the two variables is represented by $\phi_i(2 \times 2)$ matrix, where $i = 1, ..., k$. The long-term cointegration relationship determining the effects the lagged values of the variables have on the other variable is portrayed by $\Pi(2 \times 2)$ matrix.

The vector autoregression shows that the time trend is significant in this model specification therefore it would be accounted for in the computations. Then, to test for cointegration of the observed time-series data the Johansen tests (Trace test and Likelihood ratio test) would be employed with results displayed in the Table 3 below. The results point to a cointegration relationship between the variables as with both the tests the null hypothesis of no cointegration could be rejected in the first vector (with the trace test on the 90% confidence interval and with the likelihood ration test even on the 95% interval) and therefore it could be said there is one cointegrated vector.

Rank	Test statistic	Trace	p-value	L_{max}
0	24.3950	0.0740	21.7730	0.0192
1	2.6226	0.9044	2.6226	0.9058

Table 3: Output from the Johansen test for the break-even electricity price (in USD) and the Bitcoin market price

Consequently, the final vector error correction model specification could be estimated while using the specification with the restricted trend. The estimates are displayed in the Table 4 below.

Lastly, to test for the unit roots in the error correction term in the last model the augmented Dickey-Fuller test would be performed. The null hypothesis of a unit root presence was rejected ($p = 0.0016$) for the used model specification with restricted trend. The stochastic process is therefore stationary and the constructed vector error correction model could be used for the final interpretation.

In addition, it is necessary to inspect whether the standard time-series assumptions hold in the regression analysis. That is, to check for the normality of error terms, chech for remaining serial correlation and to test for possible heteroskedasticity. As for the normality, the utilized data set contains a large number of daily observations, therefore the χ^2 statistic is high ($\chi^2(4) = 1146.34$ and $p < 0.0001$) in the Doornik-Hansen test, rejecting the null hypotheses of normality in error terms. However, due to a large set of daily data the model is still valid despite such results. As displayed in the Table 3, the Durbin-Watson statistic is around 2 for both equations (precisely 2.0905 for the break-even electricity price equation and

2.0004 for the Bitcoin market price equation) meaning that there was no autocorrelation detected in the residuals.

	Coefficient	SE	t-statistic	p-value
Break-even electricity price equation				
Constant	-0.1226	0.0281	-4.3620	<0.0001
$\Delta log(ElPrice\_BE_{t-1})$	-0.9225	0.0230	-40.0500	<0.0001
$\Delta log(ElPrice\_BE_{t-2})$	-0.6033	0.0276	-21.8400	<0.0001
$\Delta log(ElPrice\_BE_{t-3})$	-0.2912	0.0219	-13.3100	<0.0001
$\Delta log(BTC\_Price_{t-1})$	1.0003	0.1245	8.0370	<0.0001
$\Delta log(BTC\_Price_{t-2})$	0.6755	0.1284	5.2610	<0.0001
$\Delta log(BTC\_Price_{t-3})$	0.4447	0.1251	3.5550	0.0004
EC_{t-1}	-0.0432	0.0102	-4.2290	<0.0001
R^2	0.5083	Durbin-Watson statistic	2.0905	
$\overline{R}^2$	0.5063	$\hat{\rho}$	-0.0453	
Bitcoin market price equation				
Constant	0.0072	0.0052	1.3950	0.1632
$\Delta log(ElPrice\_BE_{t-1})$	-0.0024	0.0042	-0.5630	0.5735
$\Delta log(ElPrice\_BE_{t-2})$	0.0058	0.0051	1.1380	0.2554
$\Delta log(ElPrice\_BE_{t-3})$	0.0021	0.0040	0.5112	0.6093
$\Delta log(BTC\_Price_{t-1})$	0.2680	0.0229	11.7200	<0.0001
$\Delta log(BTC\_Price_{t-2})$	-0.0906	0.0239	-3.8400	0.0001
$\Delta log(BTC\_Price_{t-3})$	0.0337	0.0230	1.4680	0.1422
EC_{t-1}	0.0021	0.0019	1.1410	0.2538
R^2	0.0695	Durbin-Watson statistic	2.0004	
$\overline{R}^2$	0.0657	$\hat{\rho}$	-0.0002	

Table 4: Vector error correction model final estimates

There might be remaining serial correlation testing on 7 lags ($F(28, 3912) = 3.391$ and $p < 0.0001$) and the null hypothesis of homoskedasticity was also rejected testing on 7 lags ($\chi^2(63) = 520.021$ and $p < 0.0001$). Therefore, the heteroskedasticity and autocorrelation consistent (HAC) standard errors estimators would be used during the process of model estimation. Then, the statistical significance of the explanatory variable (Bitcoin market price) could be tested along with the joined significance.

