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Estimating the Marginal Industry Cost of Extracting Bitcoin within Its Network: Implications for Evaluating the Expected Profitability of Individual Farms

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ABSTRACT

With the expansion and greater acceptance of the Bitcoin network, a more in-depth economic understanding of it becomes necessary. One of the needed dimensions being chosen as a goal in this research is the evaluation of Bitcoin mining industry costs. Due to the similarity of Bitcoin mining to exhaustible natural resources, paying attention to the main factors of mining and their associated costs at the industry level, which is far less uncertain and more inclusive rather than farm or one miner, is needed. With the information obtained about the cost of mining Bitcoin industry, the expected cost of the individual farm engaged in this activity will be presented. From 60 sample miners whose publication dates were from the beginning of 2019 onwards as representative blocks, the average hash rate and the average time to create each 2016 blocks in the period from the beginning of 2019 to the 20th of June 2024, were used to evaluate the cost of Bitcoin industry. The difference between the price and the marginal costs of miners (called economic rent of Bitcoin production) was also evaluated. This was in contrast to previous studies assuming price was equal to marginal cost of mining cost. The findings showed that a significant part of the costs in the Bitcoin industry was related to energy use, while capital services costs covered a smaller share of the industry's costs. One possible area of further research would be to investigate the role of social industry costs.

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1. Introduction

It has been more than a decade since Bitcoin was introduced to the world as the first digital currency. Central and monetary authorities have no role in the creation, oversight, and security of Bitcoin. In fact, the basis of creating Bitcoin is the computational work of mining machines, the predetermined rules of the system, and the defined variables of this system, such as the difficulty variable and the reward variable. All Bitcoin transactions are recorded cryptographically in a ledger called blockchain (a set of blocks). In a time interval of about 10 minutes, a group of new transactions confirmed in a block is added to the previous block chain. In this network, a software algorithm (proof of work) is used to validate and confirm accepted transactions and add them as the new block. A 256-bit hash based on all transactions in the block along with a 256-bit hash of the previous block header and a random number (nonce) are accepted as input to the hash function in mining machines (Küfeoglu, 2019). As such, if the output of this hash function is smaller than the predetermined goal of the system, a new block is confirmed and added to the blockchain and the finder of the correct nonce is rewarded. If the output of the hash function is greater than the predetermined goal of the system, a new nonce is selected and the process described earlier is repeated again and again. Mining machines which were used in the early years of bitcoin production and mining were CPU[1] and GPU[2]. However, with the passage of time, Asic[3] machines replaced them. Asics are microchips created specifically for a specific purpose of mining digital currencies based on a certain hashing algorithm. Asic miners are different in terms of some characteristics such as the hash rate, efficiency, and noise, each of which is explained below briefly:

1. Hash rate is the average number of hashes that a miner can do per second.

1. Central Processing Units
2. Graphics Processing Units
3. Application- Specific Integrated Circuits

2. The efficiency of the miner is the amount of electricity (in Joules) used for each Terahash (TH).
3. Noise is the amount of noise caused by the operation of the miner in decibels for the people working in the farm. There have been a lot of studies on issues such as whether Bitcoin is money or an asset, the correlation between Bitcoin and other assets in investors' portfolios, factors affecting the price of Bitcoin, etc. Nevertheless, since the beginning of Bitcoin's birth, there seem to be relatively few studies about the cost structure of mining (e.g., Hayes 2017, and Baleani 2020). Most of such cost studies are in the form of farm cost analysis and evaluations of a firm engaged in this activity but not the Bitcoin industry as the whole. However, the cost information determines the amount of cost coverage of the price and is the basic element in determining the profitability of mining process in the Bitcoin network. Past cost shows miners' past performance and is used to improve and change future performance. Having cost information in allocating resources for those investors who want to enter the field of Bitcoin mining is important and could be helpful in creating an investment portfolio with maximum value. In fact, cost information is essential for making strategic decisions and financial success. Bitcoin is similar to natural resources due to the existence of mining, in which new coins can only be produced through the use of efforts of human agents who use computer resources to obtain Bitcoin. In economic dealings with this asset, the same process should be used as for exhaustible natural resources. In connection with exhaustible natural resources, one of the important tools of economic analysis is the extraction cost function. Therefore, in the case of Bitcoin, it is necessary to find paths leading us to the cost values for creating Bitcoin.

