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A MINER FOR EVERYONE? VALUING A BITCOIN MINING OPTION

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ABSTRACT

The world of cryptocurrencies began in 2008 when the pseudonym Satoshi Nakamoto released the Bitcoin whitepaper and registered the domain bitcoin.org. On the 3rd of January 2009 Nakamoto created the first block of the Bitcoin blockchain and started mining the first ever Bitcoins on a computer central processing unit. This paper takes a deeper look at the world of Bitcoin mining. The real option of having the possibility to start mining at any point in time is valued using the net present values of such an operation and applying the Longstaff and Schwartz method. The analysis extends over Portugal, Germany, Poland, Hungary and Turkey, while considering three different miners and assessing whether the operations is to be considered profitable. Importantly, the research is framed from the viewpoint of an individual, who is thinking about acquiring a single Bitcoin miner to start operations from home and hereby creating passive income. Bitcoin, electricity prices and the total Hash Rate have been forecasted using different approaches such as the Monte Carlo simulation and Exponential Smoothing. The results show that even though the option has a positive value in all cases, the level of electricity prices is a decisive factor for probability of option exercise. While in Germany and Portugal only a few of the 10,000 forecasted paths lead to exercise with a needed Bitcoin price of several millions, in Türkiye several hundreds of exercises can be obtained at a much lower necessary Bitcoin price, representing a significantly more valuable real option.

O mundo das criptomoedas começou em 2008, quando o pseudónimo Satoshi Nakamoto publicou o whitepaper sobre a Bitcoin e registou o domínio bitcoin.org. Em 3 de janeiro de 2009, Nakamoto criou o primeiro bloco da blockchain da Bitcoin e começou a minerar as primeiras Bitcoins numa unidade central de processamento de um computador. Este documento analisa em profundidade o mundo da mineração de Bitcoin. A opção real de ter a possibilidade de iniciar a mineração em qualquer momento é avaliada utilizando os valores actuais líquidos dessa operação e aplicando o método de Longstaff e Schwartz. A análise estende-se a Portugal, Alemanha, Polónia, Hungria e Turquia, considerando três mineradoras diferentes e avaliando se as operações devem ser consideradas rentáveis. É importante salientar que a investigação é enquadrada do ponto de vista de um indivíduo que está a pensar em adquirir uma único mineradora de Bitcoin para começar a operar a partir de casa e assim criar um rendimento passivo. A Bitcoin, os preços da eletricidade e a Hash Rate total foram previstos utilizando diferentes abordagens, como a simulação de Monte Carlo e a suavização exponencial. Os resultados mostram que, embora a opção tenha um valor positivo em todos os casos, o nível dos preços da eletricidade é um fator decisivo para a probabilidade de exercício da opção. Enquanto na Alemanha e em Portugal apenas algumas das 10.000 trajectórias previstas conduzem a esse exercício, com um preço necessário da Bitcoin de vários milhões, na Turquia podem ser obtidas várias centenas de cenários de exercício a um preço necessário da Bitcoin muito inferior, o que representa uma opção real significativamente mais valiosa.

Keywords: Cryptocurrency, Bitcoin mining, Real Option Theory

JEL Codes: C53 ; G10; G17; O33.

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LIST OF ABBREVIATIONS

ASIC – Application Specific Integration Circuits

BTC – Bitcoin

CAPEX – Capital Expenditures

CPU – Central Processing Unit

ECB – European Central Bank

FPGA – Field Programmable Gate Arrays

GPU – Graphic Processing Unit

kWh – Kilowatt Hour

LSM – Least-Squares Monte Carlo

PoS – Proof of Stake

PoW – Proof of Work

TH/s – Tera Hash per Second

W – Watt

TABLE OF CONTENTS

FIGURES AND TABLES

1. INTRODUCTION

The vision of Satoshi Nakamoto, the pseudonym under which Bitcoin was fabricated, was to create a "purely peer-to-peer version of electronic cash" (p.1), which would enable users to send payments without a third-party financial institution. The network relies on a timestamp server, which is public and visible for everyone, proving that the data in question must have existed at a certain point in time (Nakamoto, 2008). This public and distributed ledger consists of so-called blocks. Each of the blocks incorporates a list of transactions done within a certain time period (Baron et al., 2015; Kroll et al., 2013). Since all users of the network are anonymous, a consensus mechanism had to be implemented. The consensus, that the block created is the right one and will be added to the blockchain, is archived with the "Proof of Work" mechanism (PoW). To create a new block a computer must find the right Hash function, which can only be done by guessing the input (Baron et al., 2015). This cryptographical puzzle demands large amounts of computing power (Kroll et al., 2013). The idea is based on the premise that whoever finds the right solution for the block shows that they have put a lot of work into it (in form of computing power and electricity) (Tapscott & Tapscott, 2016). This process is called mining.

Following Satoshi Nakamoto's lead, people started mining Bitcoins on their personal computers (Cocco & Marchesi, 2016; Ghimire, 2019). Over time an increasingly larger number of people joined in on the mining activities, which lead mining to evolve. Today miners use hardware known as ASIC miners (Cocco & Marchesi, 2016). A significant entry of companies into this space has been noted, with some being valued at several billion US Dollars (CompaniesMarketCap, n.d.). A person interested in Bitcoin and the cryptocurrency space could additionally be tempted to engage in mining activities on their own accord, which raises the question as to whether it is possible to run a profitable mining operation from home. Bitcoin can be described as a highly volatile asset class (Walther et al., 2018), therefore, the profitability of a mining operation is affected by its price and other external factors. Hence the research question of this paper does not focus on whether mining is profitable right now, but takes into account a variety of possible future prices:

How valuable is the real option of having the possibility of starting a Bitcoin mining operation for a person based in one of the five examined European countries at any point in time starting on 01.05.2024 until the 31.12.2025?

This research uses different types of forecasts: (1) electricity and Bitcoin prices are determined using the Monte Carlo simulation and (2) for the Hash Rate Exponential Smoothing has been applied. The sample focuses on data from five countries: Portugal, Germany, Türkiye, Poland and Hungary. The scope behind the chosen country focus is to represent the electricity price margin in European countries. Hereby, Germany displays one of the highest and Türkiye one of the lowest electricity prices. Portugal has been chosen as the benchmark, despite it lying in the upper European range. Poland and Hungary represent countries of lower price range and are useful for comparison. The selection offers a sensitivity analysis to electricity prices, a dampened Hash Rate forecast provides the sensitivity analysis for the Hash Rate forecast. The obtained data is used to see whether an option on the underlying real event can create value and if there are possibilities where mining may create positive returns and allows for passive income to be obtained.

First a general introduction to the topic is presented, explaining and discussing the most relevant information about blockchain technology and the Bitcoin network. Its functions are laid out and the aspects of mining, incentives, hardware and pools are inspected. Subsequently, the relevant literature on former research is examined. The main section presents and discusses the forecasts, how models and calculations are set, explained and runed, while also elaborating on how results are interpreted and discussed.

2. BACKGROUND

The financial crisis of 2008/9 triggered a significant decline in public trust in the international banking system and the traditional financial institutions and their capabilities to maintain economic stability. The loss in trust, which is essential for currencies and their value (Henke, 2021), allowed for the emergence of a new kind of currency: cryptocurrencies.

“This has never happened before—trusted transactions directly between two or more parties, authenticated by mass collaboration and powered by collective self-interests, rather than by large corporations motivated by profit” (Tapscott & Tapscott, 2016, p. 22).

Cryptocurrency is defined as a digital currency, which operates via a decentralized system and does not rely on financial institutions or governments (European Central Bank, 2012; Tang, 2024; Zohuri et al., 2022). Blockchain technology and cryptography can be used to provide anonymous and secure transactions (Beer & Sharma, 2022; Stamatoyannopoulos, 2022), which are not controlled by any entity, authority, or institution (Baron et al., 2015; Beer & Sharma, 2022). As Bilotta and Botti (2018) point out, the difference between cryptocurrency and a virtual/digital currency is that the former is managed by a decentralized cryptographic system, whilst the latter is regulated by a central server. The European Central Bank (ECB) (2012) declared in 2012 that these currencies do not qualify as money from a legal and economic literature perspective. The ECB defined them as "a digital representation of value, not issued by a central bank, credit institution or e-money institution, which in some circumstances can be used as an alternative to money" (ECB, 2012, p. 4). A central aspect of cryptocurrencies and the substantial innovation behind them is their ability to remove the intermediary in financial transactions, which would typically be banks and other financial institutions (Henke, 2021; Yetmar, 2023). Transactions occur directly between two parties through digital wallets (Henke, 2021; Tang, 2024; Yetmar, 2023) and bypass financial intermediaries, as well as governmental regulatory and monitoring agencies (Zohuri et al., 2022). This, as described by Beer and Sharma (2022), empowers users with financial freedom.

Bitcoin (BTC) has dominated the cryptocurrency space and has the largest market cap since its advent. It was mainly created as a solution to the so-called double-spending problem without the need for a third trusted party. It refers to the challenge of ensuring that a payee can trust that the owner of a coin has not already spent it elsewhere before completing a transaction, thereby avoiding the risk of double spending it (Nakamoto, 2008). All other cryptocurrencies created since Bitcoin are called “altcoins” (Yetmar, 2023). It is still unknown who stands behind the pseudonym of Satoshi Nakamoto, the creator of Bitcoin, and whether it is a single person or a group of programmers, where he/she/they are from and what he/she/they are doing today[1].

3. BLOCKCHAIN TECHNOLOGY AND BITCOIN MINING

3.1 Blockchain

The underlying technology of Bitcoin and other cryptocurrencies is the blockchain technology (Fincham, 2019; Liew et al., 2022; Stamatoyannopoulos, 2022). Werbach (2016) states that there is no consensus on the terminology of blockchain and defines it as a method for storing data in consecutively chained blocks. Alternatively, blockchain may refer to the whole of blockchains comparable to "the internet" or simply to the underlying technology of Bitcoin, the public ledger. Werbach (2016) acknowledges that the term “distributed ledger technology” might be more accurate. Whitaker (2019) defines blockchain as a special database structure. The innovation lies in the fact that the ledger is public and distributed. Goldenfein and Hunter (2017) elaborate further and explain that blockchain is a mean of ensuring that a record, the ledger, exists at a specific time. Thereby it does not have to be a history of transactions as for Bitcoin and other cryptocurrencies, but can be anything from a file, a piece of music, email, digital art, birth certificates, financial accounts, insurance claims, votes, etc., as long as it can be encoded in data and subsequently stored and accessed on the blockchain (Goldenfein & Hunter, 2017; Tapscott & Tapscott, 2016).