4.2 Comments on the estimates, Granger causality and response to shocks

As for the final estimates of the vector error correction model, in the Table 4 it is shown that in the break-even electricity price equation the coefficient associated with the error correction term is negative ($\delta_1 = -0.0432$) therefore it navigates y back to the equilibrium as needed. In the Bitcoin market price equation this coefficient is positive ($\delta_2 = 0.0021$) however, the results do not show any significance in the error correction term in this equation - the possibility that $\delta_2 = 0$ could not be rejected.

Moreover, in the break-even electricity price equation all the variables are estimated to be significant. Meaning that the break-even electricity price is affected by its own lagged values, and that in a negative way as a percentage increase in the lagged values is followed by a percentage decrease in the dependent variable and a percentage decrease in the lagged values of the break-even electricity price results in a percentage increase in the value of the dependant variable ($\beta_{21} = -0.9225$, $\beta_{22} = -0.6033$, $\beta_{23} = -0.2912$). Therefore, when the break-even electricity price suddenly deviates it returns towards the preceding values rather quickly as the estimated coefficients are negative, significant and of quite extensive percentage values. It is also affected by the lagged values of the Bitcoin market price, when a percentage change in the lagged values of the Bitcoin market price is accompanied by a relatively large percentage change in the same direction in the break-even electricity price ($\alpha_{21} = 1.003$, $\alpha_{22} = 0.6755$, $\alpha_{23} = 0.4447$). Therefore, with a sudden percentage increase in the Bitcoin market price the break-even electricity price would react by relatively large percentage increase. This appears as a logical situation due to the fact that the break-even electricity price estimates basically determine the final profitability of Bitcoin mining (with higher break-even electricity price there is higher chance on earning higher profits) so with increasing price of Bitcoin the break-even electricity price would increase as well marking greater potential for profitability with higher value of the gained block reward along with transaction fees. On the other hand, in the Bitcoin market price equation the only variables estimated to be significant in this model specification are the first two lagged values of the Bitcoin market price with the first lag having a positive effect on the dependent variable and the second lag having negative but relatively low effect on the current value of the Bitcoin market price ($\alpha_{11} = 0.2680$, $\alpha_{12} = -0.0906$). It could be seen in the Table 3 that in the break-even electricity price equation the estimated coefficients for the Bitcoin market price are approaching one, with the coefficient for the first lag being equal to approximately one ($\alpha_{21} = 1.003$). This is rather problematic in the model interpretation. However, there is a valid reason for such happening. In the section 2 of this thesis it could be seen that the break-even electricity price is computed using multiple variables, including the Bitcoin market price itself. Therefore, as Bitcoin market price is included in the equations determining the final values of the break-even electricity price estimates it is natural that it would have a significant effect on its final values. This issue would be further discussed and corrected for in the following subsection 4.3.

Despite the fact that the coefficients being close to one seem to be problematic, it appears to be rational as with rapidly increasing Bitcoin market price the break-even electricity price would notably increase as well with rewards for mining suddenly bringing greater revenues in the short-run before other factors (such as more miners joining the system and raising the network hashrate) manage to impact the network.