Given that the amount of hash rate used by a miner is relatively low compared to the total hash rate used for a block, uncertainty and risk should be taken into account in the evaluation of the cost of the Bitcoin mining company due to the randomness of Nonce. For this reason, pilot studies in the field of evaluating the cost of extracting firms do not seem to have led to reliable and transparent economic information. In this research, to obtain mining costs, information related to a sample of 60 machines whose production year was from 2019 onwards, was calibrated by using representative blocks (average of 2016 blocks) in the period from the beginning of 2019 to June 20, 2024. Having estimated industry mining costs, then expected individual farming costs were calculated. Ratio using to obtain expected individual farming costs is tatal hashrate of individual miner to the total hashrate of all miners selected economically in the base block. In fact, in this research, we made the evaluation basis of the cost of the entire Bitcoin industry, which can also be a guide for individual firms for risk averter managers as well.

In the following section, firstly literature reviews is presented. Secondly, the model for the research is explained. Thirdly, data needed for calibrating the model is presented and its appropriateness is explained. Fourthly, the finding of the research and justification for validity of the results are presented. Finally, the conclusion and policy recommendations are provided.

2. Literature Review

In the study of Hayes (2017), the hash power level was considered to be hypothetically 1000 Gigahash/second or 1 Terahash/second. However, in reality, the miner's hashing power could be more or less than such value and does not note that hash rate of combination of machines capacities are not fully divisible to make 1000 hashrate chosen as the base. The expected number of bitcoins produced by the miner per day can be calculated according to the following formula:

$$\frac{BTC^*}{day} = (\beta\rho/\alpha)\theta \quad (1)$$

where $\frac{BTC^*}{day}$ is the expected level of Bitcoin production when mining is done directly, β is the reward for creating a new block, ρ is the hash power used by a miner, θ is the number of seconds in a day divided by 2^{32} (normalized probability of a single hash to solve a block), and α is the difficulty level. The Bitcoin production rate at the time of writing this article was approximately 0.0003 ($\frac{BTC^*}{day}$) for one Terahash per second of mining effort.

Hayes (2017) modeled the miner's mining cost per day as follows:

$$E_{day} = (\rho/1000)(\frac{\mathrm{D}}{\mathrm{kWh}}.\mathrm{w\ per}\frac{\mathrm{GH}}{\mathrm{s}}.hr_{day}) \quad (2)$$

Where E_{day} is the dollar cost of each producer per day, ρ is the hash power used by the producer, $\frac{\mathrm{D}}{\mathrm{kWh}}$ is the dollar price of each kilowatt hour, and w per GH/s is the energy consumption efficiency of the producer's hardware.In this study, economic theory used was that in a competitive market, marginal production value is equal to marginal cost and price. Considering this issue and since the daily cost is dollar/day and production is BTC/day, as well as the fact that the division of these two ratios is equal to dollar/BTC, the price is obtained as follows:

$$P^* = \frac{E_{day}}{\frac{BTC^*}{day}} \quad (3)$$

However, it should be noted that since Bitcoin is a commodity similar to exhaustible resources and not a production commodity related to a single period, the use of the equality equation of the price of Bitcoin and the marginal cost of mining in the study of Hayes (2017) cannot be defended based on exhaustible natural resources. As compared to the study conducted by Hayes (2017) in which the electricity use was considered as an important factor to mining costs, in 2020, Baleani divided mining costs into two parts:

1) Costs related to electric energy use;

2) Investment costs in ASIC machines.

He asserted that if ASIC machines are highly efficient and miners use renewable energy, energy-related costs are of less priority and the costs related to machines and buildings would be decisive. In Hayes' model (2017), costs were calculated based on daily energy costs, but this periodicity was not compatible with the periodicity of difficulty (adjustment of difficulty after every 2016 block). Thus, in the new model (Baleani, 2020), energy costs were formulated as follows:

$$E_t = \rho_t . k_t . EF_t . n_t . 24h \quad (4)$$

where ρ_t is the average hash per second of the network (hash rate), n_t is the number of days of production of 2016 blocks, k_t is the price per kilowatt hour, and EF_t is the energy efficiency of mining hardware. In Baleani's research, on the other hand, the following assumptions were made for the formulation of capital costs:

1. The increase in the hash rate that surpasses the previous maximum level is due to the investment in new ASICs machines.
2. Investment costs are divided according to the useful life of the machine.
3. At the end of the useful life of machines, their hash rates are replaced by new machines.