3.2 The Bitcoin blockchain

Aggarwal and Kumar (2021) state that a blockchain, in relation to Bitcoin, is a public ledger that stores every transaction in an unchangeable format. Henke (2021) agrees by labeling it as a global decentralized database, a public digital ledger, which records each transaction and overall number of Bitcoins. Decentralization ensures that the ledger is not stored on one but on a large quantity of participating computers, called "nodes," that form the peer-to-peer bitcoin network (Tapscott & Tapscott, 2016). The blockchain is public, meaning that all transactions ever made can be viewed at any given point in time (Goldenfein & Hunter, 2017; Yetmar, 2023). Anonymity is provided by the fact that the identities of the participants cannot be linked to the interacting addresses (Baron et al.,

[1] Note that in this paper Satoshi Nakamoto will be addressed to as “he”, but there is no particular reason to believe that Satoshi is a man rather that a woman. The pronoun is chosen since Satoshi is a male name.

2015; Yetmar, 2023). To provide virtual security, the blockchain uses encryption or a cryptographic algorithm (Goldenfein & Hunter, 2017; Tapscott & Tapscott, 2016).

The public and distributed ledger consists of blocks. Each block incorporates a list of transactions executed within a certain time period, a timestamp, some metadata, a nonce, and an encrypted digital signature of the preceding block, called Hash, linking the blocks together (Baron et al., 2015; Kroll et al., 2013). This mechanism is the root of the name “blockchain” (Baron et al., 2015; Goldenfein & Hunter, 2017). The timestamp provides proof that the data was existent at a certain point in time (Nakamoto, 2008). The Hash can be described as a "unique encrypted string of data" (Goldenfein & Hunter, 2017, p. 8). It acts as an identifier and cannot be altered unnoticed. Thereby it validates that no previous block has been tweaked (Kroll et al., 2013). By linking the encrypted blocks, a cryptographically connected chain is created (Goldenfein & Hunter, 2017). Furthermore, the Hash ensures a backward link on the blockchain (a forward link cannot be created since the future blocks are still nonexistent) which creates an exclusive trail back to the beginning of the ledger - to the first block called the genesis block. On average blocks are created every ten minutes (Eyal & Sirer, 2013; Kroll et al., 2013) and constitute "the heartbeat of the bitcoin network" (Tapscott and Tapscott, 2016, p. 23).

3.3 Bitcoin Mining

Mining refers to the process of creating new blocks (Baron et al., 2015; Mueller, 2020). Miners are participants of the blockchain network and generally referred to as "nodes". However, not all "nodes" are miners, given that the majority of nodes focus on verifying the input data. Miners are obligated to donate large amounts of computing power to it. As previously mentioned, each new block consists of a Hash of the preceding block and a nonce, which is a random number. To mine a new block, a computer has to come up with the right Hash. The Hash must start with a certain but random number of zeros. Additionally, the value of the Hash must be smaller than a set value (Eyal & Sirer, 2013; Meshkov et al., 2017). It is unpredictable, which nonce will deliver the right Hash and computers must simply try different nonces to find the solution. As Tapscott and Tapscott (2016) put it, "It’s really like winning the lottery because there’s no skill involved" (p. 220-221). This process, which is often referred to as a “cryptographical puzzle” (Eyal &

Sirer, 2013; Meshkov et al., 2017), demands a lot of computational work to solve, but the result is easy to verify for the residual "nodes" of the network (Kroll et al., 2013).

As more miners enter the space, the time needed to come up with the right Hash decreases, potentially disrupting the intended interval of one block every ten minutes. Consequently, an algorithm therefore adjusts the difficulty to counteract and maintain the average time of a block mined (Eyal & Sirer, 2013; Kroll et al., 2013). Once the right combination is found, the miner publishes it and provides the "Proof of Work". The other "nodes" can easily confirm its validity, and the block is added to the chain (Baron et al., 2015; Mueller, 2020). By engaging in this activity, miners maintain the blockchain (Eyal & Sirer, 2013), they bundle outstanding transactions to a block and provide verification (Aljabr et al., 2019).

3.4 "Proof of Work" – (PoW)

"Proof of Work" is a consensus mechanism, which ensures correct behavior despite the anonymity on the blockchain. It relies on the notion that, whoever finds the right solution for the block (mining) shows that he/she put a lot of work into it (in form of computing power and electricity) (Tapscott & Tapscott, 2016). Biryukov and Khovratovich (2017) determine that "Proof of Work" refers to a "computationally hard problem, which requires a lot of memory to generate a proof (called 'memory-hardness' feature) but is instant to verify" (p. 1). Nakamoto (2008) uses "Proof of Work" as a synonym for what is mining and Cocco and Marchesi (2016) write that "mining is the process which allows to find the so-called 'proof of work' that validates a set of transactions and adds them to the massive and transparent ledger of every past Bitcoin transaction known as the 'Blockchain'" (p. 2). Due to the nature of this mechanism, it is sometimes referred to as "brute force" (Li et al., 2020; Mukhopadhyay et al., 2016; Narayanan et al., 2016).

The answer as to why such a computationally difficult and energy-consuming mechanism was implemented in the Bitcoin blockchain is security. The "Proof of Work" mechanism is important as it maintains the decentralized network and attaches one secure and correct block after another. It guarantees that all the transactions registered on the blockchain happened the way they are recorded, and the balances of the users are rightful (Baron et al., 2015; Kroll et al., 2013).

To tackle the double-spending problem without the need for a third trusted party, Nakamoto (2008) proposed with Bitcoin and its underlying blockchain technology the following solution: "For our purposes, the earliest transaction is the one that counts, so we don't care about later attempts to double-spend. The only way to confirm the absence of a transaction is to be aware of all transactions" (p. 2). The “Proof of Work” executes the suggested solution once the computational effort to create a block has been made. To change it, all previous blocks have to be redone and surpass the “honest” chain. When introducing Bitcoin to the world, Nakamoto (2008) explained:

> The majority decision is represented by the longest chain, which has the greatest proof-of-work effort invested in it. If a majority of CPU power is controlled by honest nodes, the honest chain will grow the fastest and outpace any competing chains (p. 3).

“Proof of Work” was and is often criticized due to its high energy consumption and its related costs. Additionally, as mining rewards decrease over time, critics say that it may lead to increased transaction costs in order to keep miners incentivized and operating (King & Nadal, 2012).

3.5 “Proof of Stake” – (PoS)

Other mechanisms exist that are implemented in cryptocurrencies, such as the “Proof of Stake” (PoS) (Beer & Sharma, 2022). The concept is that validators do not have to run complex computations but hold a certain amount of a cryptocurrency and store or stake (hence the name) them in a pool (Beer & Sharma, 2022; Tapscott & Tapscott, 2016). The staked tokens are used as collateral and, instead of the work intensive PoW, the system chooses randomly among stakers, as to who is going to confirm that the transaction has been done on the blockchain (Beer & Sharma, 2022). This system eliminates the competition found on “Proof of Work” blockchains (Lin, 2023). Instead of mining, cryptocurrencies that implemented “Proof of Stake” interact in a process called “forging”. Stakers are rewarded with transaction fees and newly forged (or minted) tokens depending on their staked amount (European Central Bank, 2012; Lin, 2023).

The main advantages of the “Proof of Stake” mechanism are higher speed and lower energy consumption (King & Nadal, 2012; Lin, 2023; Tapscott & Tapscott, 2016). However, it also has downsides, as shown by Tapscott and Tapscott (2016) in their citation of an interview with Austin Hill:

> I don't think proof of stake ultimately works. To me, it's a system where the rich get richer, where people who have tokens get to decide what the consensus is, whereas proof of work ultimately is a system rooted in physics. I really like that because it's very similar to the system for gold. (Hill as cited in Tapscott & Tapscott, 2016, p. 41)

Some cryptocurrencies use other mechanisms or a combination of mechanisms (Tapscott & Tapscott, 2016), but "Proof of Work" and "Proof of Stake" are the two most common ones (Zohuri et al., 2022).

3.6 Incentive for miners

To incentivize miners to dedicate these large amounts of computing power and electricity to engage and secure the blockchain Satoshi Nakamoto (2008) incorporated a bounty in the form of Bitcoins into the system. Miners or "nodes" receive Bitcoins in return for their work. When a computer finds the right solution and mints a new block to be added to the chain, the very first transaction on this block is a payout of Bitcoins to the creator of the block (Baron et al., 2015; Eyal & Sirer, 2013; Nakamoto, 2008). The reward is not split between all the miners but is given to the one who finds the solution the fastest (Ciaian et al., 2021; Eyal & Sirer, 2013; Mueller, 2020; Tapscott & Tapscott, 2016).

> This adds an incentive for nodes to support the network and provides a way to initially distribute coins into circulation since there is no central authority to issue them. The steady addition of a constant amount of new coins is analogous to gold miners expending resources to add gold to circulation. In our case, it is CPU time and electricity that is expended (Nakamoto, 2008, p.4).

The incentive system was built to be inflation-free (Nakamoto, 2008), consequently, the maximum number of Bitcoins to ever exist was set at 21 million coins (Eyal & Sirer, 2013; Tapscott & Tapscott, 2016). To ensure the set limit, the reward system works the following way: At the beginning of each block, mined approximately every ten minutes, the reward was set at 50 Bitcoins. Every 210,000 blocks the reward amount is cut in half (Kroll et al., 2013; Rosenfeld, 2011), which corresponds to almost exactly every four years. This event is known as "Bitcoin halving" or just "halving" (Kroll et al., 2013; Tapscott & Tapscott, 2016). There have been four halvings at the time of writing, in 2012, 2016, 2020 and 2024, where the block reward of 6.25 Bitcoins was cut to 3.125 Bitcoins.