Furthermore, it would be tested for Granger causality in the lagged values of both variables to test for the join significance of the lagged values of each variable in the equations, with the following results. In the short-term the null hypotheses of no Granger causality is rejected ($F(4, 1966) = 25.448$

and $p < 0.0001$) in the break-even electricity price equation for the Bitcoin market price therefore there is causality from the lagged values of the Bitcoin market price towards the break-even electricity price and the Bitcoin market price affects the values of the break-even electricity price. As for the Bitcoin market price equation, the null hypotheses could not be rejected when testing for Granger causality in the lagged values of the break-even electricity price ($F(4, 1966) = 1.4172$ and $p = 0.2257$) so there is no causality in the lagged values of break-even electricity price towards the Bitcoin market price. In the long-term the results are rather similar pointing out that there is causality in the first case ($F(7, 1962) = 15.797$ and $p < 0.0001$) however the null hypotheses can not be rejected in the second scenario again ($F(7, 1962) = 1.0496$ and $p = 0.3941$). Meaning that there is causality in the lagged values of Bitcoin market price towards the break-even electricity price both in the short-run and in the long-run but it is not in the lagged values of the break-even electricity price towards Bitcoin market price values and that in the short-term and also in the long-term time horizon.

To further examine the effects the inspected variables have on one another, the impulse-response functions yielding from the estimated vector error correction model would be explored. Those could be seen in the Figure 6, portraying the effects a single standard deviation shock in one of the variables has on the another one and that in the short-term as well as in the long-term.

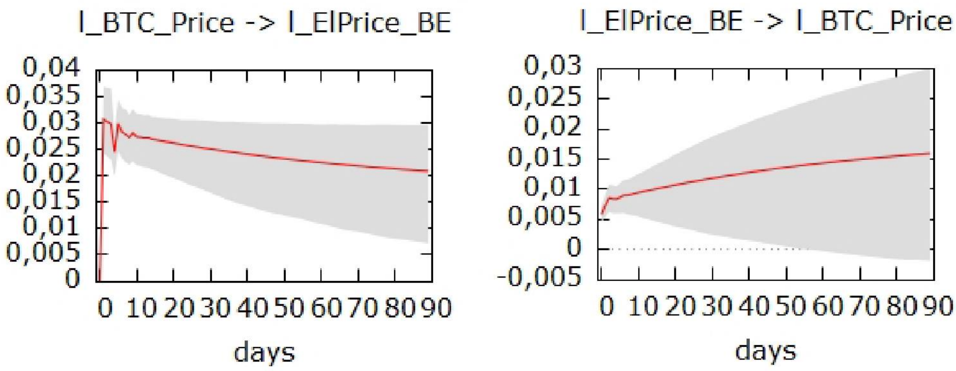

Figure 6: The impulse-response functions portraying the effects of shocks between the break-even electricity price (in USD) and the Bitcoin market price

In the first graph, in the Figure 6, the curve displays the reaction that the estimated break-even electricity price has on the single standard deviation shock in the Bitcoin market price. It is shown here that there is a sudden reaction in the break-even electricity price value to the shock in Bitcoin market price which then gradually levels off over the course of approximately 3 months. However, the reaction is only of a minor extent in the short-run as with one standard deviation shock to the Bitcoin market price the reaction in the break-even electricity price is approximately 3% ($0.03 \cdot 100\%$) as of one day. Then further declining in the long-run. The second graph portrays the opposite reaction, that is, the effect a single standard deviation shock in the break-even electricity price has on the Bitcoin market price. The curve demonstrates that with the shock to the break-even electricity price the Bitcoin market price reacts with again only a slight change in the short-run as the proportion of the initial reaction is around 0.75% ($0.0075 \cdot 100\%$). Then followed by a minor increase in the effect in the long-run slowly stabilising over the upcoming 3 months.

4.3 Adjusting the model

To eliminate the above mentioned problem of the coefficient associated with the first lag of Bitcoin market price being equal approximately to one in the break-even electricity price equation in the model estimation, the input data on the break-even electricity price would be divided by the Bitcoin market price. This would remove the Bitcoin market price from the said variable and it would lead to clearer model interpretation. It is essential to note that such operation results in the numbers on the break-even electricity price suddenly showing values in BTC (instead of the original USD).