To show the effectiveness of newly purchased machines (when the new maximum hash rate is reached), the hash rate function is used to estimate investment costs:

$$\Delta\theta_t = \Delta\rho_{t+1}^{max} \quad (5)$$

Where $\Delta\rho_{t+1}^{max}$ shows the increase in hash rate of the maximum hash rate function (ρ_t^{max}) (there is a break between the purchase of machines and their installation and expansion in the network). Now, considering the cost per Terahash per second (TH/S) in the form of c_t , periodic investment costs are calculated as follows:

$$I_t = \sum_{j=-r}^{t} (\Delta\theta_j c_j + \Delta\theta_{j-r} c_j) \frac{n_t}{d_t} \quad (6)$$

where c_t is average cost for each hash per second at time t, $\Delta\theta_j c_j$ is the amount of investment in new machines that have caused the hash rate to rise, $\Delta\theta_j c_j$ is the amount of hash rate from the previous machines of the network replaced by new machines, r is an index that shows the interval of useful life of machines, which means that old machines are replaced at time t-r by new machines at time t, the cost per TH of which is equal to c_t, and d_t is the number of days waiting for machines to become obsolete, which have started at 730 days and changed to 1095 days after 2016. Assuming that all mined bitcoins are exchanged during the period, we have the following equation for the price:

$$\rho_t^* = \frac{E_t + I_t}{(2016\beta_t + F_t)} \quad (7)$$

Where β_t is the number of Bitcoins as a reward for creating a new block and F_t is the exchange fee paid to miners. Although in Baleani's research (2020), a more comprehensive method was presented for extracting cost values compared to that of Hayes (2017), it should be noted that the idea that we will have lower costs by supplying energy from renewable resources and the costs of energy supply will have lower priority seems questionable. In economic evaluations, opportunity costs are the basis of evaluation in accurate economic calculations (whether source of energy is from exhaustible or renewable resource). Also, the use of equalization of marginal cost and price is not defensible as was done in the model of Hayes (2017). Furthermore, the uncertainty about the success of the firms in extracting Bitcoins was not evaluated. In introducing the mining cost function, Dai et al. (2021) introduced the miner cost function as a function of the sales amount (Q_t) and miner inventory level (H_t), $C(Q_t, H_t)$, unlike the previously described models. Unlike the hoteling model of exhaustible resources where the production rate was the control variable, they used the fact that in the bitcoin mining the amount of extraction is fixed and given by the system protocols and the selling rate of Bitcoin is the control variable. Thus, the optimization problem will be to find the selling amount of Bitcoin that maximizes its cumulative discounted expected profit. The optimization problem of a miner in the Bitcoin network is formulated as follows:

$$\int_0^\infty e^{-\beta t}\left(P_t Q_t - C(Q_t, H_t)\right)dt \tag{8}$$

Where β is the discount rate, P_t is the price of Bitcoin, $P_t Q_t$ is the income stream, $C(Q_t, H_t)$ is the cost function, and H_t is the miner's inventory level. The miner's inventory level is a function of the sales amount, block reward, and transaction fees. In this study, in appearance, the exhaustible resource model was used to design the cost function, but the statement that the amount of extraction is constant is true for the entire industry, not true for an individual firm which can be variable. Also, success of extraction by a firm is uncertain, which is not taken into consideration. Meanwhile, the cost function in exhaustible resources should be based on the efforts made in extraction and that part is missing in this model. In addressing the miner optimization problem in the Bitcoin network, Goorha (2021) introduced the production function of Bitcoin mining as a function of capital and energy inputs:

$$B(t) = F(K(t), E(t)) \tag{9}$$

The miner saves some of the bitcoins he mines for investment, V (t), and sells the rest in the market C (t). So, the following equality holds:

$$\beta(t) = V(t) + C(t) \tag{10}$$

If we consider the share of stored Bitcoins from miner's extracted Bitcoins as $v(t)$, the amount of Bitcoin miner sales can be formulated as follows:

$$C(t) = \left(1 - v(t)\right)\beta(t) \tag{11}$$

The condition of capital growth is introduced as follows:

$$\dot{K}(t) = v(t)\beta(t) - \delta(t)K(t) \quad (12)$$

In the above formula, $\delta(t)$ is the capital obsolescence rate. By dividing the variables by the amount of energy, the production function, the amount of Bitcoin miner sales, and the motion equation are rewritten as follows:

$$f(k) = F(k, e)$$

$$c(t) = \left(1 - v(t)\right)f\left(k(t)\right)$$

$$\dot{k}(t) = v(t)f\left(k(t)\right) - \delta(t)k(t) \quad (13)$$

After that, the miner's optimization problem, i.e., maximizing sales according to the constraint of capital movement, is introduced as follows:

$$MAX \ \int_0^H \left(1 - v(t)\right)f\left(k(t)\right)dt$$

$$\dot{k}(t) = v(t)f\left(k(t)\right) - \delta(t)k(t)$$

$$f_k(k) > 0 \quad f_{kk}(k) < 0 \quad (14)$$

It should be noted that the use of the hoteling model in the form of a competitive firm is permissible under reliable conditions, but a Bitcoin mining firm faces risk and uncertainty and should be included in the micro foundation of a firm behavior. As explained, there are few studies in the field of Bitcoin mining cost. In most of these studies, the base of analysis is a representative firm or what is common to call a farm. Though farm analyses stated above are trying to do cost evaluation of mining Bitcoin, they seem to have two main shortcomings: either they make assumption of equality of price and marginal costs or neglect including individualistic risk of mining Bitcoin. While in the industry analysis being done in our research there is no individualistic risk involved nor assuming unrealistic assumption of equality of price and marginal cost is needed.