Since the number will get diminishingly small over time, the last Bitcoin will be mined in the year 2140 (Kroll et al., 2013; Tapscott & Tapscott, 2016).

Nakamoto (2008) explains that the incentives will be running even when there are no or only a small fraction of Bitcoins left to be mined, because rewards are also funded by transaction fees. Transaction fees are already part of the mining rewards, but once all Bitcoins are in circulation, they will constitute 100% of the rewards (Kroll et al., 2013).

3.7 Hash Rate

Mueller (2020) describes the Hash Rate as "the aggregate computing power of miners" (p. 1). It is the rate at which Hashes are processed per second (Peter & Tyler, 2019). Ciaian and colleagues (2021) further elaborate that it measures the performance of a miner's computing power and the speed of operation. A Hash rate of 100 Hashes per second (H/s) indicates that a mining hardware makes 100 guesses for the Hash of the next block in one second (Ciaian et al., 2021). Generally, the higher the Hash rate, the better the chance to solve the puzzle and receive the rewards (Mueller, 2020).

The Hash Rate of the Bitcoin blockchain, retrieved from blockchain.com on the 21.02.2024 was 556,818,000 tera Hashes per second (TH/s), that is 556 quintillion or 556 billion billions Hashes per second (Blockchain, n.d.).

3.8 Mining Hardware

The difficulty to find the right Hash and add another block to the chain increases when more miners join the race, since the Bitcoin blockchain is designed to create one new block every 10 minutes. The former has allowed for mining hardware capacities to follow and improve (Cocco & Marchesi, 2016; Ghimire, 2019; Tapscott & Tapscott, 2016). To have a chance of successfully mining cryptocurrencies special hardware is needed (Baron et al., 2015).

The adaptation of difficulty happens every 2016 blocks, which is every two weeks. The difficulty is adjusted so that with the current Hash Rate, the 10-minutes-per-block-ratio is upheld (Haliplii et al., 2020; Podhorsky, 2021).

Ghimire (2019) and Cocco and Marchesi (2016) arrange mining hardware into generations, explaining that Central Processing Units (CPU) was the first generation of Bitcoin mining. This was conducted on standard computers (Narayanan et al., 2016). Due to increased mining difficulty and higher efficiency and mining power, the second-generation mining was done via Graphic Processing Units (GPU). Third-generation mining was done with Field Programmable Gate Arrays (FPGA) and the fourth and actual generation with Application Specific Integration Circuits (ASIC). While FPGA, GPU and CPU can mine various currencies, it is not possible with ASIC (Cocco & Marchesi, 2016; Ghimire, 2019). ASICs are algorithm-specific, meaning that a specific ASIC mining hardware is adapted to a particular mining algorithm and is solely designed to mine a specific cryptocurrency without any other use (Mueller, 2020). ASICs are the predominant mining hardware currently used (Narayanan et al., 2016).

The hardware differs in terms of energy consumption, computing power, costs, and efficiency. Therefore, it is essential to choose the right hardware for its needs.

3.9 Mining pool:

An important factor, which miners have to consider is that, mining a cryptocurrency does not guarantee a reward, but rather work according to the "first come first serve" principle, meaning that the first miner to find the right solution for the next block will get all the rewards and the other miners have to try again on the next block (Eyal & Sirer, 2013; Narayanan et al., 2016; Yetmar, 2023). The probability of finding the right solution is proportional to the share of computational power put in by a miner. (Eyal & Sirer, 2013; Konoth et al., 2018; Li et al., 2019) The aforementioned implies a high variance in terms of rewards (Konoth et al., 2018).

To counter that problem and smoothen the inflow of expected rewards, miners came together to bundle their computing resources and established mining pools. (Ciaian et al., 2021; Cocco & Marchesi, 2016; Konoth et al., 2018; Li et al., 2020). In a mining pool, all participants work to solve the crypto puzzle, and rewards are shared proportionally to the contribution (Konoth et al., 2018; Li et al., 2020). Eyal and Sirer (2013) note that pools do not change expected rewards of miners but decrease the variance and make revenue forecasting more predictable. Narayanan and colleagues (2016) describe mining pools as mutual insurance for miners and note that the pool manager charges a small fee in the form of a cut of the mined rewards for the service.

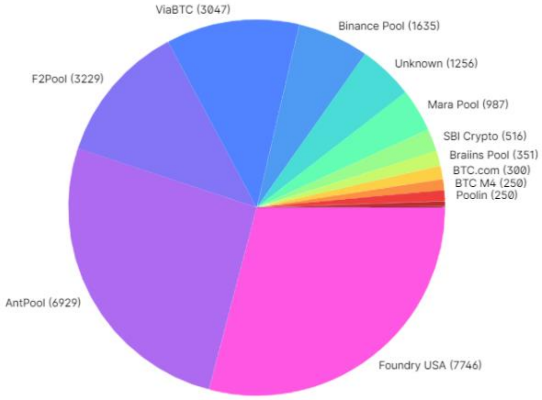

Figure 1. Hash Rate distribution of the largest mining pools. Source: blockchain.com.

4. LITERATURE REVIEW

Literature related to blockchain technology and cryptocurrencies has been growing since cryptocurrencies have gained public attention. Nakamoto (2008) set the starting point with the Bitcoin whitepaper, in which he explained the new technological advancement, which Bitcoin was at that time. Over time Bitcoin was subject to great interest and many other cryptocurrencies followed. Stamatoyannopoulos (2022), the European Central Bank (2012), Tang (2024), Yetmar (2023), Zohuri and colleagues (2022) and many others explain Bitcoin and other cryptocurrencies and described the underlying technology and its use cases. Tapscott & Tapscott (2016), Werbach (2016), McKinney and colleagues (2018) provided detailed insights into the underlying blockchain technology.

The first entities to hear of Bitcoin early on started mining them on their personal computers (Ghimire, 2019). With the passing of time the currencies became more popular, competition in the field of mining increased and mining hardware evolved with it. Sun and colleagues (2022) discovered that currently the purpose for mining is economic in nature. The economics of mining has been widely discussed in the scientific literature, with a specific focus on different aspects. Islam and colleagues (2022) and Dilek and Furuncu (2018) have written about the energy consumption of Bitcoin and cryptocurrency mining and the related environmental effects, a factor that has been heavily criticized. Náñez Alonso and colleagues (2021) conducted an analysis on the sustainability of cryptocurrency mining by including into the Environmental Performance Index different factors such as energy price, methods of energy creation, legal aspects and human resources. It was concluded that from the top ten most stainable countries, eight are European and the remaining two are Japan and South Korea. Looking at the actual Hash Rate per country, they concluded, that most mining is done in China, Russia, USA and Kazakhstan, which are all non-sustainable countries (Náñez Alonso et al., 2021).

Several authors have conducted extensive research into the economics and techniques of Bitcoin and cryptocurrency mining and have examined various aspects, leading to some important insights: In its early stages Kroll and colleagues (2013) researched the basic economics of mining by modeling the mining process, addressing different mining strategies and vulnerabilities in the protocol. A large quantity of studies followed by focusing on the security aspect of mining. Ciaian and colleagues (2021) concluded that blockchain security depends highly on mining rewards and the currencies price. Eyal and Sirer (2013) introduced the theory of selfish miners, a strategy in which participating miners might earn excess revenue and conclude that the Bitcoin protocol is not as flawless as it might seem. Hacioglu and colleagues (2021) focused on describing different strategies such as hosted mining (owning a miner which is located in a mining center and hosted externally), home mining (having the miner at home) and cloud mining (renting a certain amount of Hash Rate and receiving mining returns). Rosenfeld (2011) examined pooled mining, where miners unite and work together because it decreases risks and smoothens earnings for miners. Additionally, Parra-Moyano and colleagues (2019) contributed that miners with relatively higher Hash Rate have a higher probability of finding a block, which is an important sign that mining pools should be used when entering in the mining business. Li and colleagues (2019) studied the mining aspect by implementing a mean-field model and researched different cryptocurrencies that use Proof of Work. Their studies showcased that wealthier miners concentrated more mining rewards, which, as they explained, goes against the principle of decentralization. Additionally, as cost-advantaged miners, miners in areas with lower energy costs and advanced hardware, entered the game, their position became relatively dominant (Li et al., 2019). Further relevant findings are provided by Delgado-Mohatar and colleagues (2019) and Cocco and Marchesi (2016). Cocco and Marchesi (2016) provided insights into the evolution of mining hardware. Similar to the proposed model in this paper, the Monte Carlo simulation was adhered to, when forecasting various variables of importance. Delgado-Mohatar and colleagues (2019) analyzed the most efficient hardware of that point in time and used historical data to calculate the average production cost of one Bitcoin. They theorized that miners should mine until the price of a bitcoin equals the marginal cost of production. According to their research, in June 2018 it was no longer profitable to mine Bitcoin for everyone whose electricity costs were above 0.14$/kWh. This argument was strengthened by the trend of growing mining activity in China, where electricity costs are low (Delgado-Mohatar et al., 2019). Podhorsky (2021) put forward a very similar model to calculate mining profitability as proposed in this paper. It is argued that the adaptation of the difficulty acts like a government introducing taxes or subsidiaries and leads to inefficiency. The difficulty of the network to calculate the percentage reward given to an individual miner was adhered to in Podhorsky's (2021) paper, whereas in this research paper the total Hash Rate is chosen. Haliplii and colleagues (2020) conducted a similar research as the proposed by studying the profitability of Bitcoin mining and adhering to a real option approach. Their mathematical model, similarly to Podhorsky (2021), uses the difficulty, which does not change the outcomes significantly. The Hash Rate was chosen over difficulty in this model since it provides a more accurate representation of the actual percentage ownership of the network. They also used the Monte Carlo simulation and examined different mining hardware. The focus was on measuring the likelihood of breaking even on the initial investment of the miner purchase and to more extensively assess at the relationship between the difficulty and price of Bitcoin (Haliplii et al., 2020).