Now, the construction of the model would be repeated accordingly to the steps described in the previous case. Starting with the augmented Dickey-Fuller test for the variables of interest. As it was already performed for the Bitcoin market price during previous calculations and the results are known, it would be now performed for the newly estimated variable, the break-even electricity price in BTC. The output form the test ($p = 0.913$) shows that the tested variable possesses a unit root and it could therefore be said that it is nonstationary, similarly to the Bitcoin market price. Consequently, the same steps as in the previous model construction could be applied. Again, constructing the vector error correction model and then rewriting it using the vector autoregression (VAR) form while using the Bayesian information criterion to recognize that the optimal number of lags is again $k = 4$ (for both the model specification with and without a time trend), as before. Moreover, as it was in the previous case, the vector autoregression points out a significance in a time trend in this model specification therefore the time trend would be included in the estimating process. Afterwards the Johansen tests would be performed to test for cointegration between the two variables. The results, shown in Table 5, are very similar to the previous case, again revealing that there is a cointegration relationship between the break-even electricity price (in BTC) and the Bitcoin market price as both the tests (Trace and likelihood ratio) rejected the null hypothesis of no cointegration in the first vector.

Rank	Test statistic	Trace	p-value	L_{max}
0	24.1460	0.0795	21.6060	0.0205
1	2.5398	0.9121	2.5398	0.9134

Table 5: Output from the Johansen test for break-even electricity price (in BTC) and the Bitcoin market price

Then, using the specification with restricted trend, the final vector error correction model specification could be estimated, as follows in the Table 6.

Finally, to test for the unit roots in the error correction term the augmented Dickey-Fuller test would be employed. The results show that when including both constant and a trend in the model specification the unit root hypotheses could not be rejected that clearly ($p = 0.1177$). However, it inclines to the model specification being correct as the value is rather low (the null hypotheses could still be rejected at a 85% confidence interval), meaning the model could be used for final interpretation.

	Coefficient	SE	t-statistic	p-value
Break-even electricity price equation				
Constant	-0.1289	0.0273	-4.7150	<0.0001
$\Delta log(ElPrice\_BTC_{t-1})$	-0.9201	0.0226	-40.6400	<0.0001
$\Delta log(ElPrice\_BTC_{t-2})$	-0.6091	0.0215	-22.4400	<0.0001
$\Delta log(ElPrice\_BTC_{t-3})$	-0.2933	0.0215	-13.6400	<0.0001
$\Delta log(BTC\_Price_{t-1})$	-0.1880	0.1209	-1.5560	0.1200
$\Delta log(BTC\_Price_{t-2})$	0.1572	0.1246	1.2610	0.2073
$\Delta log(BTC\_Price_{t-3})$	0.1179	0.1209	0.9748	0.3298
EC_{t-1}	-0.0455	0.0100	-4.5320	<0.0001
R^2	0.5170	Durbin-Watson statistic	2.0937	
$\overline{R}^2$	0.5150	$\hat{\rho}$	-0.0469	
Bitcoin market price equation				
Constant	0.0066	0.0051	1.2900	0.1972
$\Delta log(ElPrice\_BTC_{t-1})$	-0.0022	0.0042	-0.5230	0.6010
$\Delta log(ElPrice\_BTC_{t-2})$	0.0059	0.0051	1.1590	0.2468
$\Delta log(ElPrice\_BTC_{t-3})$	0.0021	0.0040	0.5223	0.6015
$\Delta log(BTC\_Price_{t-1})$	0.2639	0.0226	11.7000	<0.0001
$\Delta log(BTC\_Price_{t-2})$	-0.0842	0.0233	-3.6220	0.0003
$\Delta log(BTC\_Price_{t-3})$	0.0361	0.0226	1.6010	0.1096
EC_{t-1}	0.0019	0.0019	1.0200	0.3080
R^2	0.0687	Durbin-Watson statistic	1.9993	
$\overline{R}^2$	0.0649	$\hat{\rho}$	0.0003	

Table 6: The adjusted vector error correction model final estimates

Again, verifying that all the standard assumptions hold. Using the Doornik-Hansen test, the normality of error terms is rejected as in the previous case ($\chi^2(4) = 1162.42$ and $p < 0.0001$) nevertheless, due to large number of daily observations in the utilized data set this is not problematic and the model could still be considered valid. In the Table 6 it could be seen that the Durbin-Watson statistic is again around 2 for both of the equations (2.0937 for the break-even electricity price equation and 1.9993 for the Bitcoin market price equation) therefore it can be concluded that there is no autocorrelation in the residuals. There might be remaining serial correlation testing on 7 lags ($F(28, 3904) = 3.416$ and $p < 0.0001$) as the null hypotheses of no autocorrelation was rejected and the homoskedasticity is also rejected testing on 7 lags ($\chi^2(63) = 521.028$ and $p < 0.0001$) therefore, as in the original model specification, the HAC standard errors estimators would be used during the model estimation.