3. Research methodology

Although the mining process in the Bitcoin network leads to a virtual asset called Bitcoin, it requires effort factors and considering the unmined amounts of Bitcoin, like the extraction of exhaustible resources. In fact, in the costs related to Bitcoin mining, effort factors in the form of miners (mining machine), energy, the quality of the working environment in terms of the absence of noise pollution, and the remaining unmined Bitcoins should be taken into account. It is important to note that noise was evaluated from the perspective of those who work in the system and not the effects of neighborhood. In evaluating the cost function of Bitcoin, in addition to paying attention to the factors of production (such as mining machines and electricity), there are other institutional factors in the protocols of this cryptocurrency that are effective in the outcome of production and should be considered in evaluations. These protocols, which occur in the form of different time periods, are listed below:

1. Each block is created in a time period of about 10 minutes.
2. Every two weeks, the average duration of the block creation time is evaluated and the difficulty variable decreases or increases to reach the base time of ten minutes on average. Hence, the number of hashes needed to create blocks will change.
3. Every 4 years, the reward for creating each block is halved. In fact, as the number of unmined Bitcoins decreases, the cost of production increases. Based upon the factors mentioned above that are effective in the process of producing Bitcoin, the cost function of Bitcoin can be introduced as follows:

$$C = C(P_e, P_M, D, X) \quad (15)$$

where P_e is the price of electricity, P_M is the price of miners, D is difficulty in bitcoin network, and X is the amount of unmined remaining Bitcoin. Since the increase in costs caused by the decrease in the amount of unmined Bitcoins is taken into consideration in how the mining reward reduces every 4 years (this phenomenon in the system protocol is called halving or dividing reward for each unit Bitcoin in 2 every 4 consecutive year), it is necessary to evaluate the costs of Bitcoin mining for different periods of 4 years separately. Having considered the above points the costs related to the effort in the form of either the cost of the total Bitcoins mined in each block or the cost per unit of mined Bitcoins in each block, which accrues for the whole system of Bitcoin industry(without explicitly entering the variable (X)). In the following, based on the variables mentioned above, the path of Bitcoin production and the cost assessment process in the Bitcoin industry are explained in more details. Creating each block through the Bitcoin network is a process that takes 10 minutes on average and requires a proportional hash rate based on the existing difficulty of the network. The current difficulty variable is checked and adjusted by the system almost every two weeks so that after creating 2016 successful blocks (after about 2 weeks), the average time to create a block will be 10 minutes. In the network, the first miner randomly finding matching nonce that results in a hash that is smaller than the system's target will be given block reward along with the fees of transaction costs occurring during the function of that particular block[1]. The value of the reward is halved every 4 years (currently equals 3.125 Bitcoins). Thus, to participate for the Bitcoin mining, one needs to buy a miner that needs electricity to operate in the production process, while its operation may also make a noise. Based on different characteristics of miners, different values of hash rate, efficiency and noise, etc., each miner's function is like a technological activity in the mining of Bitcoins similar to the situation of using activities to find isoquants in the production process of any products in micro economics analysis (Varian, 1992). From the aggregate combination of these activities, production of the industry occurs and the individual miner finding the appropriate nonce receives the block rewards.

1. These transaction fee rewards are not being accounted for in this research, due to not having documented data.

Therefore, costs are incurred for all miners collectively, but reward is given to a particular miner operating individually or in a pool of miners in a firm often called farm. In other words, each miner faces uncertainty and risk in evaluating their individual activities, but the aggregate production does not entail individual risks and is filtered by pooling all miners collectively while incurring costs for all firms. Thus if the difficulty becomes as is adjusted to be for the whole blocks which operates 10 minutes, by finding the economic costs of all combined technics by all miners together industry costs of obtaining rewards for each block is obtained and individualistic uncertainties are bring filtered away. In brief with filtering individualistic uncertainties are evaluated minimum costs associated to all prevailing technologies and due to the theories of sufficiency of cost in microeconomics (Jehle, 2011) these cost efficient chosen points are both economically as well as technically efficient points from industry point of view. Of course, the industry cost function would assume that effort resources prices (electricity and machine services) are obtained from competitive market. For the price of energy in the market, electricity price is used and the price of services by miners are also obtained by dividing the costs of purchase of each miner by its life for attaining depreciation and finding the value of services related to the time allocated to each block. Accordingly, 60 miners whose publishing time was from 2019 onwards were selected as a sample of the mining activities of this research. The method of creating cost values is explained below. The representative blocks of the Bitcoin network during the period of the beginning of 2019 and the 20th of June 2024, where each block was 2016 blocks away from the next block, were evaluated separately. In each evaluation, it was assumed that only one type of the 60 selected model machines was involved in the creation of that block. In fact, each block of 60 activities was evaluated each time considering that only one type of machine was involved by all miners in its creation. Then, the comparative costs could determine which technic or combination was economically efficient collectively. To get the number of