5. METHODOLOGY AND DATA

The following section focuses on presenting the methods that were adhered to when crafting the model. Specific focus is put on discussing specifics, crucial assumptions, important variables and the selection of the former. Any necessary calculations are laid out and explained. Additionally, the process of data collection is presented and described. All calculations, forecasts and analysis have been conducted in Python.

In order to construct a model, which will determine the value of the real option, several different scenarios of input variables have to be determined. This applies to the case of an individual, who wants to start mining Bitcoin, but has the flexibility to decide the optimal point in time to start operations. The Monte Carlo simulation and Exponential Smoothing methods are applied to forecast unknown variables to generate a significant range of outcomes and to produce robust results. Subsequently, the real option, which in this case is an American call option, due to the possibility of an early exercise, is valued using the Longstaff-Schwartz approach.

The most important variables, which are needed for the model are

- Bitcoin Price
- Bitcoin Hash Rate
- Electricity Price
- Mining Hardware.

Due to the fundamentally different nature of the input data, different forecast methods are applied according to an adequate level of appropriateness. In all calculations, the forecast horizon stretches to 31.12.2025. All forecasts and the net present value calculations are done for 609 timesteps and 10,000 simulations, resulting in 6,090,000 results for each step.

5.1 Bitcoin price

The historical data of the price of Bitcoin has been directly retrieved in Python from Yahoo Finance (Yahoo Finance, n.d.). The historical data considered for the forecast goes back until 01.01.2020, since this period captures the most relevant price changes and levels over the past years and allows for a more precise volatility calculation, as shown in Figure 2.

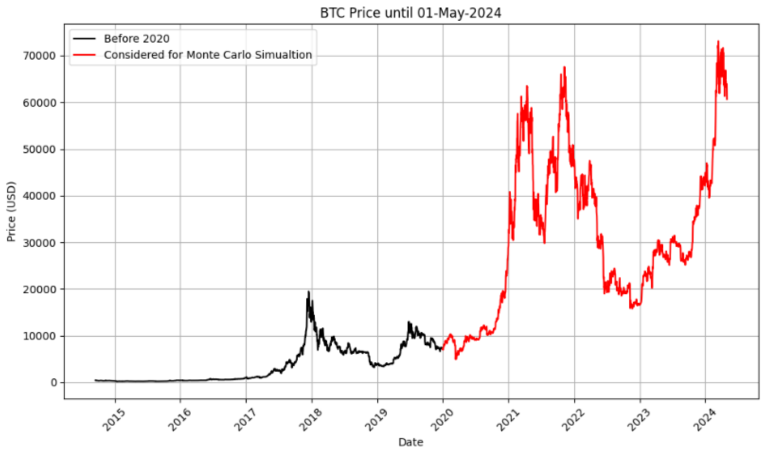

Figure 2. Historical Bitcoin prices. Own work.

Forecasting the price of Bitcoin, which is considered a highly volatile asset influenced by numerous amounts of exogenous variables (Walther et al., 2018), has been attempted by many researchers before (see for example Mudassir et al., 2020; Roy et al., 2018; Wu et al., 2018)[2]. In this paper the Monte Carlo simulation was chosen to simulate future Bitcoin prices. The advantage of this forecast technique is that it can be applied to cases with uncertainty and does not only deliver a singular final result, but a range of possible price paths, which are considered and fed into the model when pricing the real option.

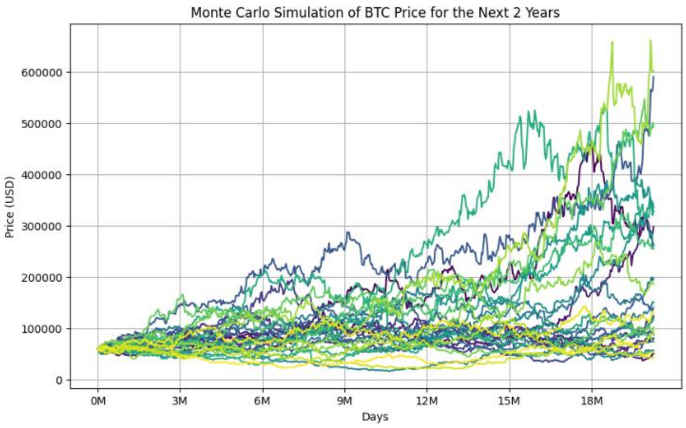

Figure 3. Monte Carlo Price Paths. Own work.

Figure 3 shows the different possible forecasts generated with the Monte Carlo Simulation. Each simulation generates a unique price chart, while following a random walk. A total of 10,000 simulations have been executed, but for visualization purposes only 30 are plotted. The underlying method used to perform the Monte Carlo Simulation is bootstrapping, introduced by Efron (1979). It carries out the resampling of historical data, in this case the historical daily returns of Bitcoin, to estimate a random distribution (Horowitz, 2001).

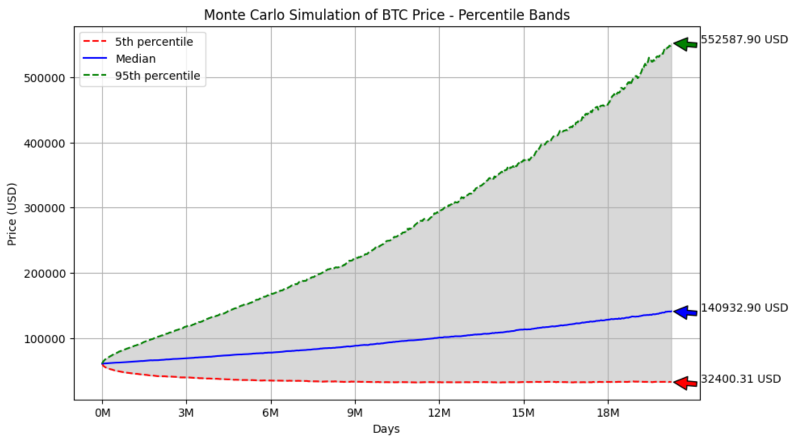

Figure 4. Bitcoin Price Distribution. Own work.

[2] Different methods have been used like Time Series Analysis, Long Short-term memory, machine learning, historical price analysis or the cost of production model.

To gain an overview of the results of the simulation, the percentile bands have been plotted in Figure 4. It puts the results of the simulation in numbers by showing the median price on the 31st of December 2025, after 609 days of forecasting, at 140,932.90$.

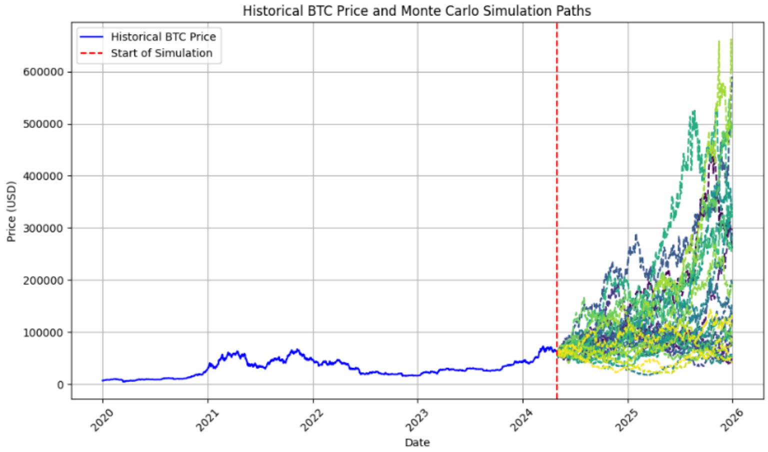

Figure 5. Historical Chart and Forecast. Own work.

5.2 Hash Rate

The historical data of the Hash Rate has been retrieved from bitcoinvisuals.com, a website providing extensive charts, statistics and data of the Bitcoin network (Bitcoin Visuals, n.d.). The historical data shows a continuing upside trend; therefore, the forecast is based on Exponential Smoothing. It emphasizes more recent datapoints, while decreasing the weights of past observations. Given the constant uprise observed since the second half of 2021, this method provides a simple way to capture the observed trend of the latest years.

Figure 6 shows the historical data chart of the Bitcoin Hash Rate. For better visualization a 7-day rolling mean has been applied to smoothen the data and remove noise. The relatively steady increase over the years reflects the growing computational power provided to the Bitcoin network, which shows steady investment in mining hardware and technology.

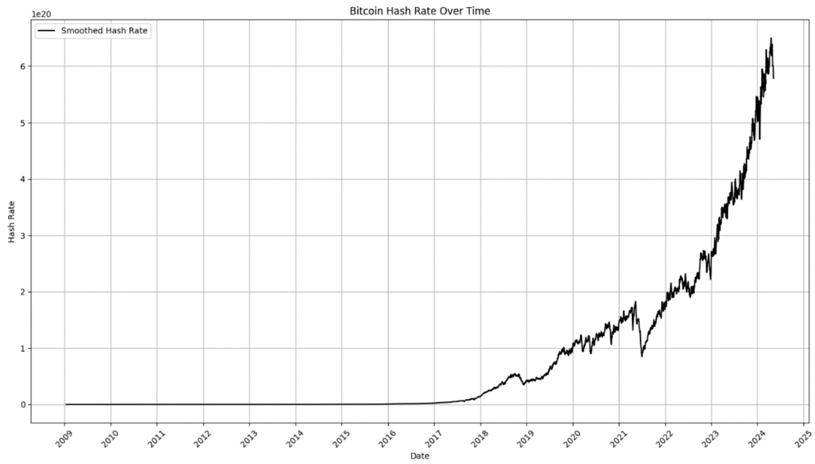

Figure 6. Historical Chart Hash Rate. Own work

When executing the Exponential Smoothing forecast method, the historical data used as an input has been cut to the last three years, to capture the most recent trend and receive a more accurate forecast. Examining the historical chart, a significant increase in Hash Rate can be observed in recent years. The downward trends have never lasted for a continuous period and have been short. Due to latest upside trends in the price of Bitcoin, significant decreases in Hash Rate do not seem likely, because the data reflects real life investment in mining equipment. A forecast focusing on all historical datapoints delivered exponential growth and unrealistic results.

Figure 7 illustrates the result of the Exponential Smoothing forecasting the total Bitcoin Hash Rate until the end of 2025, showing a doubling in total Hash Rate over the forecasted time horizon.