4.4 Interpretation of the results and further clarification

It could be seen, in the table 6, that the problem was corrected for successfully as the adjusted model yields more acceptable results. The estimated coefficients associated with the Bitcoin market price, in the break-even electricity price equation, are now all lower than one ($\alpha_{21} = -0.1880$, $\alpha_{22} = 0.1572$, $\alpha_{23} = 0.1179$) bringing more representative information. However, the lagged values of the Bitcoin market price were not estimated to be significant in this equation. Similarly as in the previous model specification the coefficients associated with the lagged values of the break-even electricity price (now in BTC), in this equation, are estimated to be strongly significant, negative and of notable values ($\beta_{21} = -0.9201$, $\beta_{22} = -0.6091$, $\beta_{23} = -0.2933$) leading to the break-even electricity price quickly returning to the original values after potential deviation.

As for the coefficient associated with the error correction term in the adjusted model the results are very similar to the previous case. The adjusted vector error correction model final estimates in the Table 6 show that, in the break-even electricity price equation this coefficient is negative ($\delta_1 = -0.0455$), as in the previous case, therefore it works in such way that it manages to navigate y back to the equilibrium by which it is correcting for the deviation. Moreover, in the Bitcoin market price equation this coefficient is positive again ($\delta_2 = 0.0019$) while similarly to the previous model estimates, there is no significance in the error correction term in this equation.

To uncover whether the effects the variables have on each other altered as a result of the model adjustment, the Granger causality would be tested for and then the impulse-response functions yielding from the estimated vector error correction model would be examined. The results from the Granger causality testing show that there is no causality from Bitcoin market price towards the break-even electricity price ($F(4, 1961) = 0.97513$ and $p = 0.4199$) and there also is no causality in the opposite direction between the variables ($F(4, 1961) = 1.4000$ and $p = 0.2315$) in the short-run. However, there is a strong Granger causality from the Bitcoin market price lagged values to the break-even electricity price in BTC ($F(5, 1961) = 3.9844$ and $p = 0.0013$) in the long-run. The results further show that there is no causality in the lagged values of the break-even electricity price in BTC towards the Bitcoin market price ($F(5, 1961) = 1.2338$ and $p = 0.2906$) in the long-run.

To support these results, the Figure 7 shows the impulse-response functions generated from the vector error correction model.

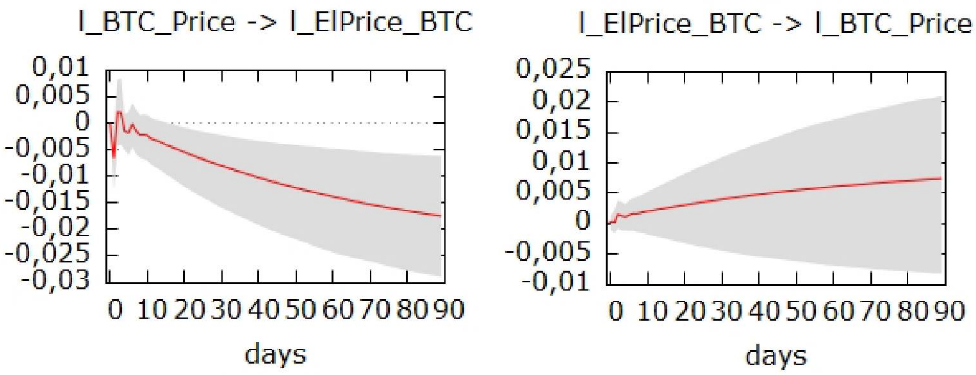

Figure 7: The impulse-response functions portraying the effects of shocks between the break-even electricity price (in BTC) and the Bitcoin market price