M-type miners creating Block i, the average hash rate of the representative block was divided by the hash rate of the machine. The number of M-type machines used in the construction of Block i is shown by n_i^M.Then the amount of electricity used, by Block i for all miners of type M is obtained by the following formula:

$$EC_i^M = miner's\ hash\ rate \left(\frac{TH}{S}\right) * efficiency \left(\frac{J}{TH}\right) * \left(\frac{seconds\ to\ create\ Block\ i}{3600}\right) * n_i^M \qquad (16)$$

where miner's hash rate (TH/S) is the hash rate of the machine in terms of tera hersh per second, efficiency (J/TH) is the efficiency in terms of joules per tera heresh, (seconds to create Block i)/3600 is the number of seconds to create Block i per hour. By multiplying these 3 variables, the amount of electricity used (watt hours) of an M-type miner is obtained. By multiplying this value by n_i^M , we will have the amount of electricity used to create a block by the miners of type M with the number of n_i^M units. To convert this amount of electricity use into kilowatt hours, it is divided by 1000. In this way, it is possible to have the amount of electricity used by M-type miners in creating Block i (EC_i^M) in kilowatt hours (it is worth noting that one joule per second is equivalent to one watt). To calculate the cost of capital services used by n_i^M miners of type M for Block i, we will have:

$$CC_i^M = n_i^M * price\ of\ miner(M) * (1 + (noise - 50) * .0062) / (number\ of miner's\ span\ life\ in\ years * 365 * \frac{3600}{seconds\ to\ create\ Block\ i} * 24) \qquad (17)$$

where $price\ of\ miner(M)$ is the price of the miner in the market, number of miner's span life in years is the number of years of useful life of the miner, and CC_i^M is the cost of capital services of M-type miners in creating Block i. A year is 365 days, a day is 24 hours, and each hour is 3600 seconds. Noise is the sound level of the miner in decibels, the harmless standard of which is assumed to be 50 db. Rodrigo (2024) considered the noise level as an effective factor on the property value of residential areas and estimated that each unit of noise caused a decrease in one dollar value of the property by an average of 0.0062$. The same approach was used here in adding to the cost of those miners having noise of above 50 db. Per unit of noise difference from the standard of 50 db, the amount of .0062 was added to the costs related to the price of the miner so that its inappropriateness in terms of noise pollution was evaluated with a higher cost for calculating the economic efficiency of that type of miner. After that, the total cost of M-type miners for creating Block i could be calculated using the following formula:

$$C_i^M = PE * EC_i^M + CC_i^M \tag{18}$$

where C_i^M is the total cost of the M-type miners for Block i and PE is the price of electricity.10 percent of this total cost is also added to this cost due to other costs, such as internet services, hardware maintenance, computer cables, etc. (CC_i^M). By dividing the cost of each block by the reward value of that block, the cost of creating one Bitcoin in the desired block was obtained, which could be then compared to the price at the time of creating each block. In this way, for each type of miner (60 sample miners were selected in this research), the information on the cost of creating a Bitcoin unit for blocks from the time of the release of this miner to July 2024 was provided. By putting this information together, for each block, the lowest cost obtained by these 60 miners to create one Bitcoin unit was taken as the basis of the marginal cost of the entire industry. In fact, all technologies in the form of activities were evaluated both technically and efficiently as well. In the last stage, among these minimum costs of different miners, the minimum cost of the industry was created in such a way that the adjustment was made for the noise cost as well.