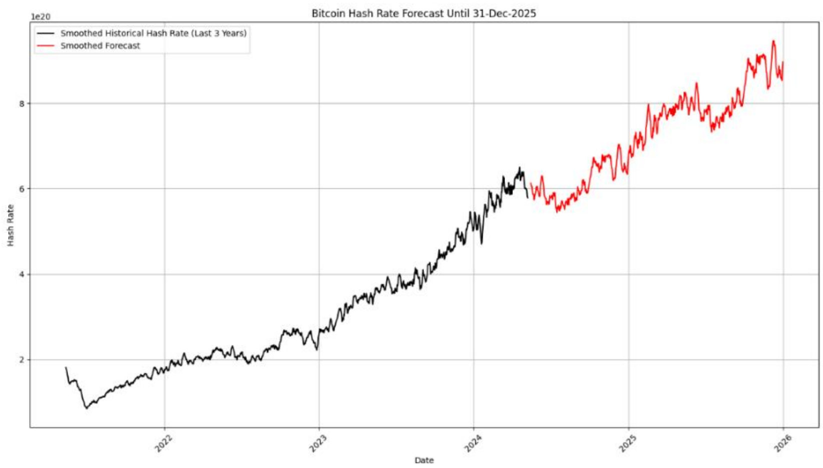

Figure 7. Exponential Smoothing of Hash Rate. Own work

Figure 8 shows the historical and forecasted graph while highlighting in blue the historical data considered for the Exponential Smoothing and in red the forecasted time period.

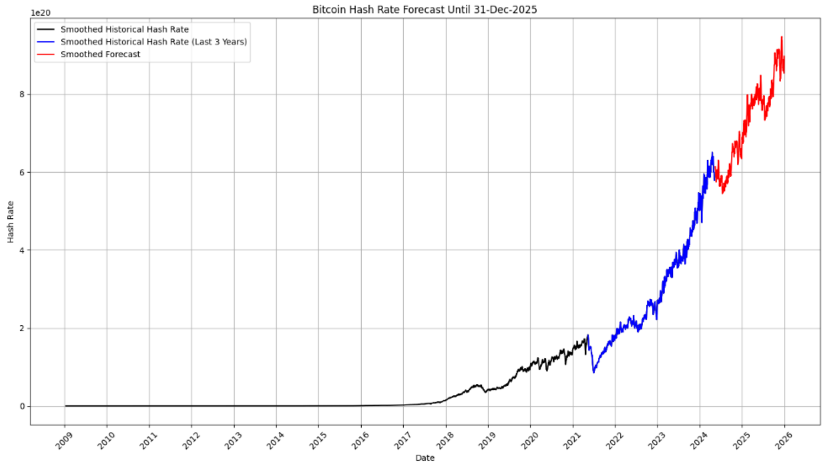

Figure 8. Historical and forecasted Hash Rate. Own work

The link between the price of Bitcoin and the Hash Rate has been established equally by different scientific works (see Fantazzini & Kolodin, 2020; Kubal, 2021). Fantazzini and Kolodin (2020) concluded in their research, that while the Hash Rate was driving the Bitcoin price in a positive way, the effect of the price on the Hash Rate was statistically insignificant, which was explained by the fact "that such an inconclusive result might have been caused by the price being on the edge of endogeneity and also possibly by unobserved exogenous shocks to the whole Bitcoin system" (p. 56). The insignificant relationship between price and Hash Rate can also be explained by the fact that Bitcoin mining, stated by Haliplii and colleagues (2020), has become a developed business, with corporations acting as large-scale mining "farms", which "buy or rent huge infrastructures of computing capacities that generate crypto-currencies and cover the operating costs" (p. 2). For actors in this business it is not economically interesting to switch off operations when prices decrease since significant CAPEX was already expended to set up operations.

The correlation between price and Hash Rate can be observed when plotting the log-normal graphs on one chart, as shown in Figure 9. Additionally, a lagging effect of the Hash Rate following Bitcoin prices changes with a delay is noted. While the price chart has up and down swings, the Hash Rate is in a relative constant upward trend, which could be seen as confidence in the Bitcoin network and its future.

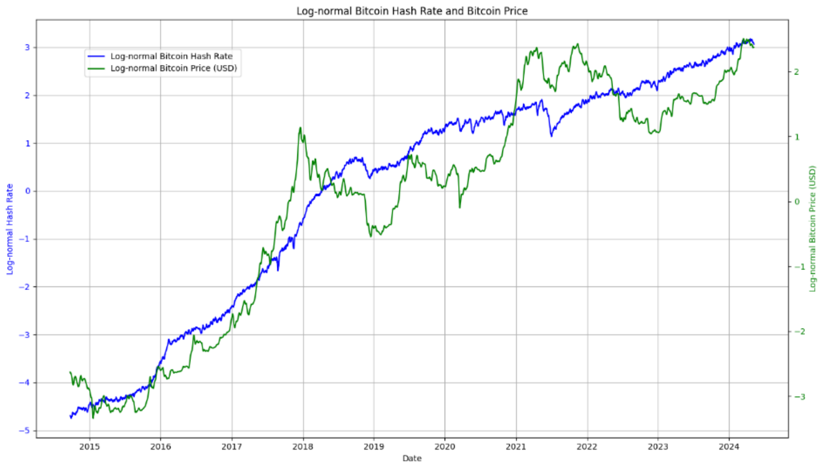

Figure 9. Log-normal Bitcoin price and Hash Rate. Own work

5.3 Electricity prices

The data for electricity prices was taken from ec.europa.eu/eurostat. Semi-annual electricity prices for household consumers reaching back until 2007/8 were retrieved from their database. Even though non-household consumer prices are significantly lower and more attractive for the analysis, the main focus of the paper emphasizes an individual end consumer perspective, who has only access to household consumer prices.

The following five European countries were chosen to better understand how profitability changes, while simultaneously performing a sensitivity analysis of the model in relation to the electricity prices:

- Portugal
- Germany
- Poland
- Hungary
- Türkiye

The selection of countries is based on the availability of electricity price data reaching back to 2007. Portugal has been chosen since it is the base country, Germany represents a country with one of the highest and Türkiye one of the lowest prices of the dataset. Poland and Hungary were chosen for comparison. To get a more precise forecast of the electricity prices, an interpolation of the data has been executed to transform the data from semiannual to daily. This fills the gap between original data points to create a continuous graph. A simple linear interpolation was used. Only Portugal electricity prices are displayed as a reference.

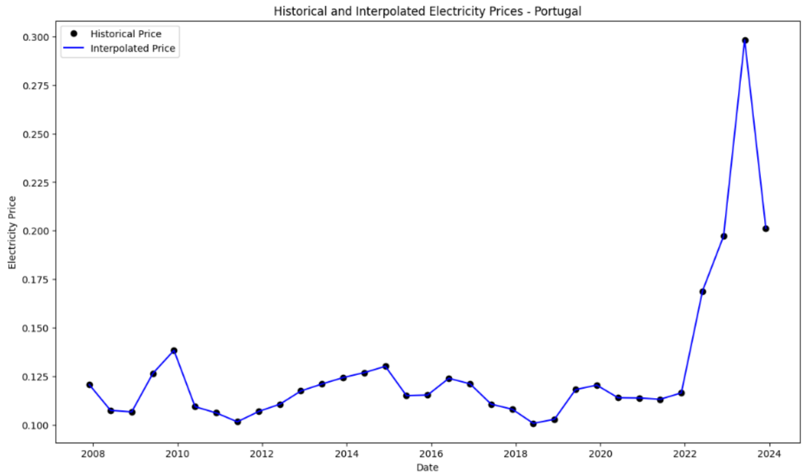

Figure 10. Electricity Prices in Portugal with Interpolation. Own work

Figure 10 shows a clear spike in electricity prices starting at the end of 2021. This increase in prices can be attributed to a combination of factors, including increased demand after the COVID-19 pandemic, supply chain disruptions and to the invasion of Ukraine by Russia at the beginning of 2022 (Kozicki et al., 2023). Notably, the chart shows a decrease of prices after peaking in 2023. This reversion must be taken into account when forecasting future electricity prices. The Ornstein-Uhlenbeck process, a stochastic process used to model mean-reversion, was applied to calculate the mean reversion speed. It captures, if existent, mean reverting behavior in datasets and is regularly used in financial modeling (Szimayer & Maller, 2004). Its influence has been reduced by a scaling factor to allow for a wider price range. The calculated estimation was then incorporated in the Monte Carlo simulation when forecasting future price paths, directing them towards the historical mean level. To capture a wider range of future price scenarios and incorporate possible unexpected market fluctuations, additional volatility was introduced into the forecast.

In Figure 11 it can be observed that forecasted prices are in a relatively narrow range, even though a volatility scale has been implemented.

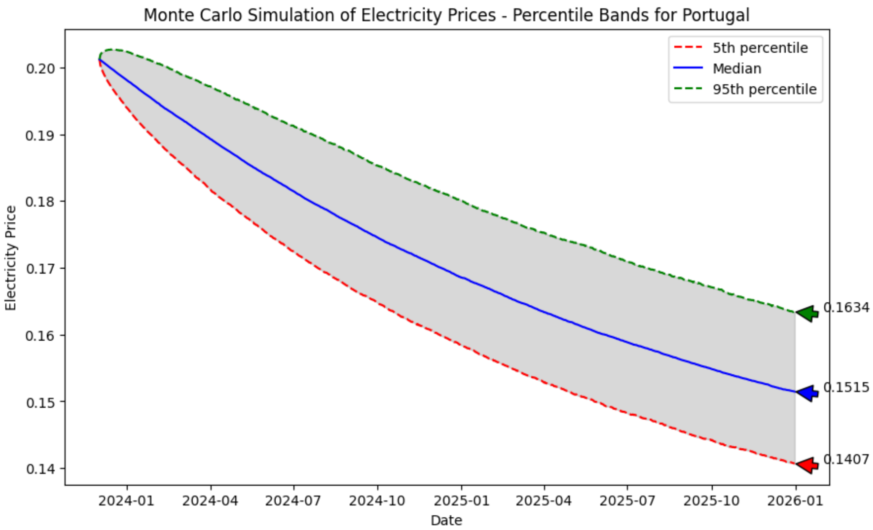

Figure 11. Distribution of Electricity Price Forecast. Own work

Figure 12 combines the historical chart with the forecast. The orange line shows the median across all simulated paths.