It could be seen, in the Figure 7 that the short-term reaction to shocks in each variable is only of a small size in both cases as with a single standard deviation shock in the Bitcoin market price the initial first day reaction in the break-even electricity price is approximately -0.5% ($-0.005 \cdot 100\%$), and with a single standard deviation shock in the break-even electricity price the first day reaction in the Bitcoin market price is less than 0.25% ($0.0025 \cdot 100\%$). Moreover, the reaction of the break-even electricity price to the shocks in the Bitcoin market price in the long-term is of larger proportions as its significance is increasing with time. As for the long-term reaction of the Bitcoin market price to the shocks in the break-even electricity price, it is only minor, slowly levelling off over the course of approximately 3 months. Compared to the original model the results are not that different in the case of a single standard deviation shock in the break-even electricity price affecting the Bitcoin market price, in both cases showing that the effect is not very significant and it moves in the similar direction, only being slightly larger in the original model. However, as for the single standard deviation shock in the Bitcoin market price having impact on the break-even electricity price the results remotely vary. The short-term reaction in the break-even electricity price is notably more significant in the original model (3%) than in the adjusted model (-0.5%). Nevertheless, the long-term reaction levelling off over the course of 3 months is of the same proportion in both models eventually however, it is negative in the adjusted model and positive in the original model. Also, the difference between the original reaction and the final reaction in the long-term is larger in the adjusted model as the curve shifts from the initial values around 0 to the final value of approximately -1.75% ($-0.0175 \cdot 100\%$). Meaning that in the long-run the Bitcoin market price has an effect of a similar significance on a single standard deviation shock both in values of the break-even electricity price in BTC and in the values in USD while the reaction of the break-even electricity price in BTC is negative and the reaction of the break-even electricity price in USD is positive.

Conclusion

This thesis discussed the topic of Bitcoin mining profitability with focus on the year 2020, based on the break-even electricity price estimates. Bitcoin mining is a process whose resulting profitability is affected by many factors and as it requires excessive amounts of energy the electricity prices have a crucial role in determining the final profitability. Therefore, the variables affecting the Bitcoin mining profitability such as the block reward, transaction fees, network hash rate and others were utilized to estimate the break-even electricity prices while the calculations were done assuming miners own the most efficient mining hardware available at the time - omitting the original investment in the necessary equipment. Then continuing with analysis of various types of mining hardware, again excluding the original investment from the calculations. It was estimated that the break-even electricity prices are rather low, not leaving space for large profits in 2020. Such results lead to speculations about the miner's source of electric power with conclusion that it would bring greater profits to miners when they have an access to extremely low-price electricity. Consequently, it is beneficial for miners to locate in countries with low household electricity prices or more so have an access to industry electricity prices in countries with low rates. In addition having specific industry contracts with more favourable terms and additional discounts on electricity. Then being located in the countries with rather cold climate by which decreasing the costs for cooling systems. There is also a popular option of acquiring electricity from renewable resources by which decreasing the expenses along with reducing the negative impacts of the Bitcoin mining industry on the environment. In conclusion, it appears to be challenging to earn significant profits by Bitcoin mining in 2020 however, it is still possible to make continuous profits under specific circumstances.

In the following part of the thesis the possible cointegration relationship between the estimated break-even electricity price values and the Bitcoin market price was investigated with results pointing to the Bitcoin market price lagged values having a significant effects on the break-even electricity price. Such results might be caused by the fact that the Bitcoin market price was used during the calculations estimating the break-even electricity prices. Therefore, the model was then adjusted and this cause was eliminated from the model. Then still showing that the lagged values of the Bitcoin market price are affecting the break-even electricity price. Moreover, illustrating that there is rather long-term reaction in the break-even electricity price values to sudden shocks in the Bitcoin market price. Meaning that with change in the Bitcoin market price, the break-even electricity price diverges form its original value, being affected by shocks in the Bitcoin market price.

To conclude, this thesis brings insights on the topic of Bitcoin mining profitability with results showing that it would be rather difficult to still earn significant profits in 2020 by Bitcoin mining. Therefore, as for the suggested topics for further research, it might be interesting to observe how would the situation evolve in the future, also taking into account the last halving event which occurred on May 11 in 2020 as the reward dropped to 6.25 BTC per mined block, having significant effect on the mining revenues. Moreover, it would be insightful to attempt computing the expenses connected with the mining hardware investments, which were omitted in this thesis. Then accounting for the original investments in the necessary equipment in the calculations and estimating its impact on the resulting Bitcoin mining profitability.

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