4. Data set

In the Bitcoin network, various blocks containing network transaction information and are recorded for miners are created in an average time interval of about 10 minutes. Every 2016 blocks (every 2 weeks), the average block formation time is checked by the system to adjust the network difficulty variable accordingly. In this research, representative blocks, each of which contained average hash rate information, as well as the time spent to create 2016 blocks recorded during a period of almost 2 weeks, were used as the basis for evaluation. In other words, the average data over 2016 blocks were looked upon as a representative of all of them individually. It is important to note that during this period of almost two weeks, the value of the difficulty variable was constant. It is noteworthy that due to the greater transparency of the Bitcoin mining industry in the United States, information related to this country was used in this research. The information related to the average hash rate of the representative blocks was collected from the btc.com website and in terms of Exahash units per second every two weeks from the beginning of 2019 until the 20th of June 2024. The average hash rate of the representative block, i.e., the average number of hashes per second in the time period of creating 2016 blocks, was used to reach the answer. To equate the hash rate unit of the representative block with the hash rate of the mining machines (bits per second), the hash rate of the representative block was multiplied by 1,000,000. The information about the average time taken to create 2016 blocks in a representative block was collected from btc.com in seconds. The changes in difficulty were applied to the model in this way.

The hash rate of the machine was the average number of hashes performed by the Bitcoin mining machine per second. The information related to this variable in terms of Terahash per second, along with the information related to the release date of miners and noise in decibels, was collected from the sites of mining companies, such as Bitmain, articles, and other internet sources.

The efficiency of the mining machine was the amount of joules used per Gigahash unit, which was multiplied by 1000 to convert it to joules per Terahash. The information related to these data was collected from the sites of mining companies, such as Bitmain, articles, and other internet sources.

The price of miners in dollars was collected from cryptominerbros.com. The information about the price of Bitcoin was collected daily and in terms of dollars from the investing.com site. By averaging the daily price values in the time interval between two representative blocks, the average price of Bitcoin for a period of almost two weeks was calculated. Then, these prices in current values were converted to the price basis of 2024 while taking into consideration the inflation rates from 2020 to 2024. According to De Vries 's (2021), the useful life for miners between July 2016 and July 2020 was between 2.15 and 1.12 years. In the present research, 2 years were considered as the number of years of useful life of miners whose publishing dates were in this time period. For machines whose publishing dates were after this period, the number of years of useful life of miners was 3 to 5 years, 5 to 7 years, and 7 to 10 years, etc. according to the different data existing in different sources and their manufacturing companies. In this research, the two scenarios of 5 and 7 years were used for this purpose. The price of electricity was fixed at $0.07 per kilowatt hour of electricity use. In a research paper, Koss (2024) used 4.6 and 10 cents per kWh to estimate the cost of mining in Texas. We used the average of these two numbers and then rounded them to 7 cents per kWh. According to the governing rules of the Bitcoin network, the reward is halved every 4 years. During the selection period of this research, 12.5, 6.25, and 3.125 units of Bitcoin were the bases of evaluation for blocks before 630,000, from 630,000 to before 840,000, and from 840,000 onwards, respectively. It is important to note that since the input prices based on 2024 were used in the process of estimating cost values, the calculated costs had a real value from the perspective of 2024. No further adjustments were needed for price changes for the inputs, but we needed to make changes for the price of Bitcoin to consider the inflation rate from 2019 to 2024.

5. Findings

By implementing the model for 60 miners with a release date from the beginning of 2019 onwards and obtaining the information about representative blocks from the beginning of 2019 to the 20th of June 2024 under the two scenarios of 2 and 5 years, as well as 2 and 7 years, the relationship between the real price and the marginal cost was obtained as shown in Figure 1.