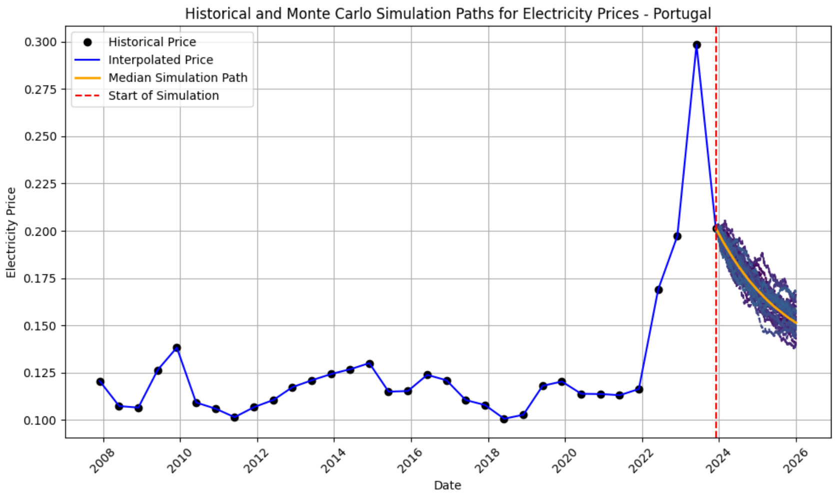

Figure 12. Historical and forecasted Electricity Prices. Own work

5.4 Mining hardware

There are several firms offering mining devices with different computational power, electricity consumption and price ranges. Choosing the right mining hardware is an essential decision when entering the cryptocurrency mining business. Due to the high prices of these devices, it may be of advantage to choose quality over quantity. For this research, mining hardware from the firm “Bitmain” has been chosen due to its reputation of building one of the most reliable hardware (CoinLedger, n.d.; Koinly, n.d.).

Three different mining devices have been chosen to compare its performance and profitability and simultaneously doing a sensitivity analysis of the different inputs. The data has been retrieved from the official Bitmain website shop.bitmain.com on 26.05.2024 (Bitmain, n.d.).

Figure 13 displays a table of the three mining devices with individual pictures, which have been used in this analysis. It shows the different specifications in Hash Rate, energy consumption, efficiency, price and reason of choice.

Bitcoin Miner	Image	Hashrate (TH/s)	Energy Consumption (W)	Efficiency (J/TH)	Price per Terahash ($/T)	Unit Price ($)	Chosen because
S19 Pro+ Hyd.		191	5252.5	27.5	12	2292	Lowest price per terahash
S21 Pro		234	3510.0	15.0	27	6318	Lowest Joules per terahash
S19 XP Hyd.		257	5345.6	20.8	23	5911	Highest amount of terahash

Figure 13. Table of Miners. Own work

5.5 Mining pool fees

The information about mining pool fees has been retrieved directly from the official websites of the mining pool operators. The Information was captured on the 30.05.2024.

- antpool.com – 0% (Antpool, n.d.)
- f2pool.com – 2% (F2Pool, n.d.)
- viabtc.com – 2% (ViaBTC, n.d.)

Due to uncertainty if Antpool will keep its zero fees policy over the forecasted horizon, for the model a 2% mining pool fee has been considered.

5.6 Exchange rate USD/EUR

The Bitcoin price taken from Yahoo Finance and used in the model is nominated in US-Dollars, therefore an exchange rate is needed for conversion into Euro. To get future data until the 31.12.2025 the forward curves on the 30.05.2024 have been retrieved from Deutsche Bank (DB Markets, n.d.). Forward curves for different time periods available have been taken and an interpolation has been used to get a continuous chart for the forecast time horizon. Since a sale of US-Dollars to Euro happens, the considered rate is the bid rate. For the period of 01.05.2024 to 30.05.2024 two historical datapoints have been taken and implemented in the forecast graph.

Figure 14 shows the historical rates until the 30.05.2024 marked in green and the forward rates for different time periods with linear interpolation in blue.

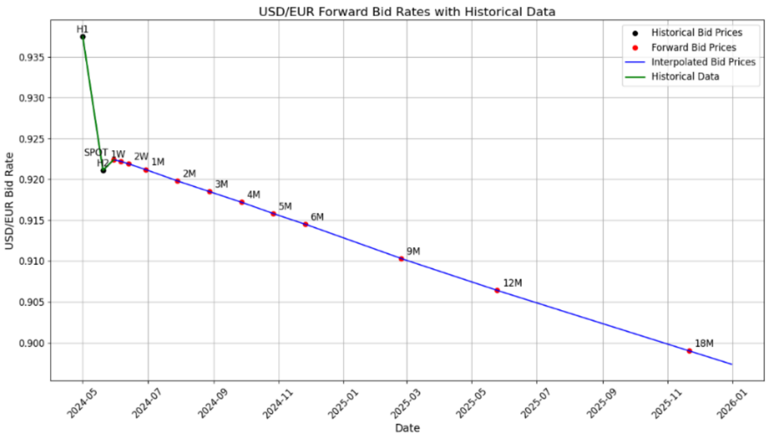

Figure 14. Interpolated Exchange Rate Forward. Own work

5.7 Risk free rate

The risk free rate considered for this model is the Germany 2 year government bond yield, since the analysis of this research paper focuses on Bitcoin mining inside Europe and the electricity prices of different European countries have been used. The yield, retrieved on the 30.05.2024 from marketwatch.com was 3.085% (MarketWatch, n.d.).

6. MODEL

To build a model to value the real option underlying this project, at first the economics of a mining operation has to be determined. Revenues and costs of Bitcoin mining are calculated as follows:

Grunspan and Pérez-Marco (2020) point out that, the profitability at a point in time t > 0 is

$$(1)\ P_t = R_t - C_t$$

Where

$$P_t = Profits\ at\ time\ t$$

$$R_t = Mining\ rewards\ at\ time\ t$$

$$C_t = Operating\ costs\ at\ time\ t$$

To calculate the daily mining rewards, it is necessary to calculate what percentage of the total network Hash Rate the own miners provide.

$$(2)\ H_t^{\%} = \frac{H_t^{h/s}}{H_{t,total}^{h/s}}$$

Where

$$H_t^{\%} = Percentage\ of\ hashrate\ provided\ by\ own\ miners$$

$$H_{t,\mathrm{total}}^{\mathrm{h/s}} = Network's\ total\ hashrate\ at\ time\ t\ in\ hashes\ per\ second$$

$$H_t^{\mathrm{h/s}} = Provided\ hashrate\ at\ time\ t\ in\ hashes\ per\ second$$

Next the daily block reward in Bitcoins must be determined. Every ten minutes a new block is mined and since the last halving in April 2024 the reward per block has been cut to 3.125 Bitcoins. Additionally, the transaction fees must be considered, which vary from day to day. Due to the variance and the unpredictability of the transaction fees, an estimated average will be taken for the calculations. The Block estimates the share of transaction fees of total miner revenue at around 13% (Hunt, 2024), while CoinDesk estimates 15% (Canny, 2024) to be a sustainable basis. In this case, to be more conservative, the used percentage will be 8%.

$$(3)\ BR_t^{btc} = \frac{B_t^{btc} \cdot 24 \cdot 60 \cdot T_t^{\%}}{10}$$

Where

$$BR_t^{\mathrm{btc}} = Block\ revenue\ per\ day\ denominated\ in\ Bitcoin$$

$$B_t^{\mathrm{btc}} = Current\ block\ reward\ in\ Bitcoin$$

$$T_t^{\%} = Rewards\ from\ transaction\ fees\ in\ percentage$$

When combining the two formulas and taking mining pool fees into account, the following formula for the daily reward can be constructed:

$$(4)\ R_t^{btc} = H_t^{\%} \cdot BR_t^{btc} \cdot \left(1 - M_t^{\%}\right)$$

$$= \frac{H_t^{h/s} \cdot 24 \cdot 60 \cdot B_t^{btc} \cdot T_t^{\%} \cdot \left(1 - M_t^{\%}\right)}{H_{t,total}^{h/s} \cdot 10}$$

Where

$$R_t^{\text{btc}} = \text{Mining revenue per day denominated in Bitcoin}$$

$$M_t^{\%} = \text{Mining pool fee per day in percentage}$$

To get the daily revenue in Euro, the simulated prices and exchange rates are fed into the formula leading to

$$(5)\ R_t^{eur} = H_t^{\%} \cdot BR_t^{btc} \cdot \left(1 - M_t^{\%}\right) \cdot BTC_t^{\$} \cdot X_t^{\$/€}$$

Where

$$R_t^{\text{eur}} = \text{Mining revenue per day denominated in Euro}$$

$$BTC_t^{\$} = \text{Price of Bitcoin at time t denominated in Euro}$$

$$X_t^{\$/€} = \text{Exchange rate of USD/EUR at time t}$$

The assumption was made that all the mined Bitcoins are sold every day.

Mining costs are calculated as follows

$$(6)\ E_t^{€} = \frac{PC_t^{watt} \cdot E_{kWh}^{€} \cdot 24}{1000}$$

Where

$$E_t^{€} = \text{Electricity costs per day denominated in Euro}$$

$$PC_t^{watt} = \text{Power consumption of a Miner per day in Watt}$$

$$E_{kWh}^{€} = \text{Price per kWh of electricity denominated in Euro}$$

To reach the net daily profit denominated in a FIAT currency (in this case Euro) discounted to today:

$$(7)\ NI_t^{€} = R_t^{€} - E_t^{€}$$

Where

$$NI_t^{€} = \text{Net income of mining rewards per day denominated in Euro}$$

Using the net income, in the next step the net present value can be calculated as follows

$$(8)\ NPV_t^{€} = \sum_{T=t}^{t} \frac{NI_t^{€}}{(1+rf)^{t/365}}$$

$$(1+rf)^{t/365} = Discount\ factor\ using\ risk\ free\ rate\ on\ a\ daily\ basis$$

$$NPV_t^{€} = Net\ present\ value\ in\ Euro\ at\ time\ t$$

It should be noted that the tax rate is not considered due to the low outcomes and the fact that most countries offer a tax allowance for individuals.