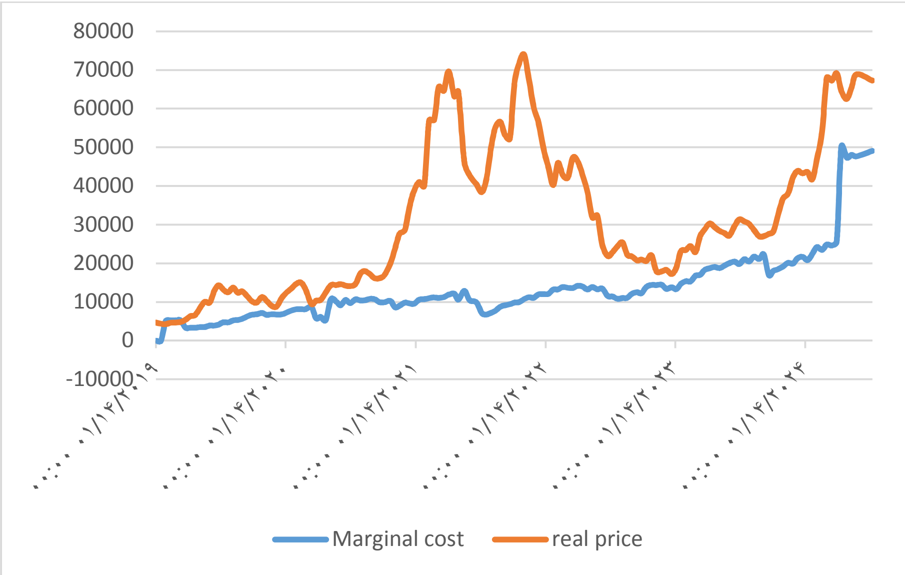

Fig 1: The relationship between the real price and the marginal cost

Source: research finding

As shown, there are no significant differences between the two selected options graphically and it is evident that the price is higher than the marginal cost for those options in the entire time period. Rent values, i.e., the difference between the price and the marginal cost of Bitcoin mining by the cost-minimizing miner can be seen in Figure 2. The existence of these values infers a wrong conclusion made about the equality of price and marginal cost by some economists implementing equality of marginal cost and price. As one can see, in the selected period of this study, the positive presence of rent is evident, similar to other exhaustible natural resources (such as gold) showing that the price is higher than the marginal cost.

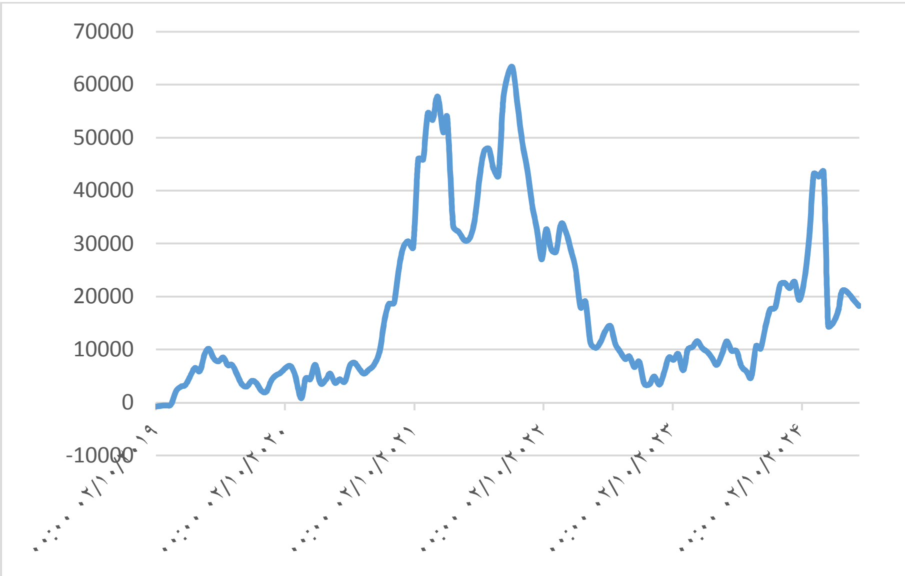

Fig 2: Rent in Bitcoin industry

Source: research findings

Using the t-test, Hypothesis H_0, which indicates the equality of the price and the marginal cost of miners for different blocks during the selected interval, is tested against Hypothesis H_1, stating that the price is greater than the marginal cost. The t-statistic value is 5.79 and the value of $t_{284,0.05}$equals 1.65. Thus, the test statistic is in the critical area and the null hypothesis is rejected emphasizing again the inequality of the price and the marginal cost of Bitcoin mining since the price is higher than the marginal cost of extraction. It should be noted that the Bitcoin price changes due to many factors, including randomness. The marginal cost is also random at least because of changes in its difficulty variable. Table 1 shows the miners minimizing the marginal cost of producing Bitcoin for representative blocks in the selected time frame of this study. As one can see, the cost of capital services at the beginning of the selected period of this article is 34.81% and then 17.14% (taking into account the useful life of 5 years of miners) and finally decreases to 12.94% (taking into account the useful life of 7 years of miners). This issue itself indicates that a major part of the mining costs in the Bitcoin industry is related to energy use and confirms the global concerns of high energy use in the Bitcoin industry and the creation of environmental pollution as a consequence.

Table 1: Miners minimizing the marginal cost of producing Bitcoin

Date	Height span	Mining machine selected	Percentage of miner capital services per one unit of Bitcoin for 2 year depreciation	Percentage of miner capital services per one unit of Bitcoin for 5 year depreciation	Percentage of miner capital services per one unit of Bitcoin for 7 year depreciation
2/10/2019 3/24/2019	562464 568512	Innosilicon T2T	31/22		
4/7/2019 3/26/2020	570528 622944	Bitmain Antminer S17	36/93		
4/8/2020 4/21/2020	624960 626976	MicroBT whatsminer M30S	33/002		
5/5/2020 6/30/2020	628992 637056	Bitmain Antminer S19 pro	34/92		
7/13/2020 9/20/2020	639072 649152	MicroBT whatsminer M50S	37/97		

Date	Height span	Mining machine selected	Percentage of miner capital services per one unit of Bitcoin for 2 year depreciation	Percentage of miner capital services per one unit of Bitcoin for 5 year depreciation	Percentage of miner capital services per one unit of Bitcoin for 7 year depreciation
10/4/2020 5/30/2021	651168 685440	MicRoBT whatsmner M30S++		13/36	9/92
6/14/2021 4/27/2022	687456 733824	Bitmain Antminer S19j pro		16/75	12/56
5/11/2022 6/22/2022	735840 741888	Bitmain Antminer S19pro+ hyd		12/158	8/997
7/7/2022 8/22/2023	743904 804384	Bitmain Antminer S19XP		24/89	19/15
9/6/2023 9/19/2023	806400 808416	Anaan Avalon A1466		24/64	18/93
10/3/2023 7/20/2024	810432 848736	MicroBT whats miner M66S Hyd		11/04	8/14

To find the expected time for a farm economically performing mining management to earn a profit equivalent to a block of efficient machine, either the following two formulas could be used to find the number of block periods needed to receive a reward.

$$Number\ of\ block\ periods\ needed\ to\ recieve\ a\ reward = \frac{total\ hashrate\ of\ all\ miners\ selected\ economically\ in\ the\ base\ block}{total\ hashrate\ of\ an\ individual\ miner\ or\ the\ pool\ hashrate} \quad (19)$$

$$Number\ of\ block\ periods\ needed\ to\ recieve\ a\ reward = \frac{number\ of\ miners\ in\ the\ base\ block}{number\ of\ miners\ in\ the\ pool} \quad (20)$$

By getting the $number\ of\ 10\ minutes$ in the above equation, we have the expected time needed for a farm with the given hash rate to earn the profit of industry in about 10 minutes.

To apply the findings of the present research for one miner or a number of miners, the following examples are considered for Block 846720, for which the miner that minimizes the cost is MicroBT whats miner M66S. The number of cost-minimizing miners used to obtain this block is about 2,000,000 units. If we consider a pool that has only 200,000 miners of this type, this number of miners will be 0.1 of the number of miners that have created this block. So, if this number of miners wants to create such a block that has been created by two million miners in 10 minutes, they will need 100 minutes of time, that is, 1 hour and 40 minutes. This way, the expected economic analysis of a pool or a farm can be done. If we consider a single miner creating this block, it will take 20,000,000 minutes, which is equivalent to about 38 years. This proves that working in the form of a miner or small units is not economical in terms of time of life span of a miner, the maximum time of which is 10 years. Through interpolation, any combination of hash rates can be evaluated in terms of time needed to expectedly get rewards. Also, if the manager is risk averter instead of being risk neutral, we can use the formula of compensating for risk ($E(X) - \beta\sigma^2(X)$), taking part of the expected profit as risk premium and possibly as insurance cost for averting the risk. Here, β is the degree of risk aversion, $E(X)$ is the expected profit, and the risk of X is measured by the variance of $\sigma^2(X)$ (Fabozzi, 2012). It is noteworthy that this study provided the necessary framework for calculating and evaluating the marginal cost in the Bitcoin industry using the US data available. For a complementary work, different scenarios that arise according to varied conditions, as well as the necessary sensitivity analysis, should be evaluated to increase accuracy of calculation and its usability.

6. Conclusion and recommendations

In this paper, an attempt was made to calculate the Bitcoin cost based on the Bitcoin industry instead of evaluating a miner. Three goals were in mind:

1. Calculating marginal rent of each bitcoin mined for the industry level
2. Eliminating individualistic risk of mining Bitcoin in calculation cost of Bitcoin.
3. Obtaining expected cost of mining Bitcoin by a farm or a pool of farms.

Also, according to the research findings, basing the equality of price and final cost in previous evaluations made in the Bitcoin field is incorrect. The reason is that due to the halving of the reward every 4 years, the market is such that the miners of Bitcoin in the next 4 years could also have a profitable activity. In fact, similar to the issue of reducing the quality of mining that exists in connection with exhaustible resources, the current miners of the Bitcoin industry enjoy a rent. Therefore, the sum of the rent and the marginal cost of mining will determine the price.

It is noteworthy that, as we saw in the findings section, the majority of the costs related to mining are made up of electricity costs. This is important because the type of energy source used in the Bitcoin industry must be carefully considered because fossil energy sources involve environmental pollution that could lead to social costs. Also, due to the scarcity of exhaustible natural resources, its use could lead to further social cost of providing energy.

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Conflicts of interest

The authors declare no conflict of interest.

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