6.1 Difficulty

Researchers attempting to model Bitcoin mining profitability in some cases used Bitcoin difficulty instead of the total network´s Hash Rate (see for example Haliplii et al., 2020 and Podhorsky, 2021). They used as a denominator the difficulty multiplied by 2^{32}, which is the number of Hashes per second needed to find a solution (Podhorsky, 2021). Following this, they used a block reward per second and multiplied the nominator by seconds per day (86400), while in this model it was calculated per 10 minutes (144). This leads to the following conclusion

$$(9)\ Difficulty = Hashrate \div \frac{2^{32}}{600}$$

Figure 15 shows the scaled Hash Rate and difficulty, verifying the equation and showing that the Bitcoin mining profitability model is consistent with the ones suggested by Haliplii and colleagues (2020) and Podhorsky (2021). It illustrates how close the Hash Rate and difficulty can be approximated using the above-mentioned scaling factor.

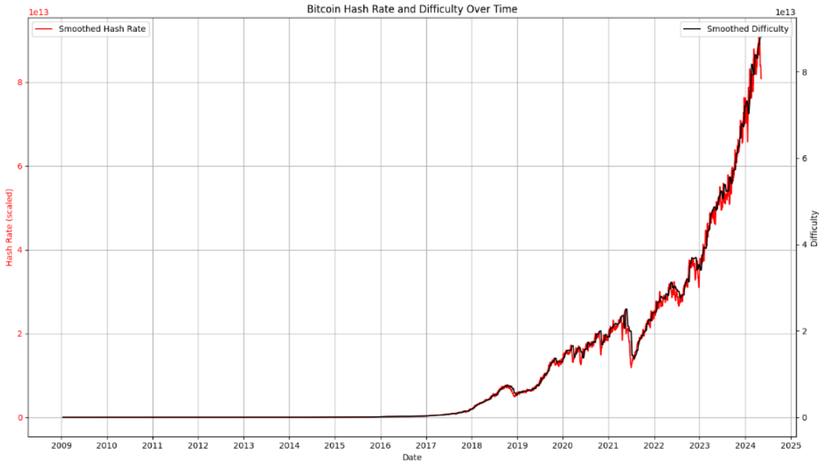

Figure 15. Hash Rate and Difficulty. Own work

The adhered approach provides the upside of accurately measuring the owned share of the Bitcoin network's computational power incorporating real-time conditions and fluctuations, which occur when miners join or leave the network. The difficulty only adjusts every two weeks. Therefore, the method used here provides a more sensitive result, which adapts quickly to changes in the Hash Rate and the calculations do not experience a two week delay as they could do when using difficulty.

6.2 Initial investment and terminal value

The analysis so far has not considered the initial investment needed and the terminal value at the end of the period. The initial investment is solely comprised of the expense of buying the mining hardware, since no other investment is needed to start the operation. It depends on the chosen hardware.

The terminal value on the other hand has been selected to be represented by the liquidation value of selling the mining hardware after the observation period has ended, which in this project is the 31.12.2025. The decision to choose the liquidation value as a terminal investment was made, because cryptocurrencies constitute a relatively new and highly volatile market and other terminal value calculations like the Gordon Growth Model would require assumptions into the far future, which could be unreliable. To determine an appropriate liquidation value, market places of used Bitcoin mining equipment, like miningwholesale.eu, zeusbtc.com or ebay.com, have been assessed. For the miners relevant for this project, no used product has been found. This might be because they are the latest generation of miners and new on the market (S19 Pro+ Hyd. release date 2022, S19 XP Hyd. release date 2022, S21 Pro release date 2024, (Cryptominer Bros, n.d.)). Cryptominer Bros (n.d.) defined various factors determining the resale value of such ASIC miners, stating that, next to market demand, mining difficulty, technological advancements, crypto market sentiment, warranty period and the condition of the miner are essential factors to be considered. Regarding the warranty, Bitmain, the company producing the analyzed miners in this project, has 180 days of warranty on all their products, which includes free repairs of potential damages or technical problems (Bitmain, n.d.). Using this additional information, a daily discount rate was calculated to be applied to the purchase price to reach the liquidation value. The taken assumption is that after the observed time period of roughly 1.5 years, the miner would lose 40% of its value. Splitting this on a daily basis, it results in a daily amortization of 0.066%, whereas if the warranty of the product is still active, meaning if the miner is liquidated before being active for 180 days, a warranty premium of 30% has been added. Additionally, a 2% base discount fee has been applied regardless the number of days until liquidation.

Discount values are calculated from the day the option is executed and the miner is bought, to the final day of the forecast period. Instant availability of the purchase and sale of a miner has been assumed. Additionally, since the purchase price is denominated in US-Dollars, the corresponding exchange rate from the previously executed forecast has been applied, depending on the day of the execution of the option and hence purchase of the mining equipment.

The calculations are as follows

$$(10)\ Initial\ investment^{€} = Initial\ investment^{\$} \cdot X_t^{\$/€}$$

$$(11)\ Liquidation\ value^{€} = Initial\ investment^{€} \cdot Discount\ factor_t$$

And

$$(12)\ NPV_t^{€} = \sum_{T=t}^{t} \frac{NI_t^{€} - Initial\ investment^{€} + Liquidation\ value^{€}}{(1+rf)^{t/365}}$$

6.3 Sensitivity analysis of Hash Rate

The suggested model is highly dependent on the forecasts used as input. With the electricity prices of various countries, a sensitivity analysis of this variable has been conducted. Bitcoin prices vary due to the Monte Carlo bootstrapping method, providing a wide price range. An important variable, which must be observed, and its sensitivity analyzed, is the Hash Rate forecast. To account for this, a slight damping factor with gradual reduction has been implemented, to produce a forecast with dampened growth. The final forecast for the sensitivity analysis has been reduced to 80% of the result of the Exponential Smoothing used in the main model. This assumption can be backed by the argument that investments into Bitcoin mining are dependent on several factors and market conditions, thus, may not grow as much as they have in the past. The entirety of the analysis procedure relies on the use of the original and the dampened Hash Rate forecast.

7. REAL OPTION VALUATION

To value the underlying real option, which is represented by an American call option, the least-squares Monte Carlo (LSM) approach introduced by Longstaff and Schwartz in 2001 has been applied. The main idea behind it is, that the holder of the option should compare the payoff of immediate exercise with its continuation value at each individual time step. The continuation value is thereby approximated by a least-squares-regression of simulated price paths. This is done by a backward induction, starting from the last day before expiry and checking at each time step whether early exercise at time t is optimal for an in-the-money path by comparing the exercise value to the continuation value. Hereby, the calculated net present values at each time step of the mining operation have been used, to determine the values. This method, as described by Longstaff and Schwartz (2001), offers a simple but effective way of determining the optimal exercise point of an American option.

8. RESULTS

The results mainly focus on Portugal and Türkiye. Portugal has been chosen as the main interest point of this paper, and Türkiye is interesting because it has the lowest electricity prices of the examined countries. The calculations done in Python produce the value of the Real Option, examine in how many of the 10,000 simulations an exercise will be triggered and the median Bitcoin price for the early exercises. Forecasted electricity prices are illustrated in three ways: median, 25th and 75th percentile, showing its range. Of additional interest is the comparison of the three miners selected and the difference between the data using the main forecasted Hash Rate referred to as "Original Data" and the dampened Hash Rate forecast named "Sensitivity Analysis". Furthermore, the analysis has been split into calculations using net present values ignoring initial investment and liquidation value and calculations incorporating the investments, labeled "without investment" and "with investment" respectively. Plots showing the forecasted price paths of Bitcoin, which lead to an early exercise, were created for each simulation step. One of them is displayed below.

Figure 16 shows the plot for the simulation using electricity prices from Portugal and the miner S19 XP Hyd. As observed in the plot and in the results, some price paths from the Monte Carlo bootstrapping method resulted in big price increases, reaching several millions of US Dollars per Bitcoin. The red cross marks the earliest exercise of the plotted price graph and the red line shows the median Bitcoin price.

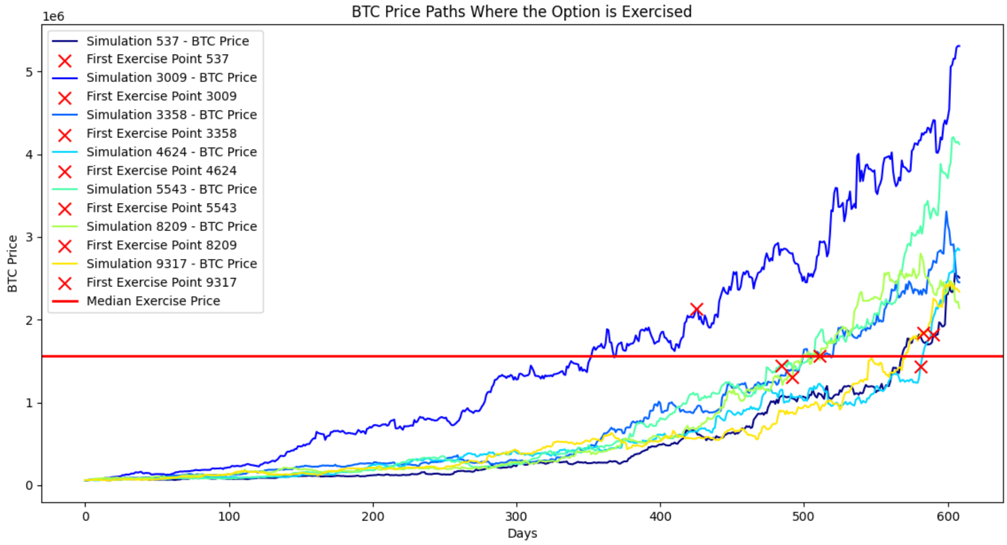

Figure 16. Bitcoin Price Paths with early Exercise. Own work

8.1 Portugal

Portugal, in comparison to Türkiye, has high electricity prices, ranging from 15.3 to 16.2 Cents per kWh, which results in relatively low option values for the original data without investment of 6.1 to 28.3 Cents depending on the mining hardware. The number of paths exercised reach from 2 for S19 Pro+ Hyd to 20 for S21 Pro and the median Bitcoin price triggering an early exercise are 2,770,172€, 1,566,932€ and 1,308,833€ respectively. It can be observed that in this case the incorporation of initial investment and liquidation value has little to no effect on prices, however, it alters the number of early exercises and its median Bitcoin prices. The results using the lower Hash Rate forecast have a significant impact on all the results, leading to a higher option value and number of early exercises and a lower median Bitcoin price for exercise points. Option values increased by 128% for S19 Pro+ Hdy, 65% for S19 XP Hyd and 48% for S21 Pro, while early exercise paths more than doubled on average. From this the important influence of the total Hash Rate on the net present value calculation can be observed.

Table I. Results with Electricity Prices of Portugal

Portugal			
Electricity Prices at 31.12.25	*Median*	*25th Percentile*	*75th Percentile*
	0.157€	0.153€	0.162€
Original Data – without investment	*Option Value*	*# Paths with exercise*	*Median Bitcoin Price*
S19 Pro+ Hyd.	0.061€	2	2,770,172€
S19 XP Hyd	0.187€	7	1,566,932€
S21 Pro	0.283€	20	1,308,833€
Original Data – with investment	*Option Value*	*# Paths with exercise*	*Median Bitcoin Price*
S19 Pro+ Hyd.	0.061€	2	2,770,172€
S19 XP Hyd	0.187€	6	1,507,425
S21 Pro	0.283€	17	1,165,516€
Sensitivity Analysis – without investment	*Option Value*	*# Paths with exercise*	*Median Bitcoin Price*
S19 Pro+ Hyd.	0.139€	7	1,786,850€
S19 XP Hyd	0.309€	12	1,406,910€
S21 Pro	0.420€	43	1,045,680€
Sensitivity Analysis – with investment	*Option Value*	*# Paths with exercise*	*Median Bitcoin Price*
S19 Pro+ Hyd.	0.139€	6	1,780,866€
S19 XP Hyd	0.309€	13	1,406,910€
S21 Pro	0.420€	40	1,076,901€

8.2 Türkiye

Türkiye's electricity prices are significantly lower than those in Portugal, reaching from 6.4 to 6.8 Cents per kWh, offering on average 42% cheaper prices. Since electricity represents the only cost in the calculation, a lower price intuitively will produce a higher value, and the results clearly show the positive impact on the option value. Option prices with the original dataset and no investment increased in comparison to the once with Portugal's electricity prices by 450% for the S19 Pro+ Hyd model, by 250% for S19 XP Hyd and by 640% to 2.09€ for the S21 Pro miner. The calculations with the lower Hash Rate show an even higher increase with S21 Pro reaching 4.75€ without initial investment, an increase of 1,031%. The number of early exercises as well shows increases, reaching over 600 for S21 Pro. The median Bitcoin price decreased, reaching lows of 328,808€ for the S21 Pro with initial investment and lowered Hash Rate.

Table II. Results with Electricity Prices of Türkiye

Türkiye			
Electricity Prices at 31.12.25	*Median*	*25th Percentile*	*75th Percentile*
	0.066€	0.064€	0.068€
Original Data – without investment	*Option Value*	*# Paths with exercise*	*Median Bitcoin Price*
S19 Pro+ Hyd.	0.336€	52	948,733€
S19 XP Hyd	0.655€	130	596,635€
S21 Pro	2.094€	350	349,377€
Original Data – with investment	*Option Value*	*# Paths with exercise*	*Median Bitcoin Price*
S19 Pro+ Hyd.	0.336€	50	933,197€
S19 XP Hyd	0.654€	124	765,758€
S21 Pro	2.082€	333	442,338€
Sensitivity Analysis – without investment	*Option Value*	*# Paths with exercise*	*Median Bitcoin Price*
S19 Pro+ Hyd.	0.501€	108	676,368€
S19 XP Hyd	1.337 €	252	485,716€
S21 Pro	4.752€	623	450,778€
Sensitivity Analysis – with investment	*Option Value*	*# Paths with exercise*	*Median Bitcoin Price*
S19 Pro+ Hyd.	0,500€	102	738.413€
S19 XP Hyd	1,331€	239	611.133€
S21 Pro	4,674€	589	328.808€

8.3 Germany

Germany has the highest electricity prices, thus, offers the lowest option values and exercise paths. To trigger an exercise with the S19 Pro+ Hyd miner with the originally forecasted Hash Rate and investment, a Bitcoin price of almost four million US Dollars would be needed.

Table III. Results with Electricity Prices of Germany

Germany			
Electricity Prices at 31.12.25	*Median*	*25th Percentile*	*75th Percentile*
	0.208€	0.205€	0.211€

Original Data – with investment	*Option Value*	*# Paths with exercise*	*Median Bitcoin Price*
S19 Pro+ Hyd.	0.012€	2	3,927,859€
S19 XP Hyd	0.083€	2	2,693,138€
S21 Pro	0.186€	8	1,640,792€

Sensitivity Analysis – with investment	*Option Value*	*# Paths with exercise*	*Median Bitcoin Price*
S19 Pro+ Hyd.	0.059€	2	2,746,763€
S19 XP Hyd	0.187€	5	1,774,882€
S21 Pro	0.299€	13	1,221,989€

8.4 Poland and Hungary

Electricity price forecasts for Poland and Hungary can be placed within the ranges observed for the other countries with Poland having a media price of 0.105€ and Hungary 0.097€. The results are in line with the expectations given the results of the displayed countries, lying within the range of Portugal and Türkiye, and are therefore put into the appendix.

9. DISCUSSION

The analysis showed that the real option generates a value in each single case. Additionally, for each scenario there is more than one early exercise, with values reaching from 2 with Portugal's and Germany's electricity prices to a maximum of 623 using Türkiye's prices. Taking into consideration that the simulation produced 10,000 different paths, the exercise probabilities are low. It is important to note that the Monte Carlo forecast of Bitcoin prices produced a wide range of paths with some reaching very high future prices. Not taking into account the simulations with dampened Hash Rate, the lowest median Bitcoin price, where early exercises are triggered, lies at 1,165,516€ for S21 Pro, with S19 Pro+ Hyd needing a future price of 2,770,172€ to be exercised. In Germany, having the highest electricity prices, an operation using S19 Pro+ Hyd would even need a price of almost 4 Million US Dollars.

It becomes clear that the S21 Pro miner is the most efficient hardware, reaching the highest option value, exercise paths and lowest median Bitcoin price needed in all of the scenarios. Despite the fact of having a lower Hash Rate than S19 Pro+ Hyd (234 TH/s vs. 257 TH/s) it has a much lower energy consumption (3,510 W vs. 5,345.6 W), offering the best choice between the three miners. The S19 XP Hyd offers the second best results and S19 Pro+ Hyd reaches the third place. Even though the first two miners have a much higher purchase price, the analysis including initial investment and liquidation value does impact the option value in some cases but does not lead to considerable changes. Consequently, it has to be noted that the assumptions about liquidation value have to be taken with caution as they are not proven to be true.

As expected, the electricity price has a huge impact on the results, given that it is the main expense in such an operation. The results clearly show that for an increased profitability a lower electricity price is essential. That is why nowadays the majority of Bitcoin mining can be observed in places with low energy costs like China, USA, Kazakhstan, Iceland or Georgia (Narayanan et al., 2016, Sun et al., 2022).

The further sensitivity analysis regarding the Hash Rate forecast similarly shows a clear impact on option prices. Depending on the country, the decrease of 20% of the total network's Hash Rate resulted in option values increasing from around 50 to over 100%. This suggests that further investigation and research would be beneficial, to predict the mining operation's profitability more accurately.

10. CONCLUSION

Interpreting the findings, it can be stated that even though the real option of the possibility to start mining does provide value, in most observed cases and countries it is low and the probability of running an efficient mining operation is small. This is mainly because high electricity prices do not allow a profitable environment. Even with Türkiye's prices the probability of exercise lies at or below 6.23%. It is therefore reasonable to redirect such operations to countries with even lower electricity prices. Analyzing and choosing the right hardware for the operation is of high importance and changes outcomes significantly. Additionally, the Hash Rate forecast must be examined in more depth since changes impact the results severely.

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APPENDICES

Python Code

Since the Python codes are extensive, a link to the code is provided.

https://colab.research.google.com/drive/1a7dd4F16DmZMb8AbsSr76vaHNf6Cfyo3?usp=sharing

Extended Results

The extended results are shared via a Google Drive link, where the following documents can be examined:

- Electricity price inputs
- Hash Rate input
- Data received from forecasts
- Discount rates for liquidation value
- Results subdivided by county and mining hardware including
    - Forecasted electricity price summary
    - Graph for each tested scenario
    - Text file for each tested scenario

https://drive.google.com/drive/folders/1dpSOW-qEqM9Pgqhv0ScPwe25aAv_juj4?usp=sharing

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This master thesis/internship report/project was developed with strict adherence to the academic integrity policies and guidelines set forth by ISEG, Universidade de Lisboa. The work presented herein is the result of my own research, analysis, and writing, unless otherwise cited. In the interest of transparency, I provide the following disclosure regarding the use of artificial intelligence (AI) tools in the creation of this thesis/internship report/project:

> I disclose that AI tools were employed during the development of this thesis as follows:
>
> - AI-based research tools were used to assist in literature and data collection
> - AI-powered software (Large Language Models) was used to assist in the creation of the Python code
> - AI-powered software (Large Language Models) was used for formatting and sorting the references

Nonetheless, I have ensured that the use of AI tools did not compromise the originality and integrity of my work. All sources of information, whether traditional or AI-assisted, have been appropriately cited in accordance with academic standards. The ethical use of AI in research and writing has been a guiding principle throughout the preparation of this thesis.

I understand the importance of maintaining academic integrity and take full responsibility for the content and originality of this work.

Moritz Grumer, 30th of June 2024